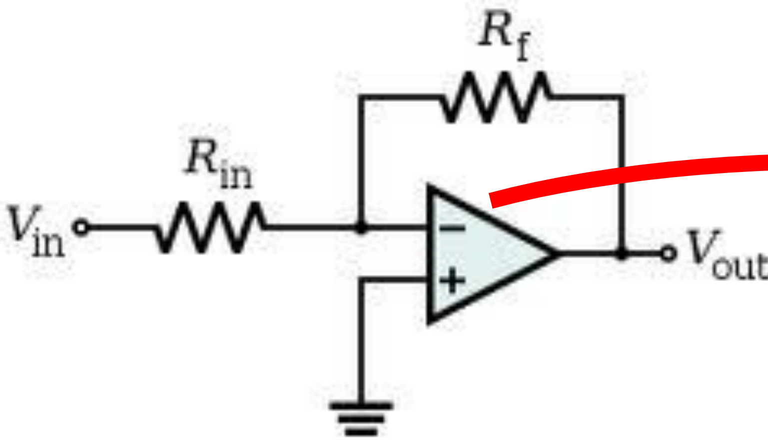
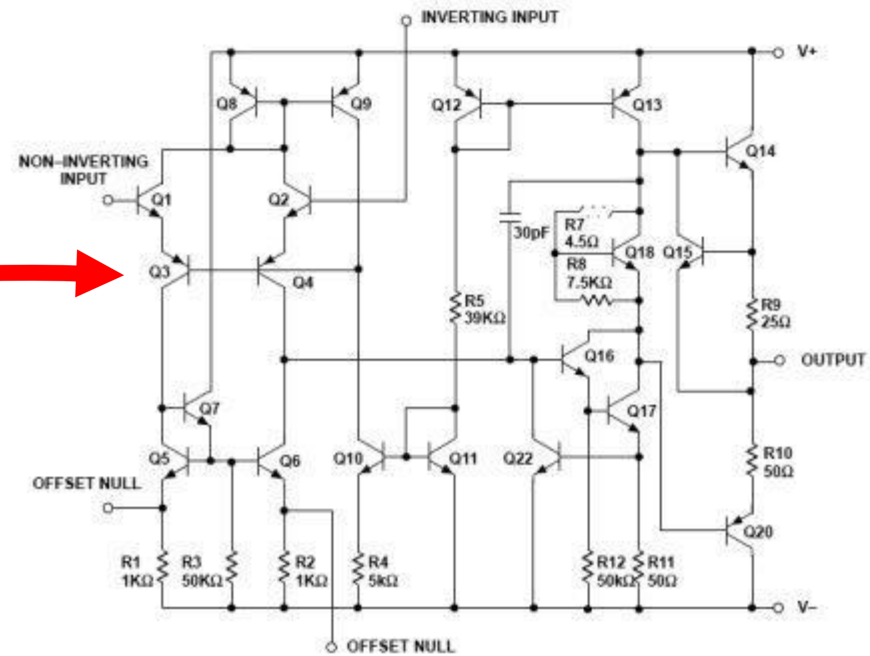
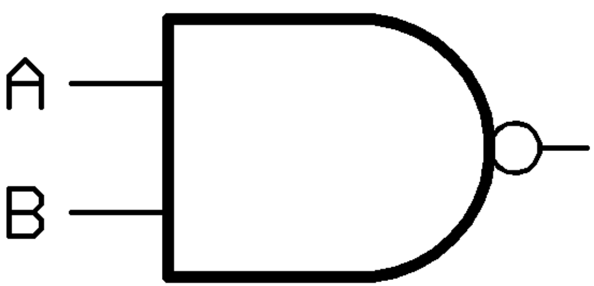
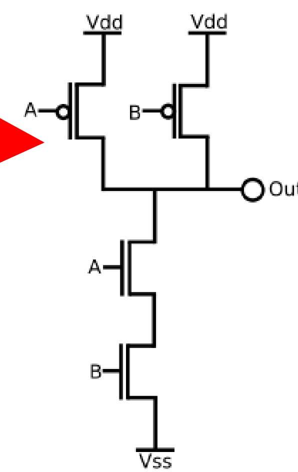
EE 40 – Semiconductor Basics

What's inside the active devices?









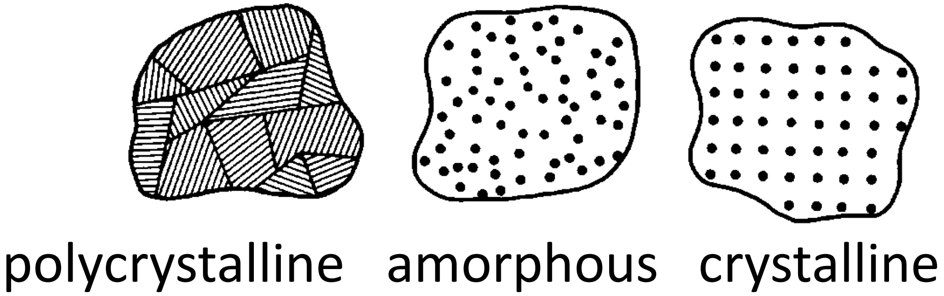
The inside of active devices

- I've been avoiding the issue of how *active* devices work all semester
  - passives
    - resistors (heat loss)
    - inductors (magnetic field storage element)
    - capacitors (electric field storage element)
  - actives
    - diodes (LED's, solar cells)
    - transistors (BJT's, MOSFET's, JFET's, etc.)

- What's *inside* classic actives?

What is a Semiconductor?

- Low resistivity => “conductor”
- High resistivity => “insulator”
- Intermediate resistivity => “semiconductor”
  - conductivity lies between that of conductors and insulators
  - generally crystalline in structure for IC devices
    - In recent years, however, non-crystalline semiconductors have become commercially very important

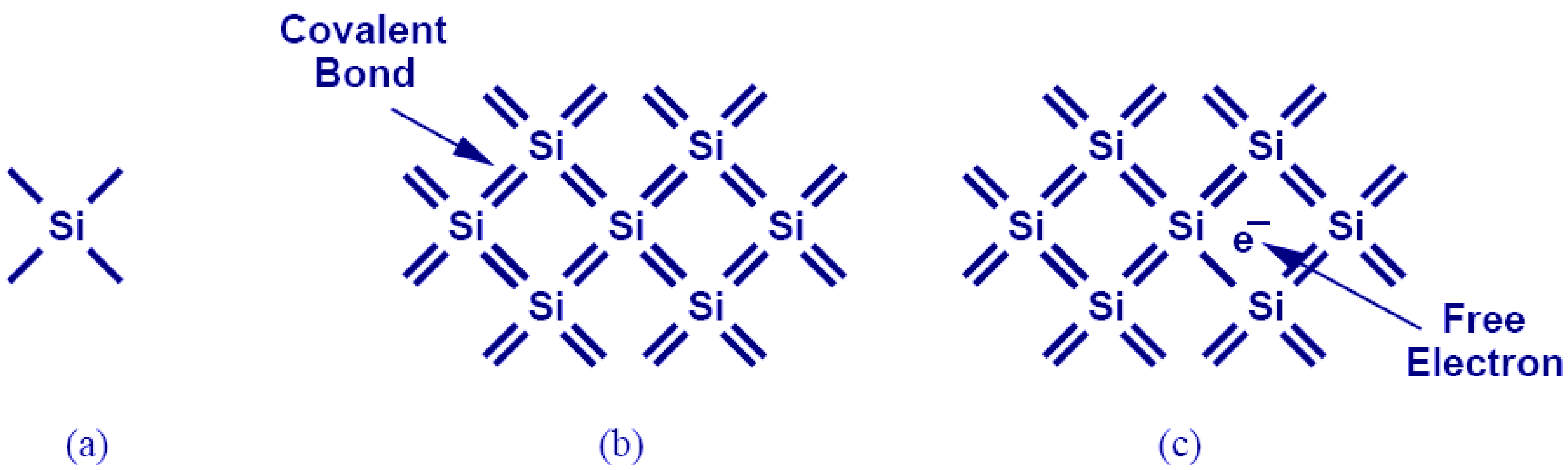


Semiconductor Materials

	III	IV	V	
	Boron (B)	Carbon (C)		
• • •	Aluminum (Al)	Silicon (Si)	Phosphorus (P)	• • •
	Gallium (Ga)	Germanium (Ge)	Arsenic (As)	
		• • •		

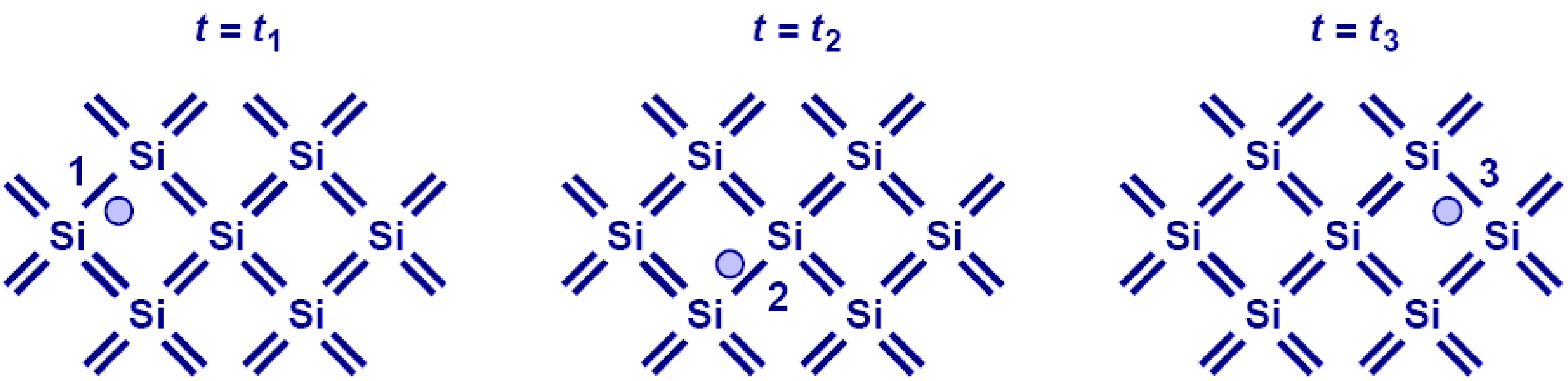
Silicon

- Atomic density: 5×10^{22} atoms/cm^3
- Si has four valence electrons. Therefore, it can form covalent bonds with four of its nearest neighbors.
- When temperature goes up, electrons can become free to move about the Si lattice.
- *These electrons can contribute to electric conduction.*



Electron-Hole Pair Generation

- When a conduction electron is thermally generated, a “hole” is also generated.
- A hole is associated with a positive charge, and is free to move about the Si lattice as well.



Generating free electrons

Two questions emerge:

1. Is there a minimum energy required to ‘pop’ an electron out of the lattice (i.e. generate a free electron)?
   - **Yes**: this is called the *bandgap energy*, Eg
   - Eg = 1.12 eV
     - 1 eV = 1.6 x 10^{-19} J
     - This is how much energy you need to move one electron across a potential of 1 V
2. How many electrons are present at a given temperature?

Carrier Concentrations in Intrinsic Si

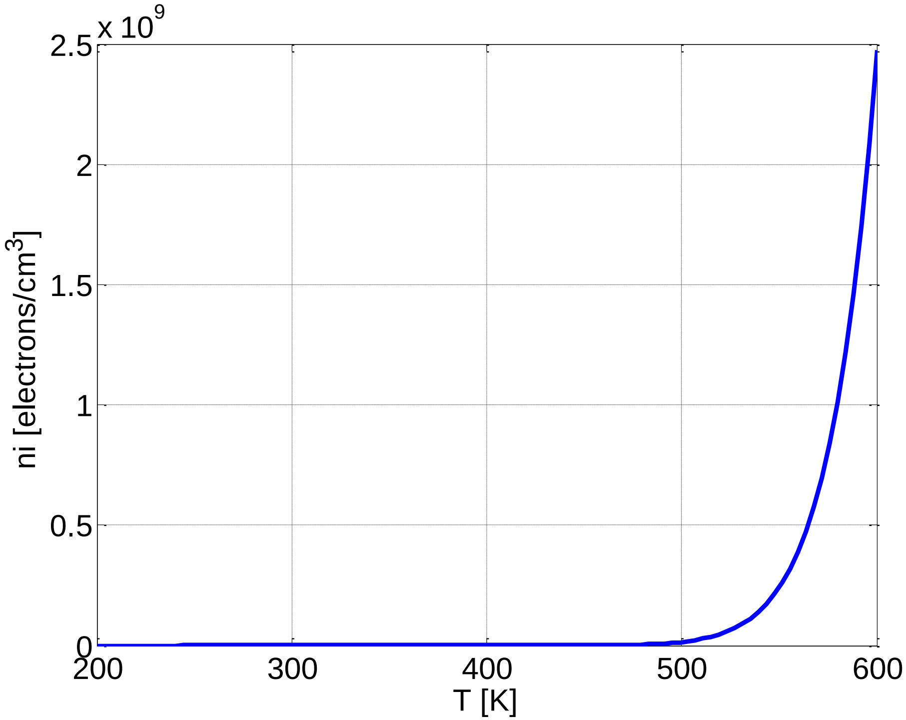
- The "band-gap energy" E_g is the amount of energy needed to remove an electron from a covalent bond.
- The concentration of conduction electrons in intrinsic silicon, n_i, depends exponentially on E_g and the absolute temperature (T):

$$n_i = 5.2\times10^{15} T^{3/2} \exp\frac{-E_g}{2kT}\, electrons/cm^3$$

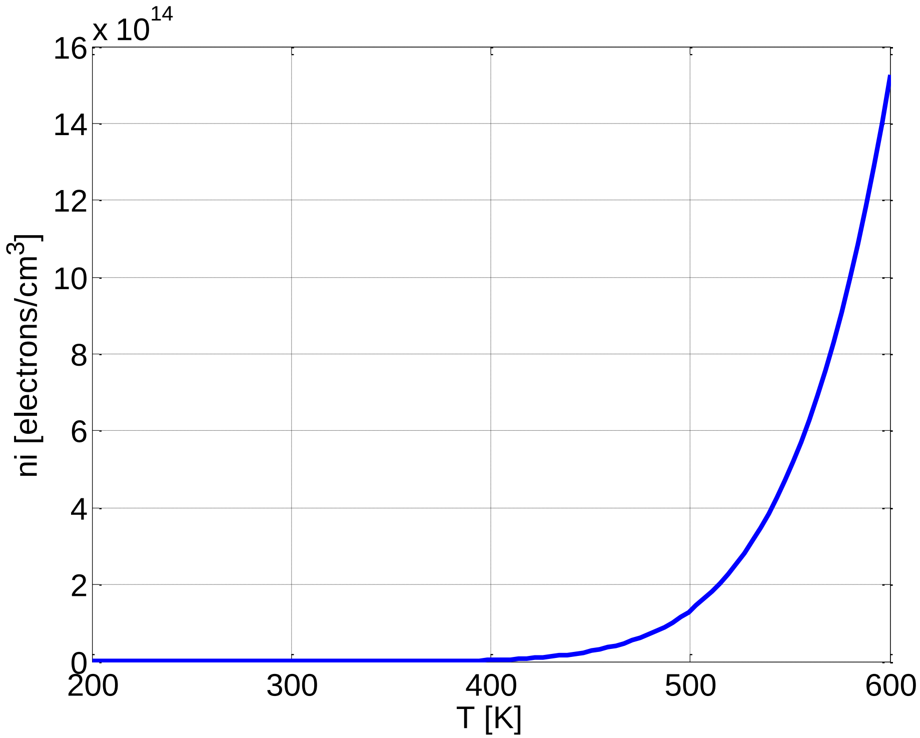
$$n_i \cong 1\times10^{10} electrons/cm^3 \text{ at } 300\text{K}$$

$$n_i \cong 1\times10^{15} electrons/cm^3 \text{ at } 600\text{K}$$

Carrier concentrations



Insulator (Diamond)



Semiconductor (Silicon)

Seems like big numbers but silicon has 5 x 10^{22} atoms/cm^3 so:
1.6×10^{15} / 5×10^{22} → **0.0000032 %** of lattice atoms have a free electron @ 600 K

Electronic Properties of Si

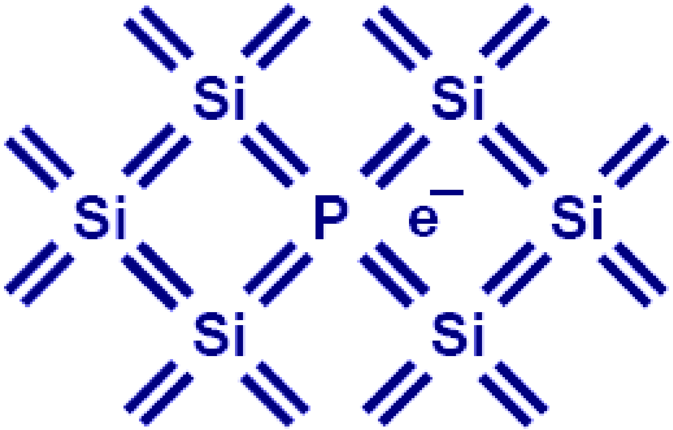
- **Silicon is a semiconductor material.**
  - Pure Si has a relatively high electrical resistivity at room temperature.

- **There are 2 types of mobile charge-carriers in Si:**
  - ***Conduction electrons*** are negatively charged;
  - ***Holes*** are positively charged.

- **The concentration (#/cm^3) of conduction electrons & holes in a semiconductor can be modulated in several ways:**
  1. **by adding special impurity atoms (*dopants*)**
  2. **by applying an electric field**
  3. **by changing the temperature**
  4. **by irradiation**

Doping (N type)

- Si can be "doped" with other elements to change its electrical properties.
- For example, if Si is doped with phosphorus (P), each P atom can ***donate*** a conduction electron, so that the Si lattice has more electrons than holes, *i.e.* it becomes "N type":

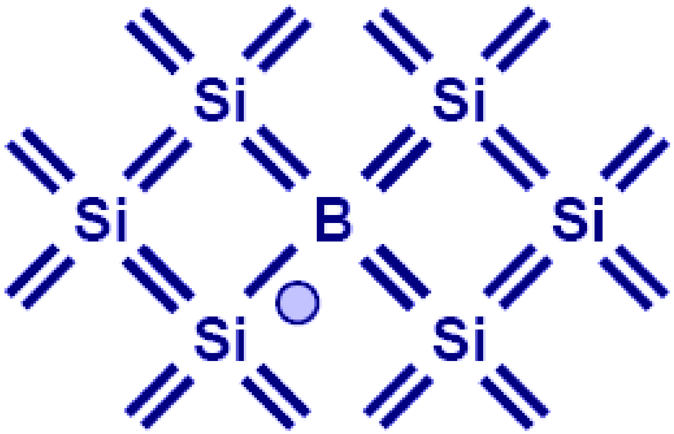


Notation:
n = conduction electron concentration

Doping (P type)

- If Si is doped with Boron (B), each B atom can ***accept*** an electron (creating a hole), so that the Si lattice has more holes than conduction electrons, *i.e.* it becomes "P type":

<u>Notation</u>:
p = hole concentration



Terminology

<u>donor</u>: impurity atom that increases n

<u>acceptor</u>: impurity atom that increases p

<u>N-type</u> material: contains more electrons than holes

<u>P-type</u> material: contains more holes than electrons

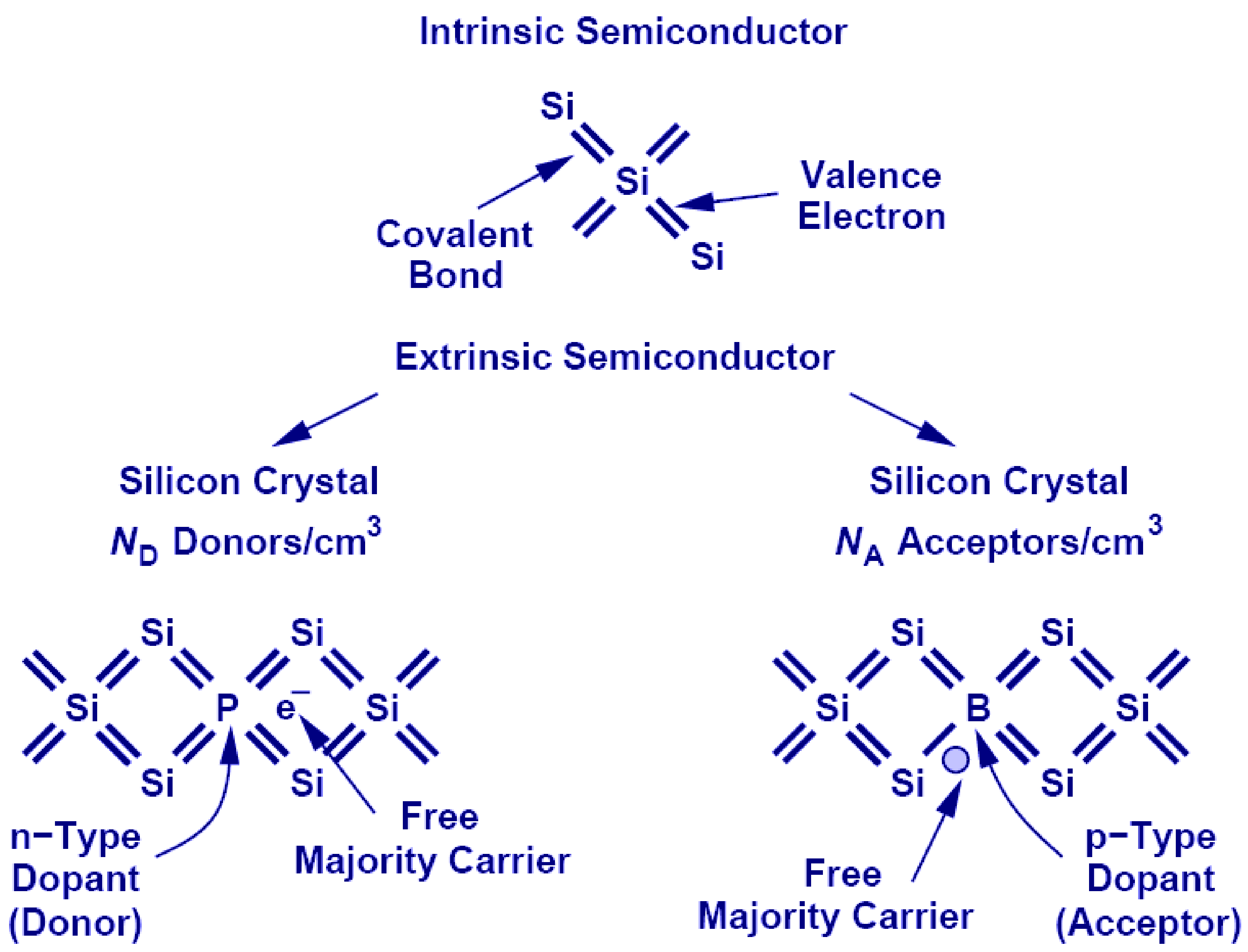
<u>majority carrier</u>: the most abundant carrier

<u>minority carrier</u>: the least abundant carrier

<u>intrinsic</u> semiconductor: $n = p = n_i$

<u>extrinsic</u> semiconductor: doped semiconductor

Intrinsic vs. Extrinsic Semiconductor



Electron and Hole Concentrations

- **Under thermal equilibrium conditions**, the product of the conduction-electron density and the hole density is ALWAYS equal to the square of n_i:

$$np = n_i^2$$

<u>N-type material</u>

$$n \approx N_D$$

$$p \approx \frac{n_i^2}{N_D}$$

<u>P-type material</u>

$$p \approx N_A$$

$$n \approx \frac{n_i^2}{N_A}$$

Dopant Compensation

- An N-type semiconductor can be converted into P-type material by counter-doping it with acceptors such that $N_A > N_D$.
- A ***compensated semiconductor material*** has both acceptors and donors.

<u>N-type material</u>

$(N_D > N_A)$

$$n \approx N_D - N_A$$

$$p \approx \frac{n_i^2}{N_D - N_A}$$

<u>P-type material</u>

$(N_A > N_D)$

$$p \approx N_A - N_D$$

$$n \approx \frac{n_i^2}{N_A - N_D}$$

Charges in a Semiconductor

- **Negative charges:**
  - Conduction electrons (density = n)
  - Ionized acceptor atoms (density = N_A)
- **Positive charges:**
  - Holes (density = p)
  - Ionized donor atoms (density = N_D)

- The net charge density (C/cm^3) in a semiconductor is

$$\boxed{\rho = q\left(p - n + N_D - N_A\right)}$$

Summary

- The band gap energy is the energy required to free an electron from a covalent bond.
  - E_g for Si at 300K = 1.12eV
- In a pure (undoped) Si crystal, conduction electrons and holes are formed in pairs.
  - Holes can be considered as positively charged mobile particles which exist inside a semiconductor.
  - Both holes and conduction electrons can conduct current.
- Substitutional dopants in Si:
  - Group-V elements (***donors***) contribute conduction electrons
  - Group-III elements (***acceptors***) contribute holes
  - Very low ionization energies (<50 meV)