

## **Lecture 2 - Semiconductor Physics (I)**

February 6, 2003

### **Contents:**

1. Silicon bond model: electrons and holes
2. Generation and recombination
3. Thermal equilibrium
4. Intrinsic semiconductor
5. Doping; extrinsic semiconductor

### **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:

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

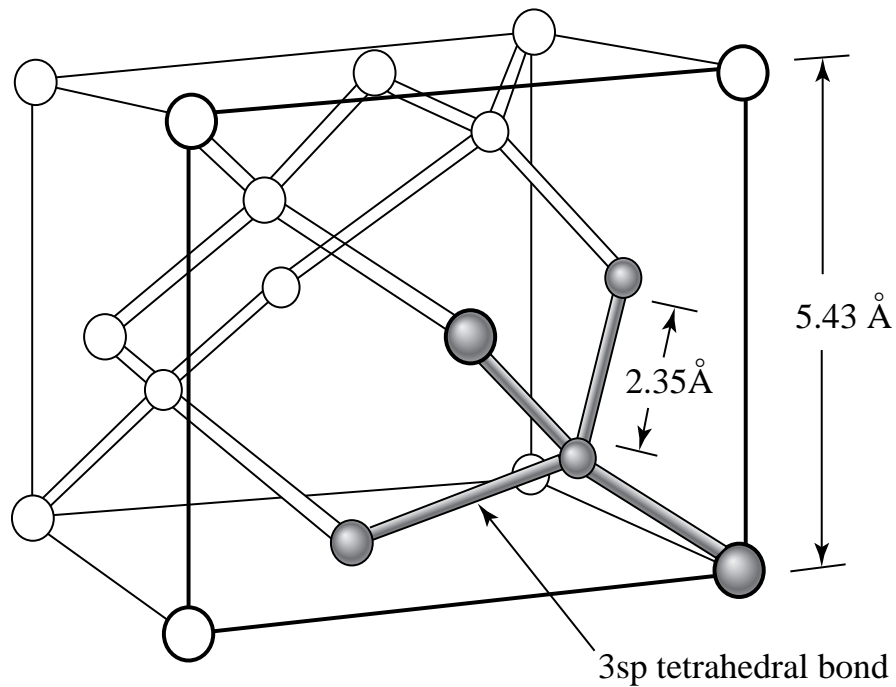
Electronic structure of Si atom:

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

Other semiconductors:

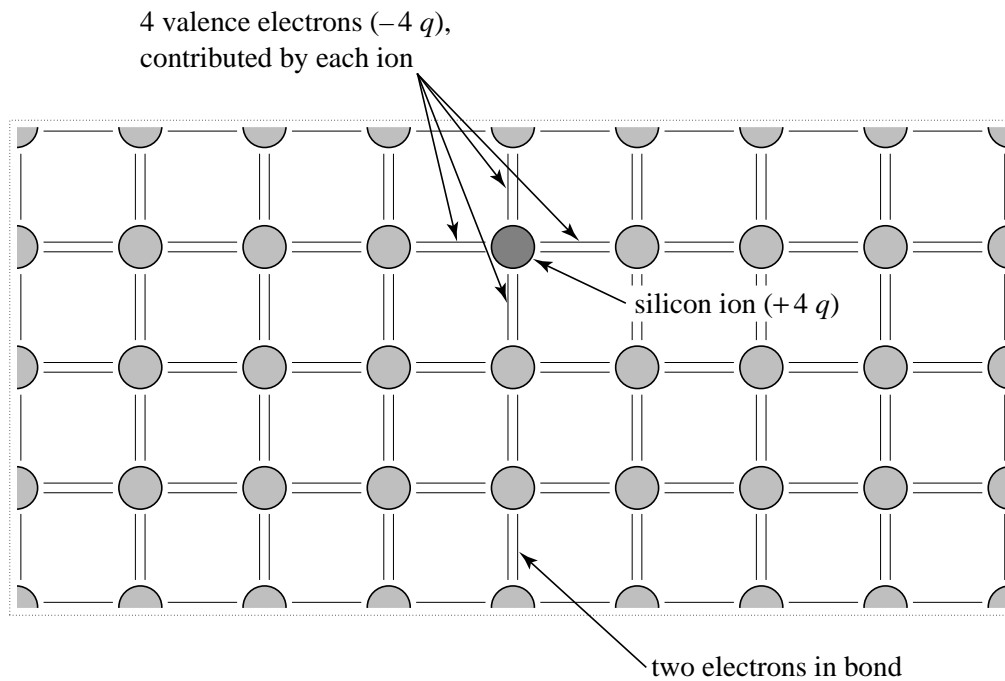
- Ge, C (diamond form), SiGe
- GaAs, InP, InGaAs, InGaAsP, ZnSe, CdTe  
(on average, 4 valence electrons per atom)

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

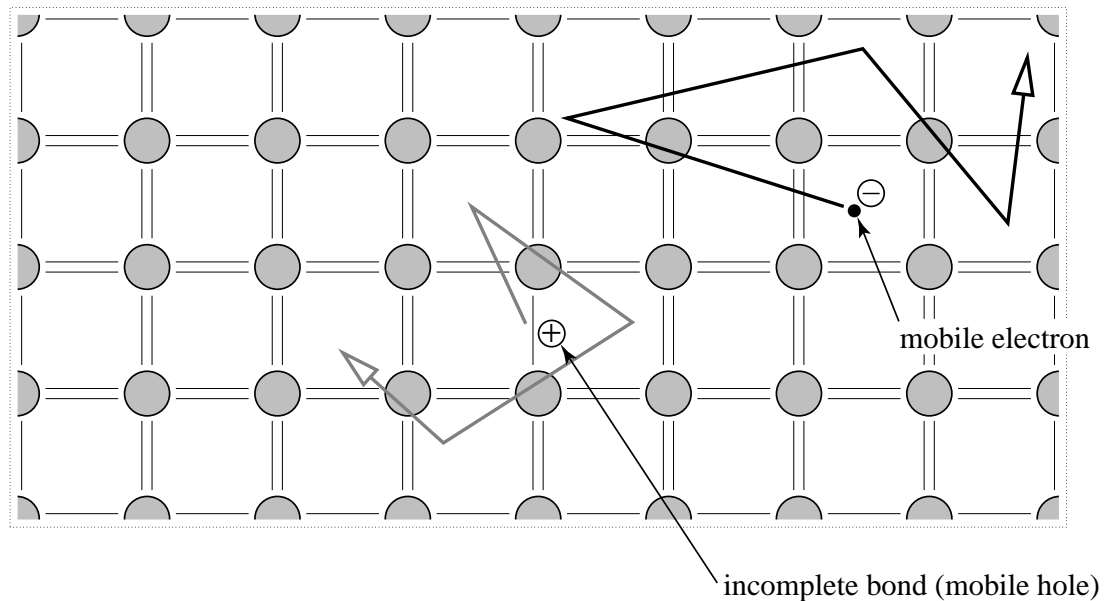
Simple "flattened" model of Si crystal:



At 0K:

- all bonds 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,  $1.6 \times 10^{-19} \text{ C}$ )

"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 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

- requires energy from thermal or optical sources (or other external sources)
- *generation rate*:  $G = G_{th} + G_{opt} + \dots [cm^{-3} \cdot s^{-1}]$
- 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  $\Rightarrow$

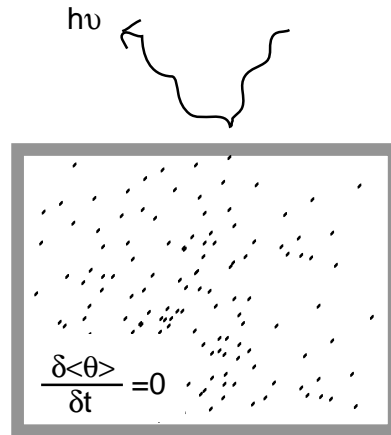
$$R \propto n \cdot p$$

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:  $R_o \propto n_o \cdot p_o$

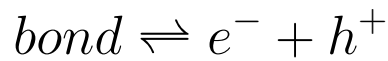
In thermal equilibrium:

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

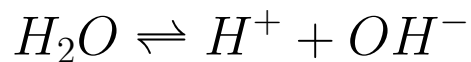
Important consequence:

*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:



similar to water decomposition reaction:



*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:

$$[H_2O] \simeq \text{constant}$$

Hence:

$$[H^{+}][OH^{-}] \simeq \text{constant}$$

## 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:

$$n_o = p_o = n_i$$

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

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]

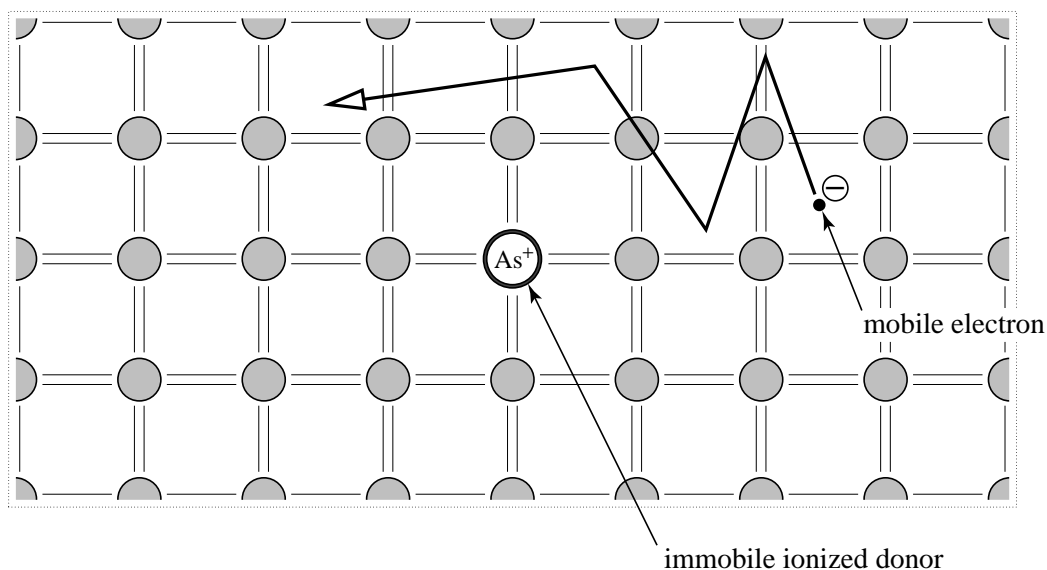
**5. Doping:** introduction of foreign atoms to engineer semiconductor electrical properties

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

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

	IIIA	IVA	VA	VIA
	<sup>5</sup> B	<sup>6</sup> C	<sup>7</sup> N	<sup>8</sup> O
	<sup>13</sup> Al	<sup>14</sup> Si	<sup>15</sup> P	<sup>16</sup> S
IIB	<sup>30</sup> Zn	<sup>31</sup> Ga	<sup>32</sup> Ge	<sup>33</sup> As
	<sup>48</sup> Cd	<sup>49</sup> In	<sup>50</sup> Sn	<sup>51</sup> Sb
				<sup>52</sup> 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)  $\rightarrow$

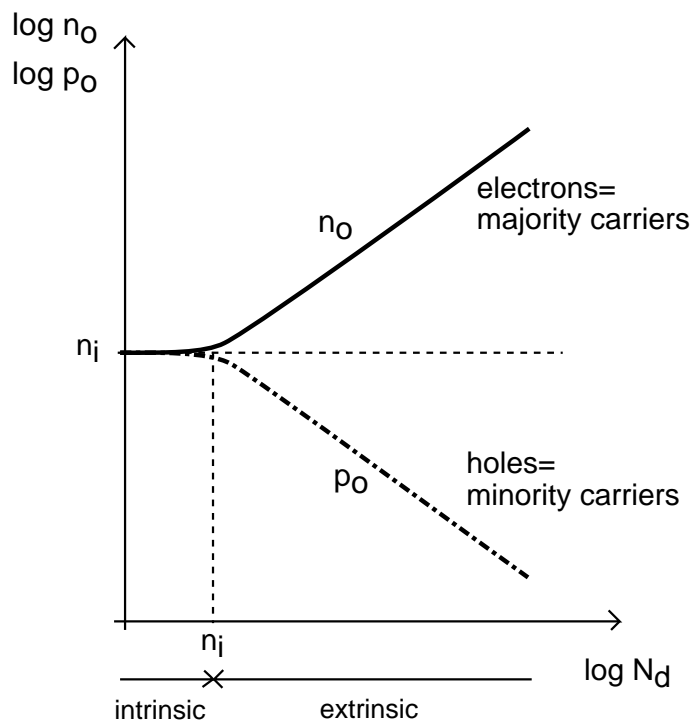
$$n_o = N_d \qquad p_o = \frac{n_i^2}{N_d}$$

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



Chemical reaction analogy:

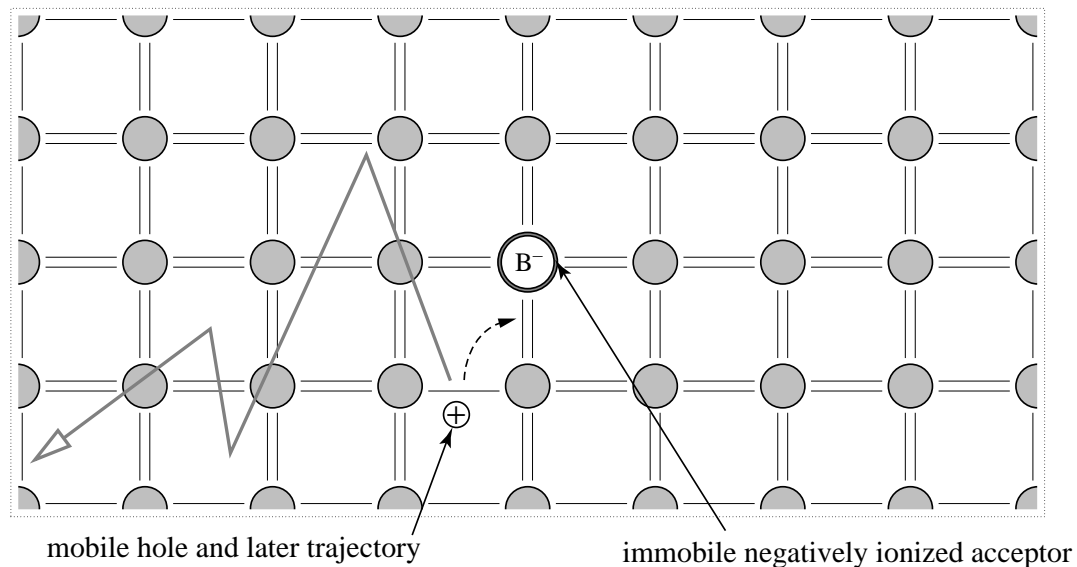


B. ACCEPTORS: introduce holes to the semiconductor  
(but not electrons)

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

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

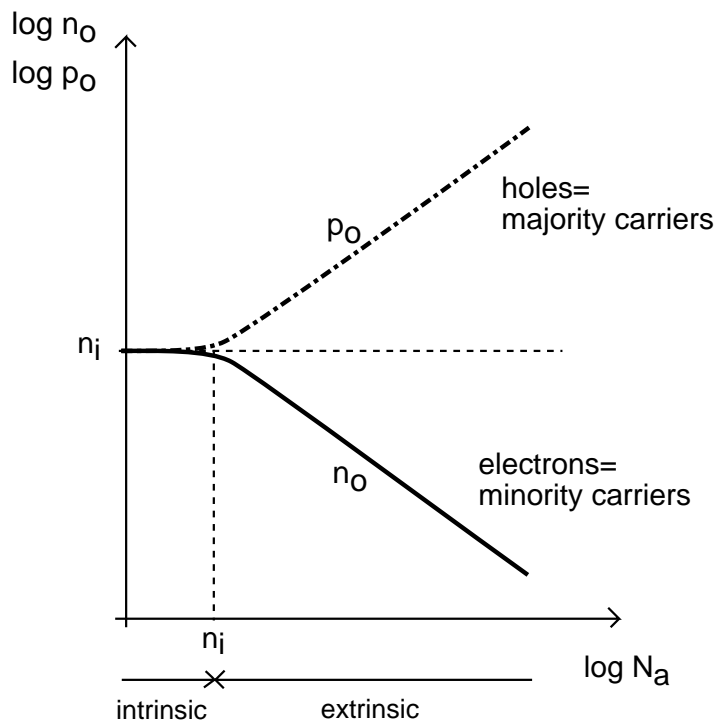
$$p_o = N_a \qquad n_o = \frac{n_i^2}{N_a}$$

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

Example:

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

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



Chemical reaction analogy:



## 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:

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

- *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:

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

- p-type semiconductor:

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