# EE 152: Basic Electronics (Semiconductor Basics)

# Outline

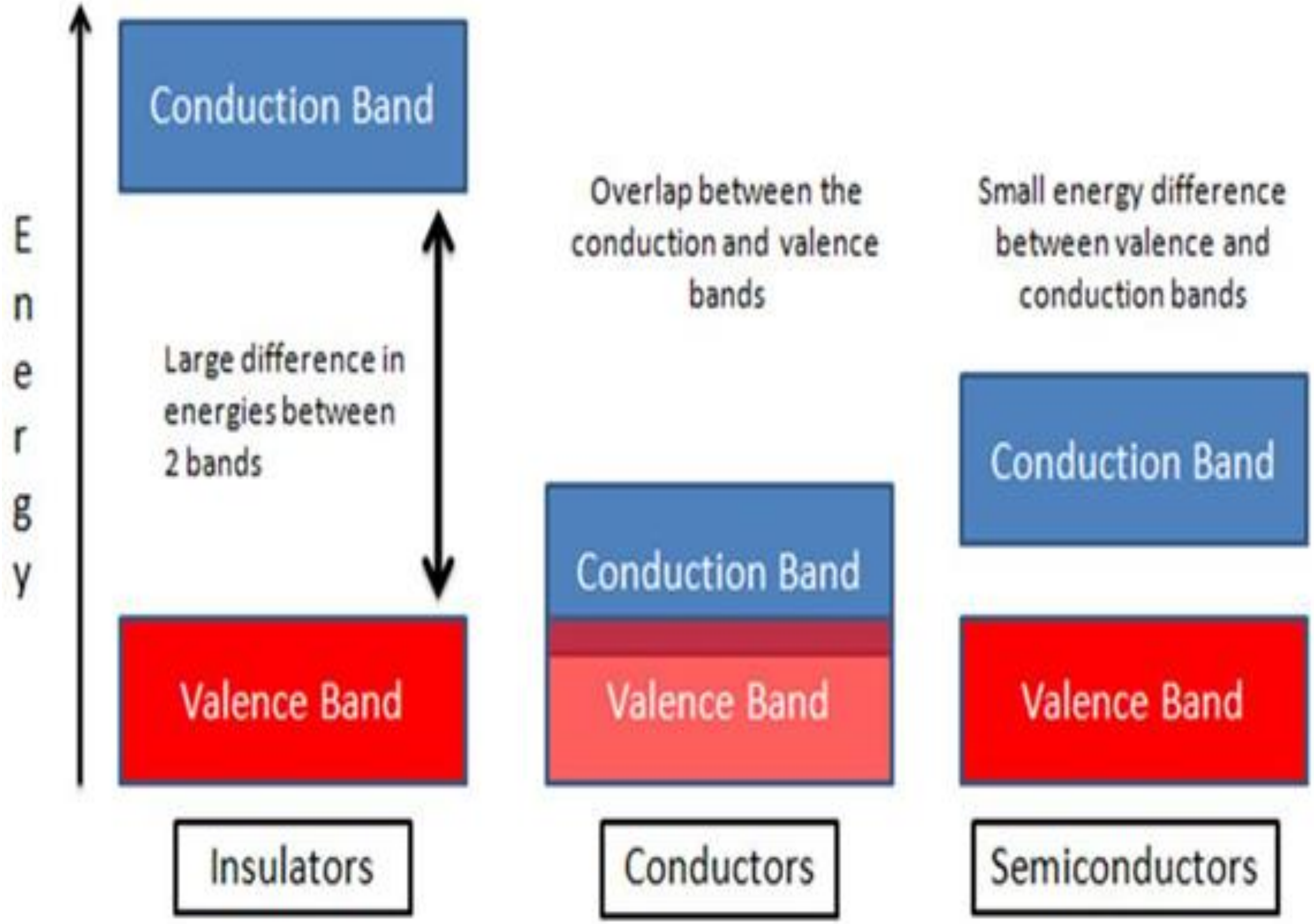
- Introduction
- Basic Semiconductor Concepts
    - Intrinsic
    - Doping
    - Extrinsic
        - N-type
        - P-type
    - Carrier movement

# Electronic Materials

- The goal of electronic materials is to generate and control the flow of an electrical current.
- Electronic materials include:

1. Conductors: have low resistance which allows electrical current flow
2. Insulators: have high resistance which suppresses electrical current flow
3. Semiconductors: can allow or suppress electrical current flow

# Conductors, semiconductors and insulators

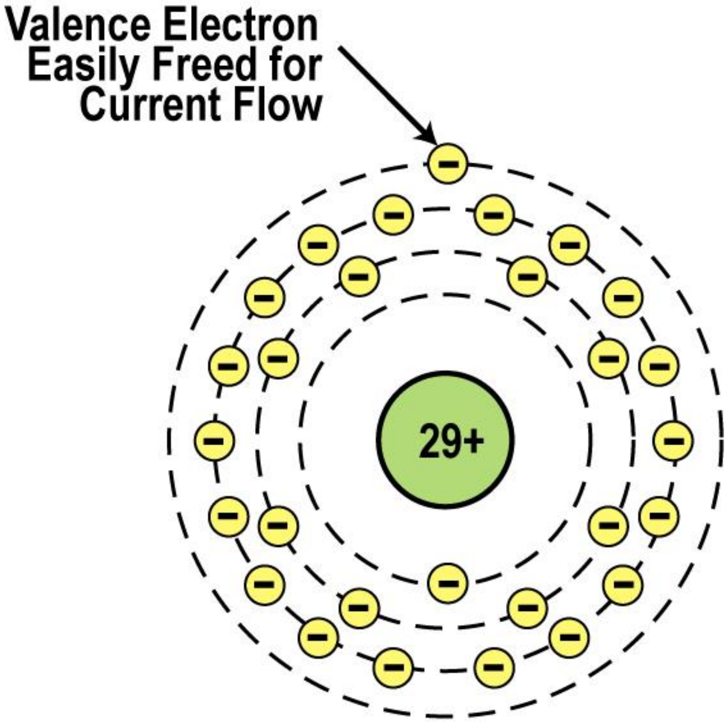


# Conductors

- Good conductors have low resistance so electrons flow through them with ease.
- **Best** element conductors include:
  - Copper, silver, gold, aluminum, & nickel
- Alloys are also good conductors:
  - Brass & steel
- Good conductors can also be liquid:
  - Salt water

# Conductor Atomic Structure

- The atomic structure of good conductors usually includes only <u>one electron in their outer shell</u>.
  - It is called a valence electron.
  - It is easily striped from the atom, producing current flow.




**Copper Atom**

# Insulators

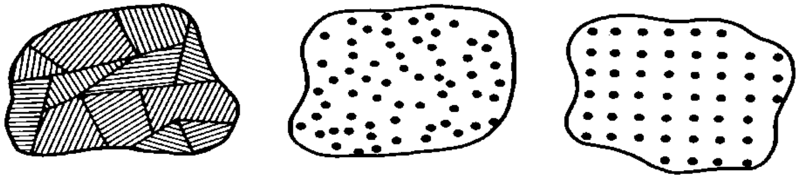
- Insulators have a high resistance so current does not flow in them.
- Good insulators include:
    - Glass, ceramic, plastics, & wood
- Most insulators are compounds of several elements.
- The atoms are tightly bound to one another so electrons are difficult to strip away for current flow.

# Semiconductors

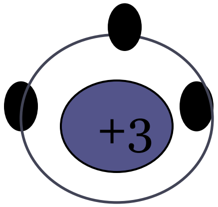
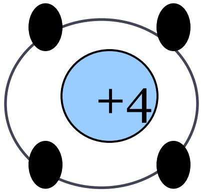
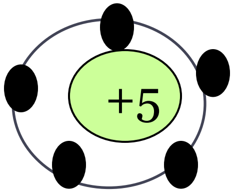
- Semiconductors are materials that essentially can be conditioned to act as good conductors, or good insulators, or any thing in between.
- Common elements such as **carbon, silicon**, and **germanium** are semiconductors.
- <u>Silicon is the best</u> and most widely used semiconductor.

# What is a Semiconductor?

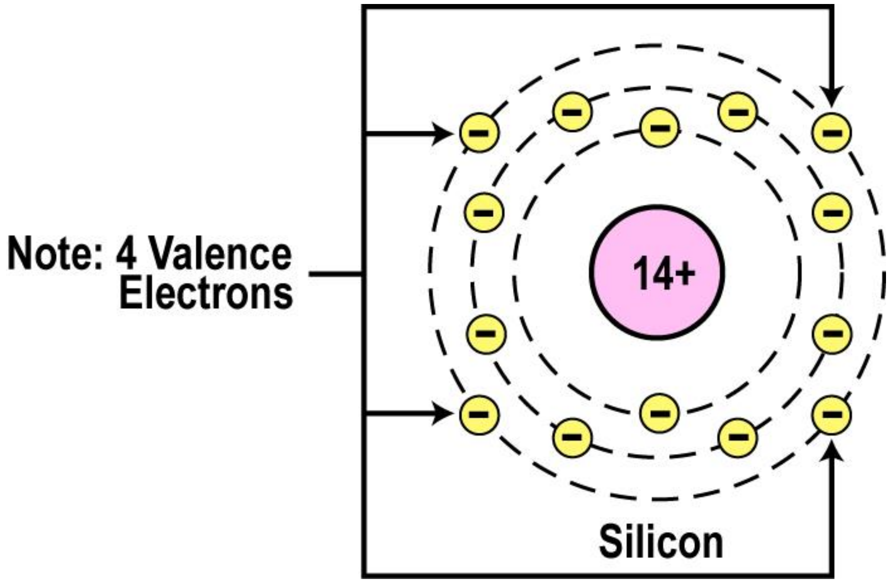
- A semiconductor is a material with conducting properties between those of a good insulator (e.g. glass) and a good conductor (e.g. copper).
- The most commonly used semiconductor is silicon.
- Low resistivity => “conductor”
- High resistivity => “insulator”
- Intermediate resistivity => “semiconductor”
  - 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 Elements in the Periodic Table

| Group III | Group IV | Group V |
|---|---|---|
|   |   |   |
| Boron (B) | Carbon (C) | Nitrogen (N) |
| Aluminium (Al) | Silicon (Si) | Phosphorus (P) |
| Gallium (Ga) | Germanium (Ge) | Arsenic (As) |
| Indium (In) | Tin (Sn) | Antimony (Sb) |

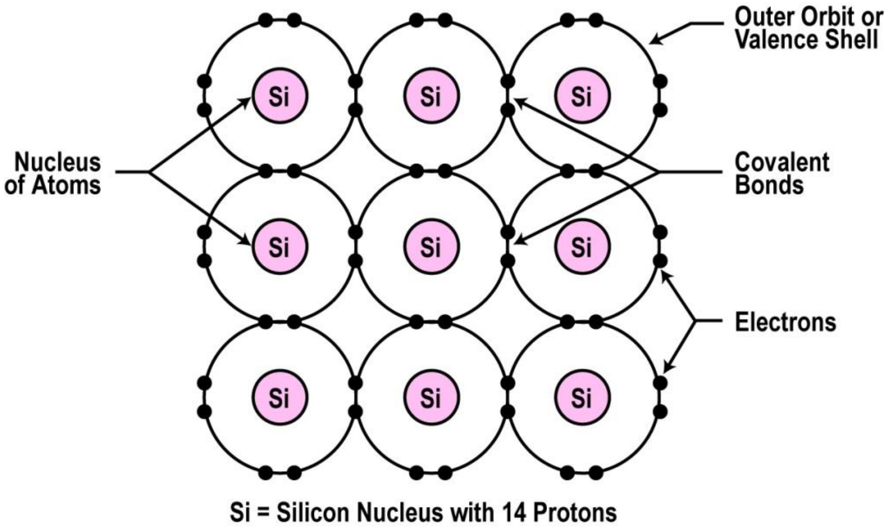
# Semiconductor Valence Orbit




- The main characteristic of a semiconductor element is that it has <u>four electrons</u> in its outer or valence orbit.

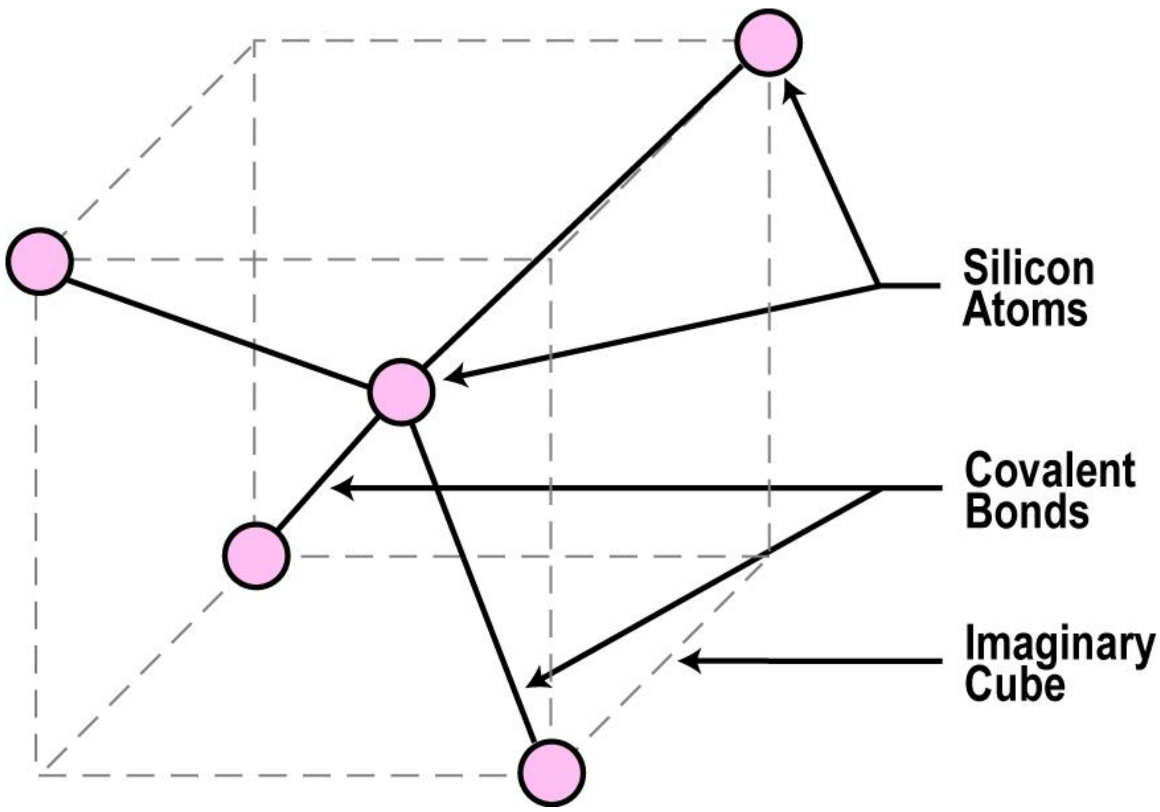
# Crystal Lattice Structure

- The unique capability of semiconductor atoms is their ability to link together to form a physical structure called a crystal lattice.
- The atoms link together with one another sharing their outer electrons.
- These links are called <u>covalent bonds</u>.



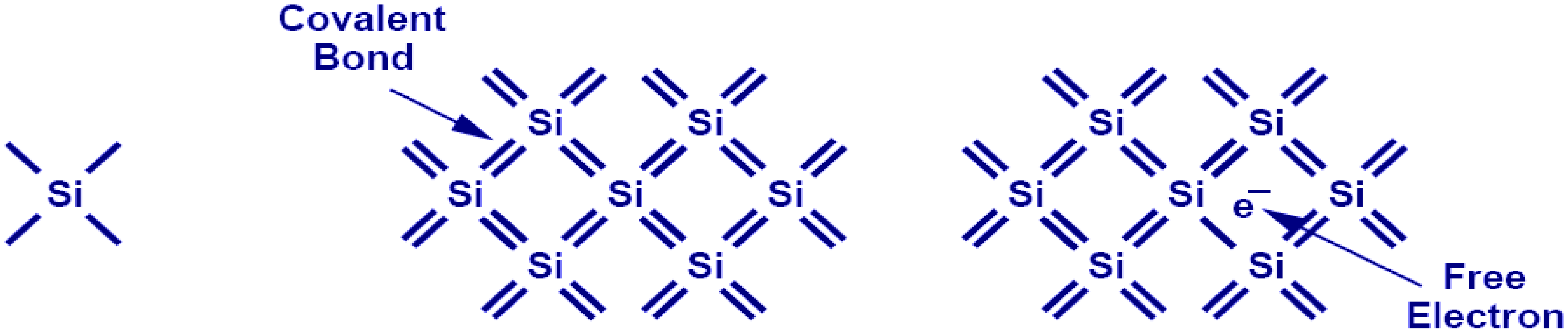

**2D Crystal Lattice Structure**

# 3D Crystal Lattice Structure



# Silicon

- Atomic density: $5 \times 10^{22}$ atoms/cm$^3$
- Each silicon atom has an outer shell with four valence electrons and four vacancies (It is a *tetravalent* element).
- In *intrinsic* (pure) silicon, atoms join together by forming *covalent bonds*. Each atom shares its valence electrons with each of four adjacent neighbours effectively filling its outer shell.
- When temperature goes up, electrons can become free to move about the Si lattice.




(a) (b) (c)

# 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**

- Thermal ionization
  - *Valence electron*---each silicon atom has four valence electrons
  - *Covalent bond*---two valence electrons from different two silicon atoms form the covalent bond
    - Be intact at sufficiently low temperature
    - Be broken at room temperature
  - *Free electron*---produced by thermal ionization, move freely in the lattice structure.
  - *Hole*---empty position in broken covalent bond, can be filled by free electron, positive charge
- Carriers

  A free electron is negatively charge and a hole is positively charge. Both of them can move in the crystal structure. They can conduct electric circuit.

- Recombination

  Some free electrons filling the holes results in the disappearance of free electrons and holes.
- Thermal equilibrium

  At a certain temperature, the recombination rate is equal to the ionization rate. So the concentration of the carriers is able to be calculated.

- Carrier concentration in thermal equilibrium

$$n = p = n_i$$

$$n_i^{\,2} = BT^3 e^{-E_G/kT}$$

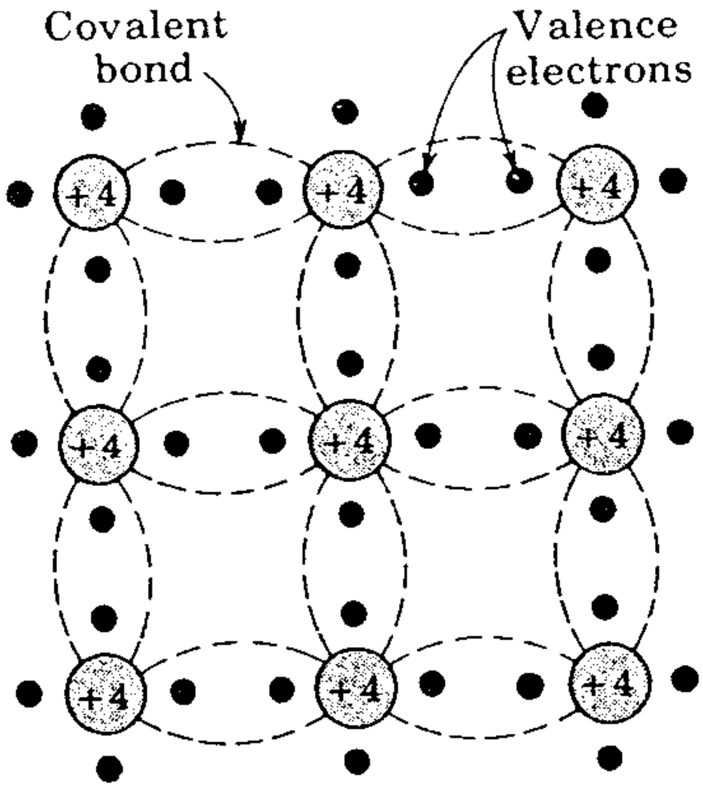
- At room temperature(T=300K)

$$n_i \cong 1.5 \times 10^{10} \quad \text{carriers/cm}^3$$

# Semiconductors can be Insulators

- If the material is pure semiconductor material like silicon, the crystal lattice structure forms an excellent insulator since all the atoms are bound to one another and are not free for current flow.
- Good insulating semiconductor material is referred to as intrinsic.
- Since the outer valence electrons of each atom are tightly bound together with one another, the electrons are difficult to dislodge for current flow.
- Silicon in this form is a great insulator.
- Semiconductor material is often used as an insulator.

# Intrinsic Semiconductors



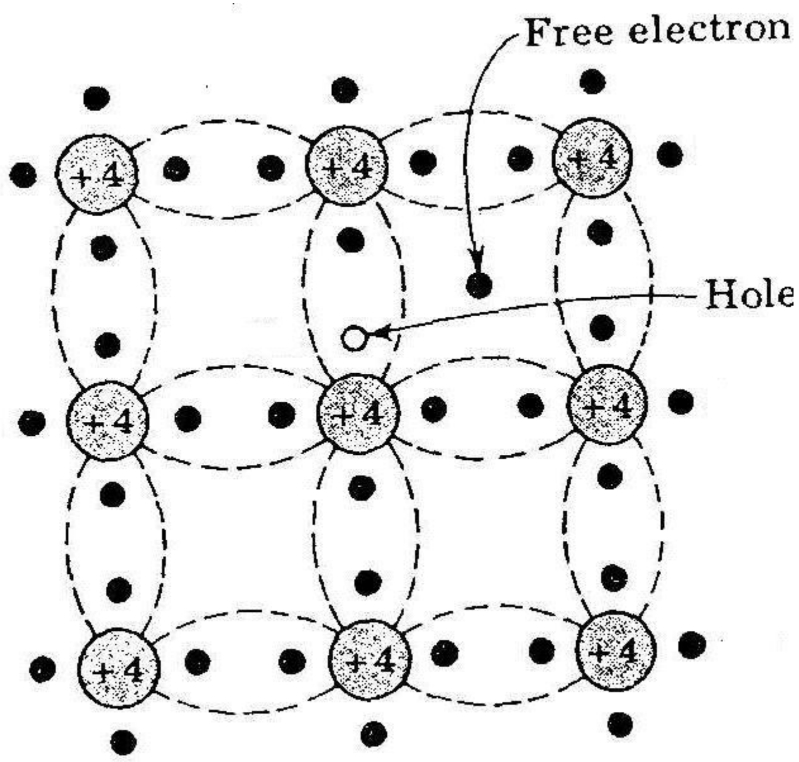
# Intrinsic Semiconductors

- The structure has zero overall charge
- The complete nature of the structure means that at absolute zero temperature (0 K) none of the electrons is available for conduction…thus far the material is an insulator.

# Intrinsic Semiconductors

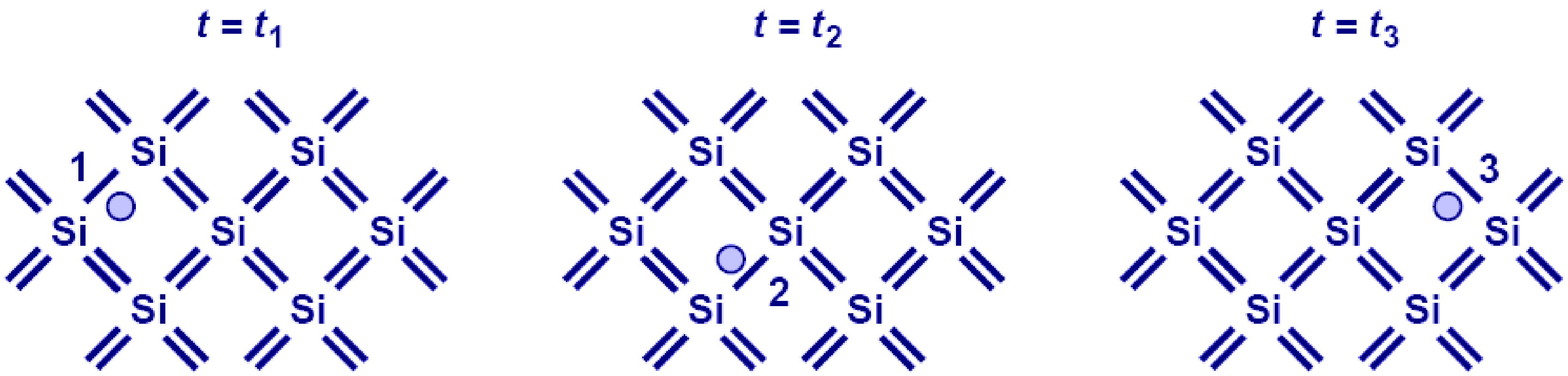
- At room temperature some of the electrons are able to acquire sufficient thermal energy to break free from their bond.
- Whenever an electron leaves its position in the lattice it leaves a vacancy known as a *hole*.
- The process is known as *electron-hole pair generation*

# Intrinsic Semiconductors



# 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.



# 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 ($T$):

$$n_i = 5.2 \times 10^{15} T^{3/2} \exp \frac{-E_g}{2kT} \, electrons / cm^3$$

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

$$n_i \cong 1 \times 10^{15} electrons / cm^3 \text{ at 600K}$$

# Intrinsic Semiconductors

- A freed electron can move through the body of the material until it encounters another broken bond where it is drawn in to complete the bond or *recombines*.

# Intrinsic Semiconductors

- At a given temperature there is a dynamic equilibrium between thermal electron-hole *generation* and the *recombination* of electrons and holes
- As a result the concentration of electrons and holes in an intrinsic semiconductor is constant at any given temperature.
- The higher the temperature the more electron-hole pairs that are present.

# Intrinsic Semiconductors

- **Two** mechanisms for conduction become possible when a bond breaks:
- 1. Due to the movement of the freed electron.
- 2. Due to neighbouring electrons moving into the hole leaving a space behind it. (This can be most simply thought of as movement of the hole, a single moving positive charge carrier even though it is actually a series of electrons that move.

# Intrinsic Semiconductors

- When an electric field (voltage) is applied, the holes move in one direction and the electrons in the other.
- However both current components are in the direction of the field.
- The conduction is ohmic, i.e. current is proportional to the applied voltage (field)

# Intrinsic Semiconductors

- The proportion of freed electrons is very small indeed:
- In silicon the energy $E_G$ required to free an electron is 1.2eV
- The mean thermal energy (kT) is only 25meV at room temperature (1/40 eV)
- The proportion of freed electrons varies exponentially ($-E_G/kT$).

# Intrinsic Semiconductors

- For an intrinsic semiconductor the number of electron and hole carriers, and thus the conductivity, increases rapidly with temperature.
- This is not very useful.
- Hence we dope the material to produce an extrinsic semiconductor.

# Doping

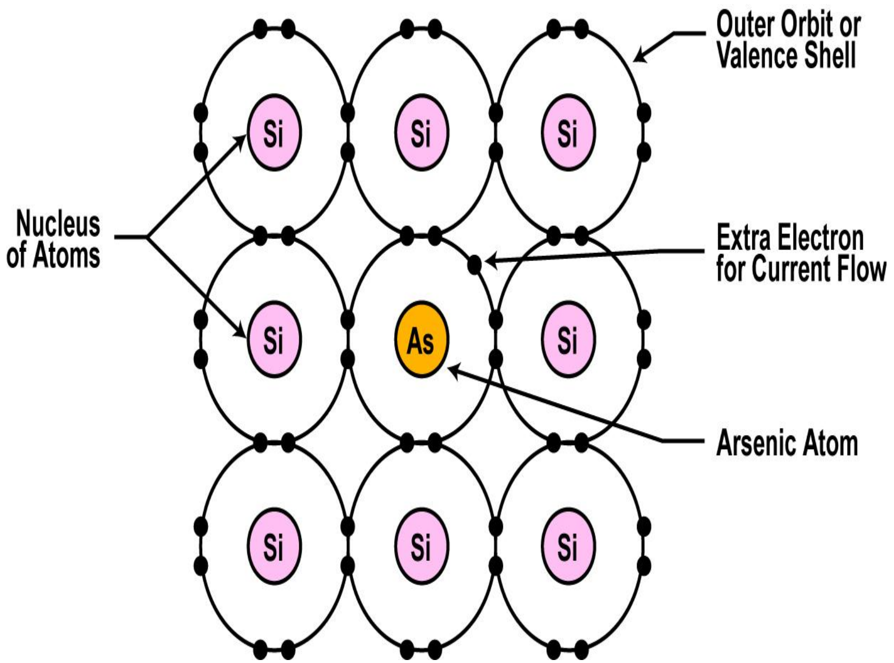
- To make the semiconductor conduct electricity, other atoms called impurities must be added.
- "Impurities" are different elements.
- This process is called doping.

# Extrinsic Semiconductors

- Intrinsic conduction is very small.
- Conductivity levels can be raised and controlled by *doping* with minute levels of impurity atoms to give *extrinsic* or *doped* semiconductors.
- Extrinsic semiconductors may be further divided into either n-type or p-type

# Semiconductors can be Conductors

- An impurity, or element like arsenic, has 5 valence electrons.
- Adding arsenic (doping) will allow four of the arsenic valence electrons to bond with the neighboring silicon atoms.
- The one electron left over for each arsenic atom becomes available to conduct current flow.

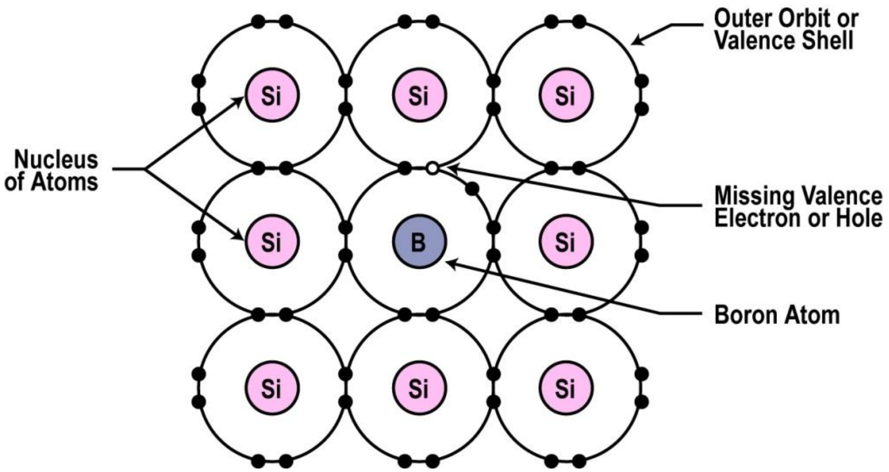


# Resistance Effects of Doping

- If you use lots of arsenic atoms for doping, there will be lots of extra electrons so the resistance of the material will be low and current will flow freely.
- If you use only a few boron atoms, there will be fewer free electrons so the resistance will be high and less current will flow.
- By controlling the doping amount, virtually any resistance can be achieved.

# Another Way to Dope

- You can also dope a semiconductor material with an atom such as boron that has only 3 valence electrons.
- The 3 electrons in the outer orbit do form covalent bonds with its neighboring semiconductor atoms as before. But one electron is missing from the bond.
- This place where a fourth electron should be is referred to as a hole.
- The hole assumes a positive charge so it can attract electrons from some other source.
- Holes become a type of current carrier like the electron to support current flow.



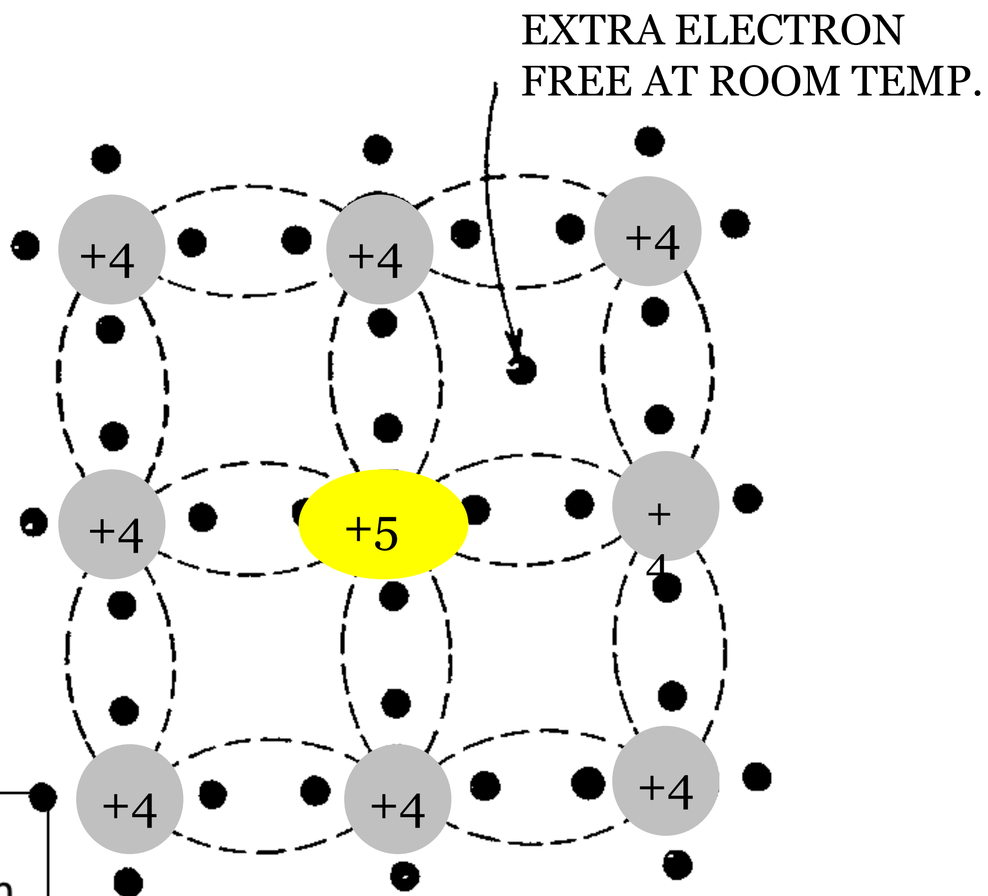
# Types of Semiconductor Materials

- The silicon doped with extra electrons is called an "N type" semiconductor.
  - "N" is for negative, which is the charge of an electron.
- Silicon doped with material missing electrons that produce locations called holes is called "P type" semiconductor.
  - "P" is for positive, which is the charge of a hole.

# N-type Semiconductors

- An n-type impurity atom has five outer (valence) electrons, rather than the four of silicon.
- Only four of the outer electrons are required for covalent bonding. The fifth is much more easily detached from the parent atom.
- As the energy needed to free the fifth electron is smaller than the thermal energy at room temperature virtually all are freed.

# N-type Semiconductors




**Notation:**
*n* = conduction electron concentration

Carrier concentration for *n* type

a) Thermal equilibrium equation

$$n_{n0} \cdot p_{n0} = n_i^{\,2}$$

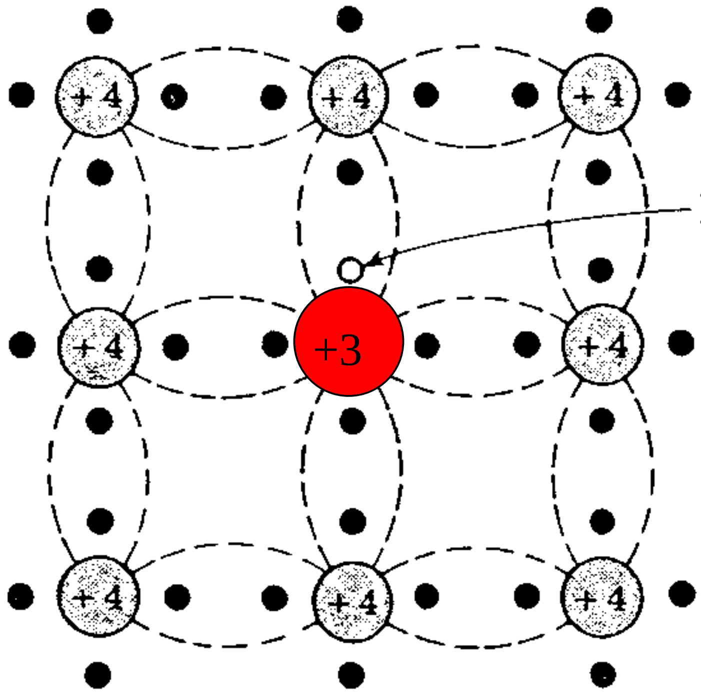
b) Electric neutral equation

$$n_{n0} = p_{n0} + N_D$$

# P-type Semiconductors

- Here the doping atom has only three electrons in its outer shell.
- It is relatively easy for an electron from a neighbouring atom to move in, so releasing a hole at its parent atom. The freed hole is available for conduction.
- The energy needed to free the electron from its parent is usually small compared to the thermal energy so each impurity atom contributes one hole for conduction (fully ionised).

# P-type Semiconductors




A neighbouring electron can move here. This creates a hole where the electron came from.

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

Carrier concentration for *p* type

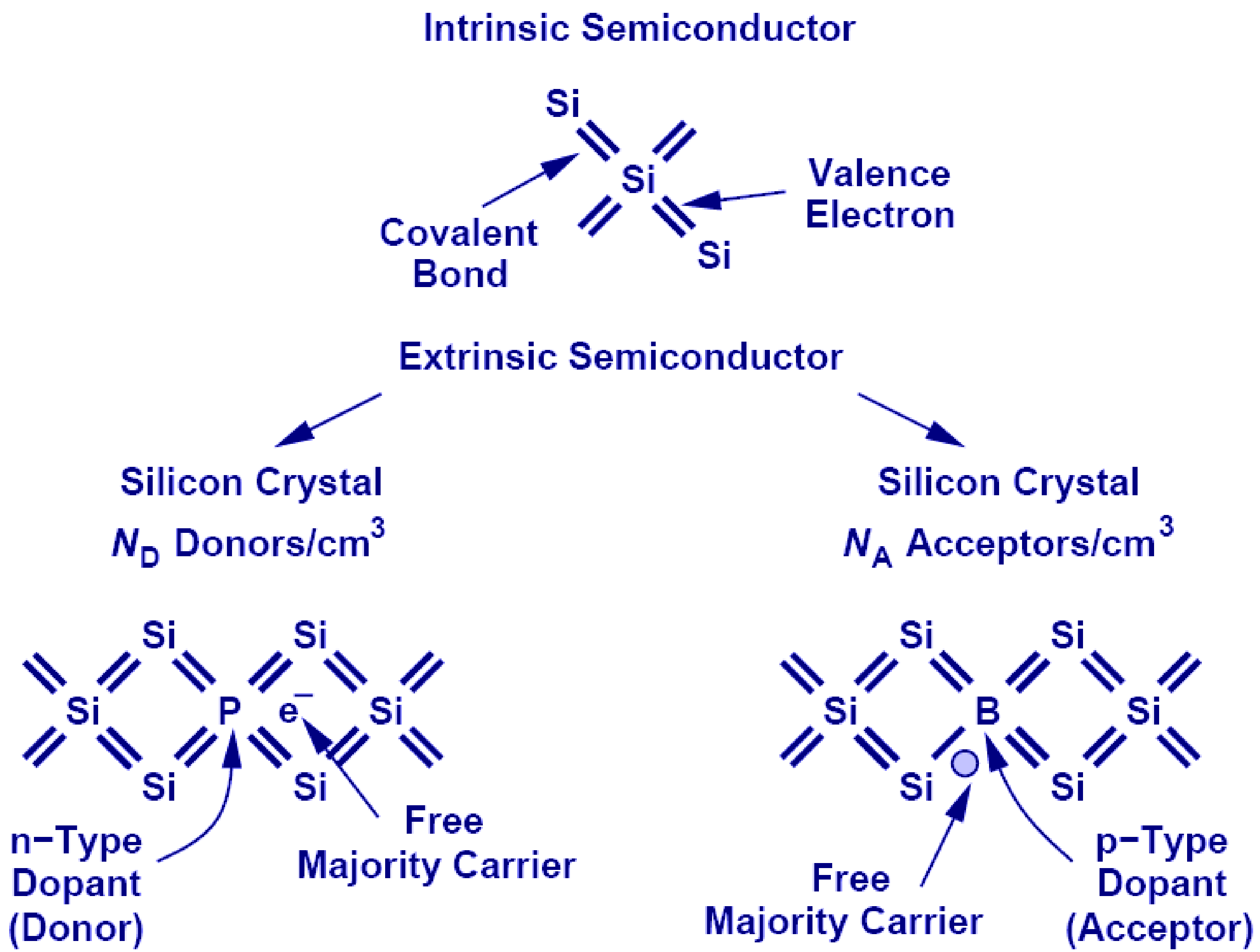
a) Thermal equilibrium equation

$$p_{p0} \cdot n_{p0} = n_i^{\;2}$$

b) Electric neutral equation

$$p_{p0} = n_{p0} + N_A$$

# Summary of Charge Carriers



# 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>

$$p \approx N_A$$

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

# Electron and Hole Densities

$$np = n_i^2$$

Majority Carriers : $p \approx N_A$

Minority Carriers : $n \approx \dfrac{n_i^2}{N_A}$

Majority Carriers : $n \approx N_D$

Minority Carriers : $p \approx \dfrac{n_i^2}{N_D}$

- The product of electron and hole densities is ALWAYS equal to the square of intrinsic electron density regardless of doping levels.

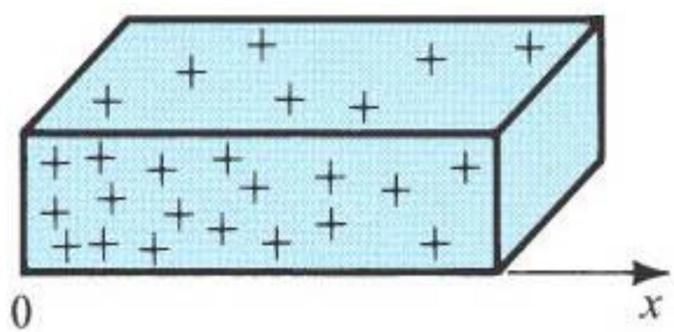
# Carriers Movement

There are two mechanisms by which holes and free electrons move through a silicon crystal.

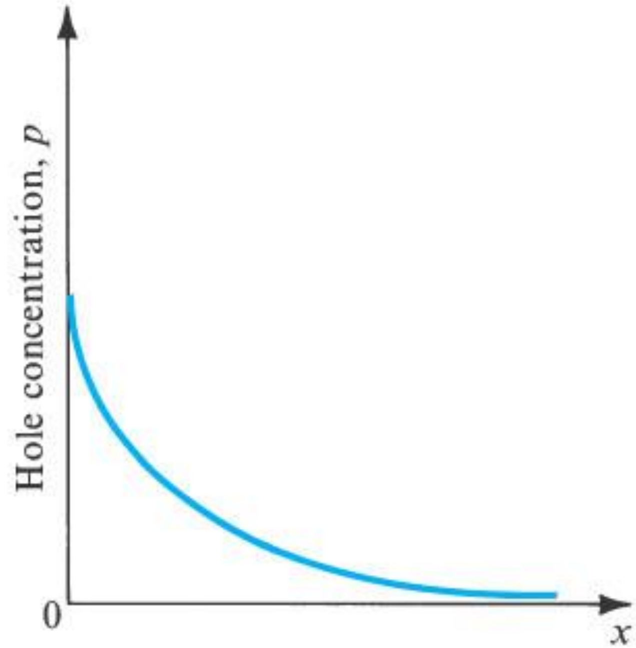
- Drift--- The carrier motion is generated by the electrical field across a piece of silicon. This motion will produce drift current.
- Diffusion--- The carrier motion is generated by the different concentration of carrier in a piece of silicon. The diffused motion, usually carriers diffuse from high concentration to low concentration, will give rise to diffusion current.

# Diffusion and Diffusion Current

- diffusion




(a)



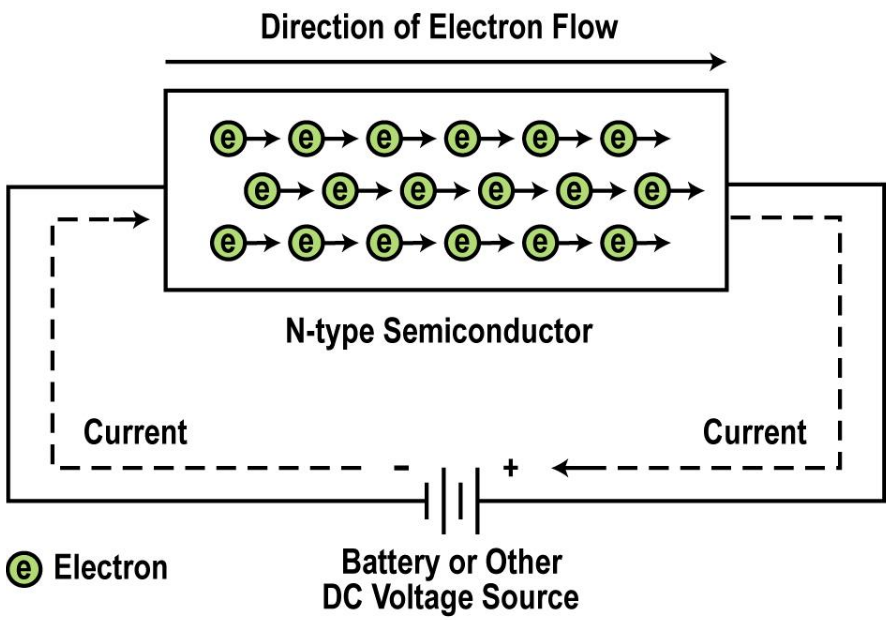

(b)

A bar of intrinsic silicon (a) in which the hole concentration profile shown in (b) has been created along the $x$-axis by some unspecified mechanism.

*The diffusion current density is proportional to the slope of the concentration curve, or the concentration gradient.*

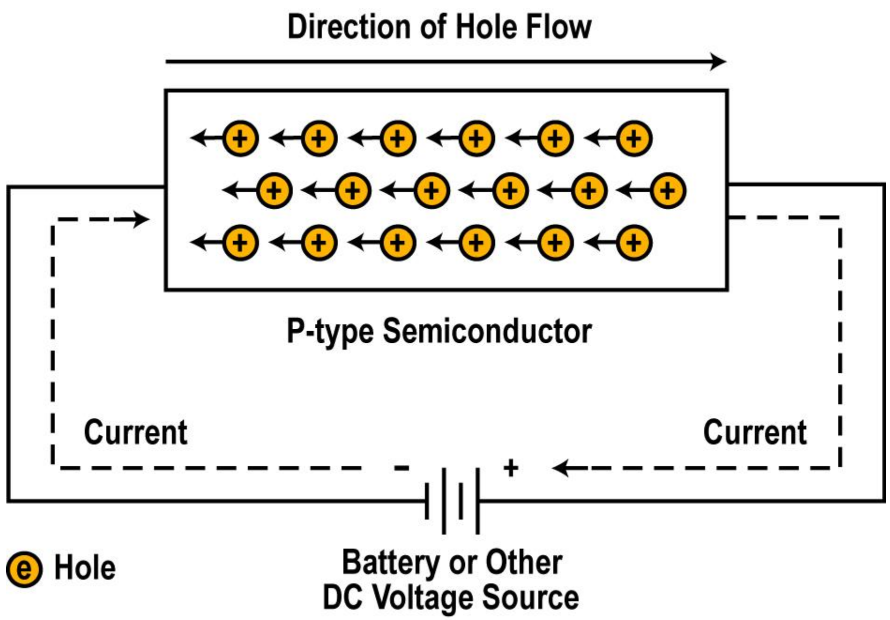
# Current Flow in N-type Semiconductors

- The DC voltage source has a positive terminal that attracts the free electrons in the semiconductor and pulls them away from their atoms leaving the atoms charged positively.
- Electrons from the negative terminal of the supply enter the semiconductor material and are attracted by the positive charge of the atoms missing one of their electrons.
- <u>Current (electrons) flows from the positive terminal to the negative terminal</u>.



# Current Flow in P-type Semiconductors

- Electrons from the negative supply terminal are attracted to the positive holes and fill them.
- The positive terminal of the supply pulls the electrons from the holes leaving the holes to attract more electrons.
- <u>Current (electrons) flows from the negative terminal to the positive terminal</u>.
- Inside the semiconductor current flow is actually by the movement of the holes from positive to negative.



# Temperature sensitivity

- In both types of <u>extrinsic</u> semiconductor virtually all available charge carries are freed from their parent atoms at room temperature. Temperature variations thus make little difference to the conductivity $\sigma$.
- For intrinsic conductivity the number of carriers, and thus $\sigma$, increases rapidly with temperature.
- For both extrinsic and intrinsic mechanisms the conductivity is zero at T=0 K

# Terminology

donor: impurity atom that increases $n$

acceptor: impurity atom that increases $p$

N-type material: contains more electrons than holes

P-type material: contains more holes than electrons

majority carrier: the most abundant carrier

minority carrier: the least abundant carrier

intrinsic semiconductor: $n = p = n_i$

extrinsic semiconductor: doped semiconductor

# In Summary

- In its pure state, semiconductor material is an excellent insulator.
- The commonly used semiconductor material is silicon.
- Semiconductor materials can be doped with other atoms to add or subtract electrons.
- An N-type semiconductor material has extra electrons.
- In an N-type semiconductor, conduction is mainly due to electrons (negative charges). Positive charges (holes) are the minority carriers.
- A P-type semiconductor material has a shortage of electrons with vacancies called holes.
- In a P-type semiconductor, conduction is mainly due to holes (positive charges). Negative charges (electrons) are the minority carriers.
- The heavier the doping, the greater the conductivity or the lower the resistance.
- By controlling the doping of silicon the semiconductor material can be made as conductive as desired.

# …that's all folks…
# …thanks for your time…