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, Sections 2.1-2.3

Why are IC’s made out of Silicon?

SILICON IS A SEMICONDUCTOR—

a very special class of materials

- Two types of “carriers” (mobile charged particles):
  - electrons and holes
- Carrier concentrations can be controlled over many orders of magnitude by addition “dopants”
  - selected foreign atoms
- Carrier concentrations can be controlled electrostatically
- ….

1. Silicon bond model:

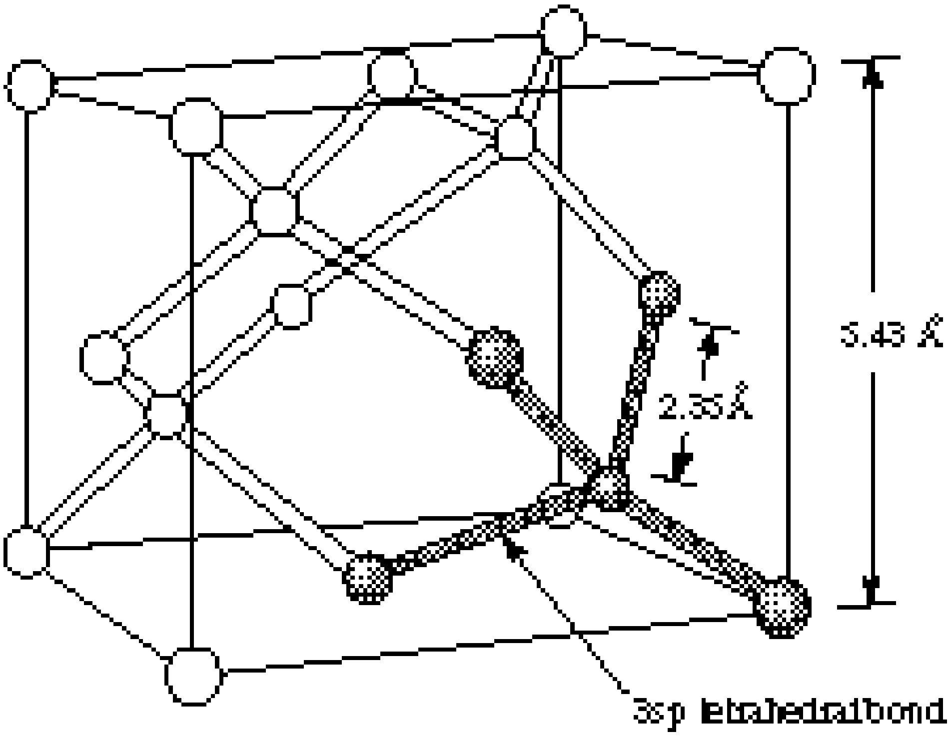
electrons and holes

Si is in 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

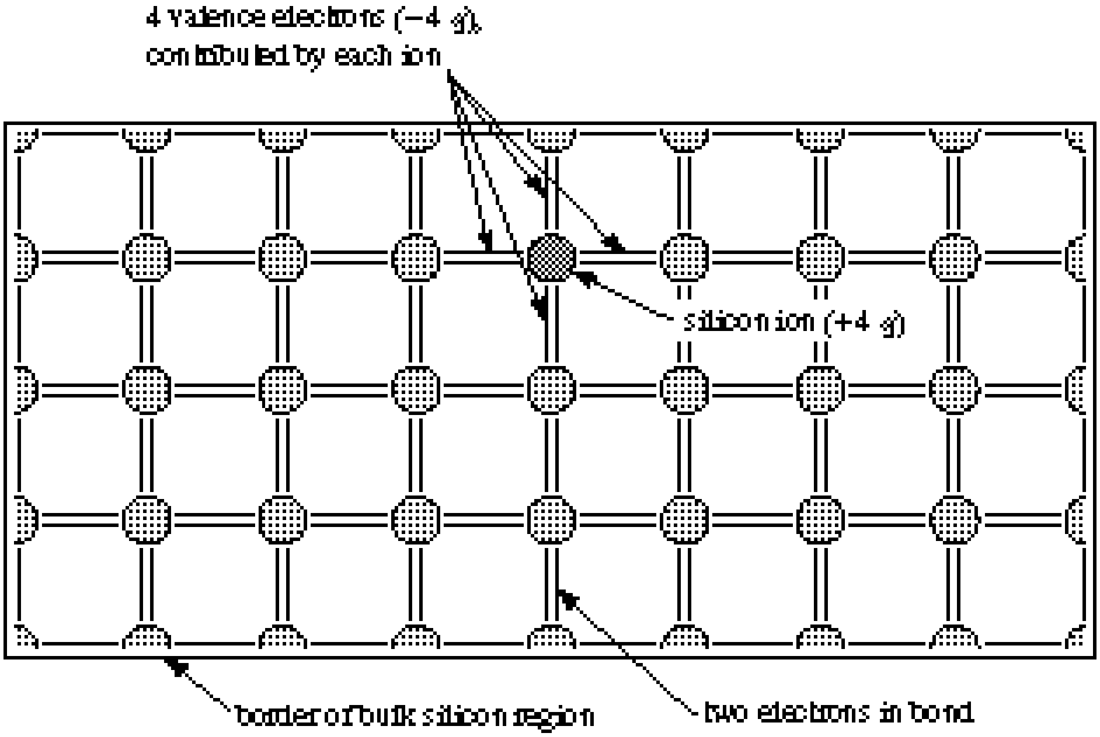
- Electronic structure of silicon atom:
  - 10 core electrons (tightly bound)
  - 4 valence electrons (loosely bound, responsible for most of the chemical properties
- Other semiconductors:
  - Ge, C (diamond form)
  - GaAs, InP, InGaAs, InGaAsP, GaN, ZnSe, CdTe (on the average, 4 valence electrons per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

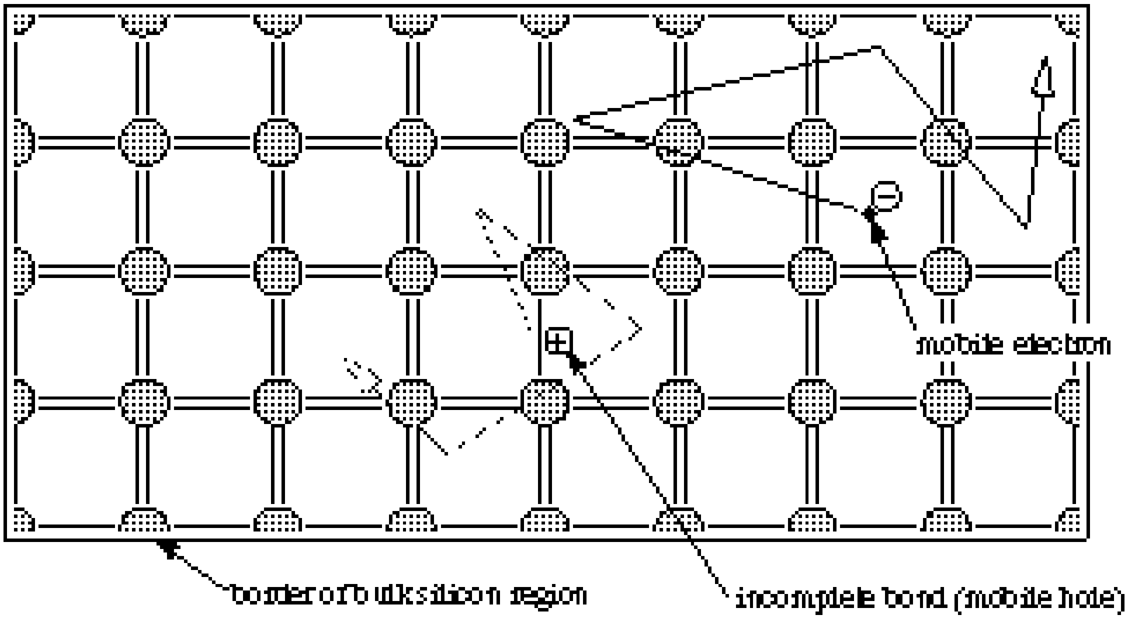
Simple “flattened” model of Si crystal



At 0K:

- All bonds are satisfied
  - – 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 <u>free</u> electron
- Not concerned with bonding electrons or core electrons
- Define:
  - n ≡ (free) electron concentration [cm^{-3}]
  - p ≡ 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***: $\mathbf{G = G(th) + G_{opt} + \ldots [cm^{-3} \cdot s^{-1}]}$
- In general, *atomic density* >> n, p

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

  - 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***: $\mathbf{R = [cm^{-3} \cdot s^{-1}]}$
- 1 recombination event requires 1 electron + 1 hole

$$\mathbf{R \qquad n \cdot p}$$

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

3. Intrinsic semiconductor

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

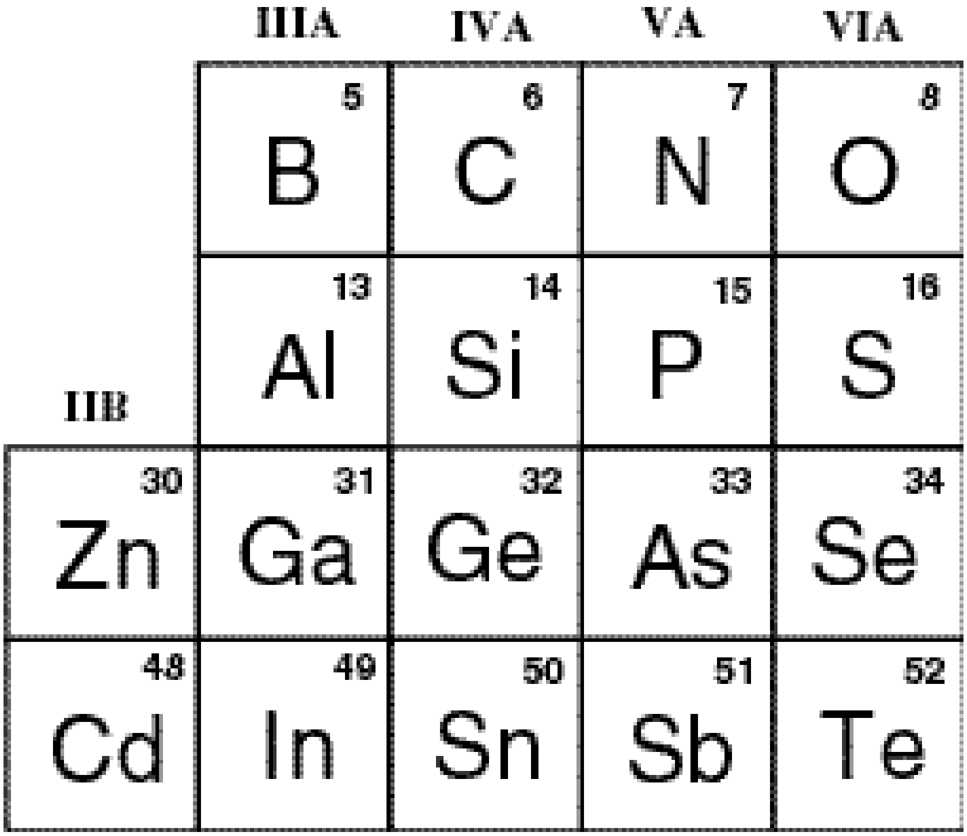
THERMAL EQUILIBRIUM =
Steady state + absence of external energy sources

4. Doping

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

A. DONORS:

- Introduce ***electrons*** into the semiconductor (but not holes)
- For Si, group V elements with 5 valence electrons (As, P, Sb)



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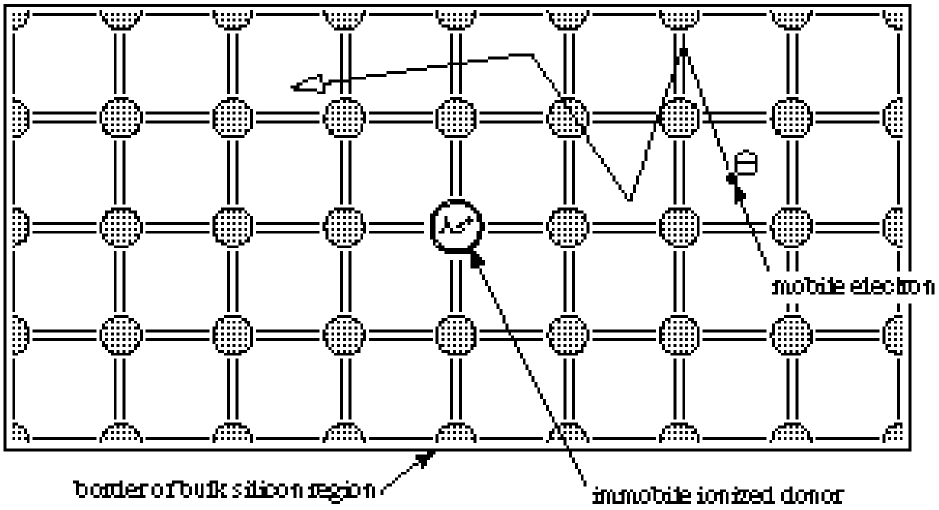
Doping: Donors Contd...

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



Define:

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

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

Doping: Donors Contd...

- If $N_d >> n_i$, doping controls carrier conc..
  - *Extrinsic* semiconductor

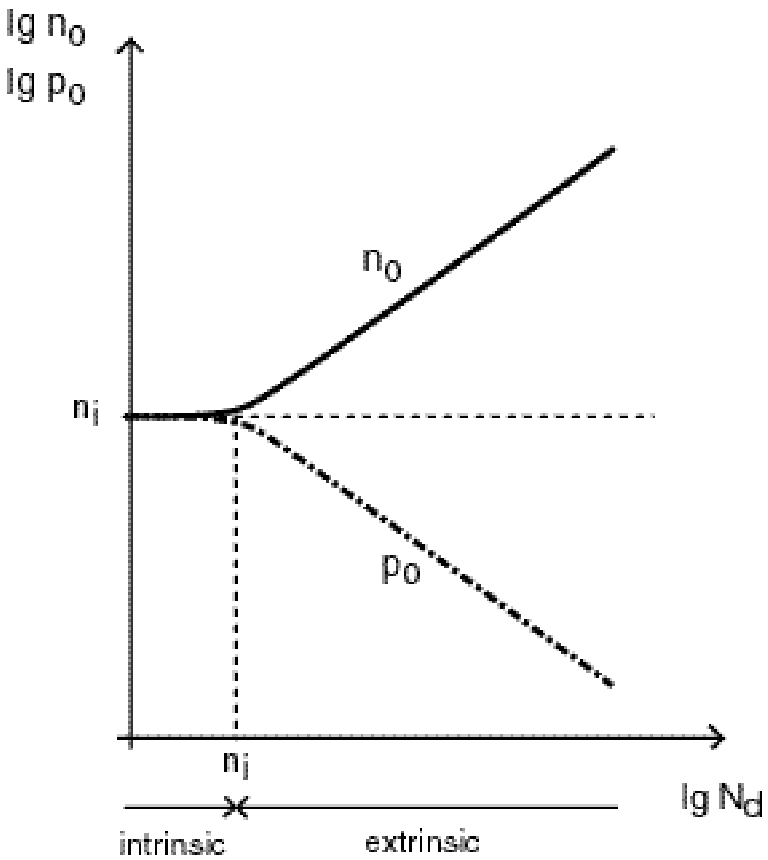
$$\mathbf{n_o = N_d} \qquad \mathbf{p_o = \frac{n_i^2}{N_d}}$$

Note: $n_o >> p_o$: ***n-type semiconductor***

Example:

$N_d = 10^{17}$ cm^{-3} → $n_o = 10^{17}$ cm^{-3} , $p_o = 10^3$ cm^{-3}

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

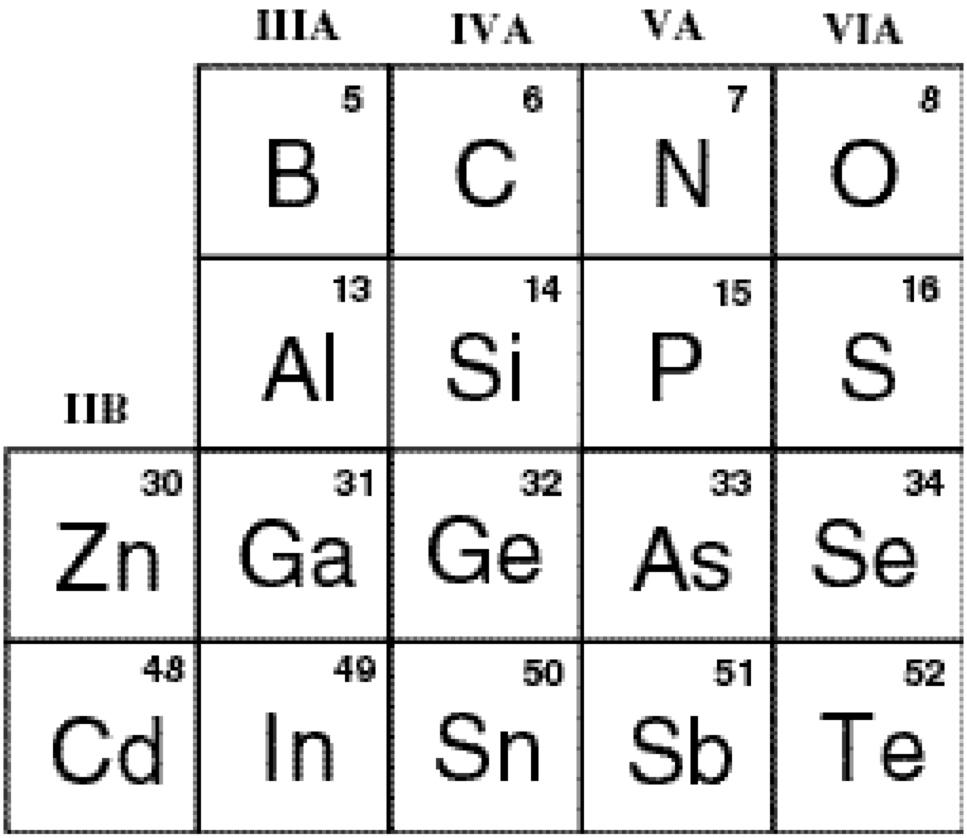


- **Electrons** = ***majority carriers***
- **Holes** = ***minority carriers***

Doping : Acceptors

B. ACCEPTORS:

- Introduce ***holes*** into the semiconductor (but not electrons)
- For Si, group III elements with 3 valence electrons (B)



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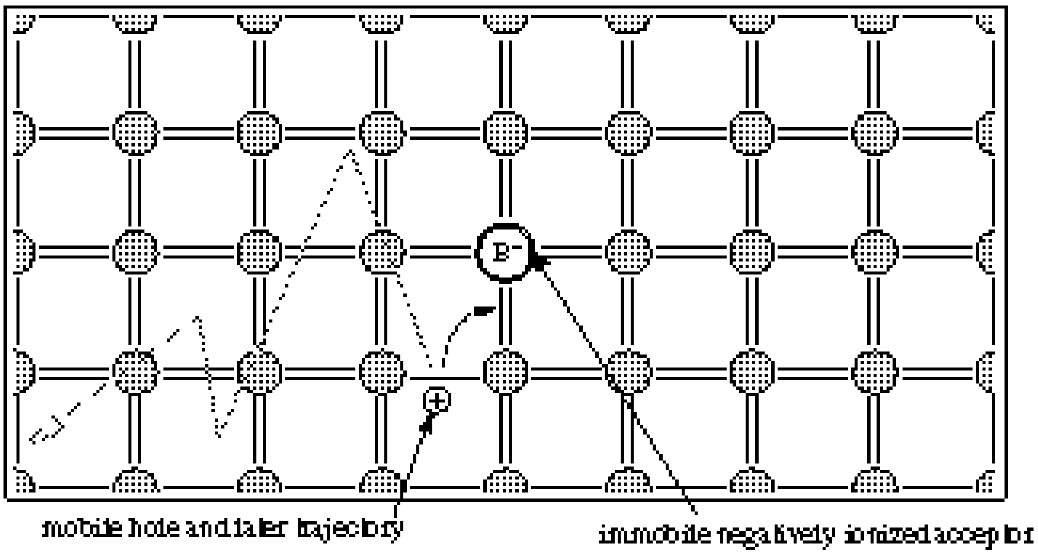
Doping: Acceptors Contd...

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



Define:

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

- If $N_a << n_i$, doping is irrelevant
  - *Intrinsic* semiconductor → $n_o = p_o = n_i$

Doping: Acceptors Contd...

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

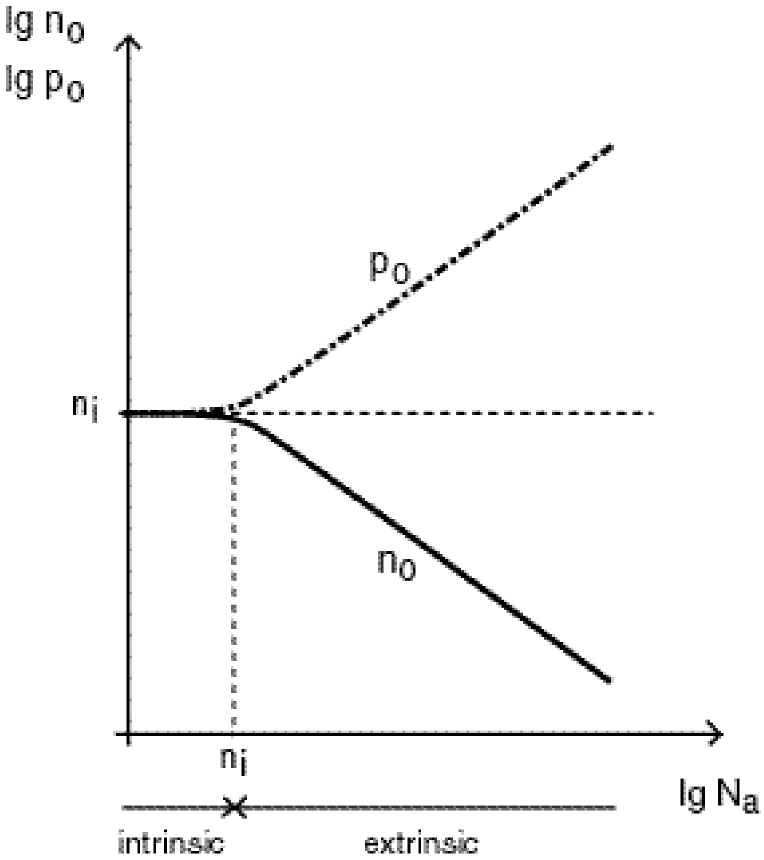
$$\mathbf{p_o = N_a} \qquad \mathbf{n_o = \frac{n_i^2}{N_a}}$$

Note: $p_o >> n_o$: ***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

- Every single atom in a semiconductor (doped & undoped) is charge neutral
  - Overall charge neutrality must be satisfied
- In general:

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

Let us examine this for $N_d = 10^{17}$ 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 contd...

Nothing is 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 "dopants"
  - selected foreign atoms
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