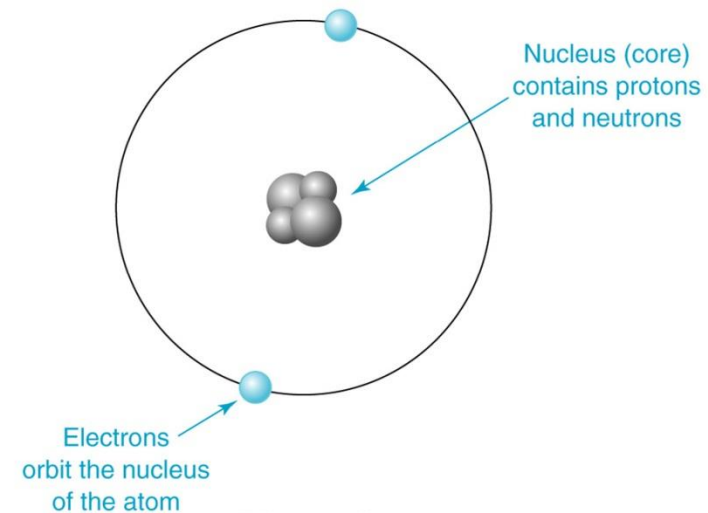


Semiconductors



Atomic Structure

- Atom – **smallest particle of matter** that retains the physical characteristics of an element
- Atomic Number of an Atom – number of protons
- Atoms contain an **equal number of protons and electrons**
- Bohr Model
 - Simplest model of an atom
 - Central core (nucleus) – contains protons and neutrons
 - Electrons revolve around nucleus

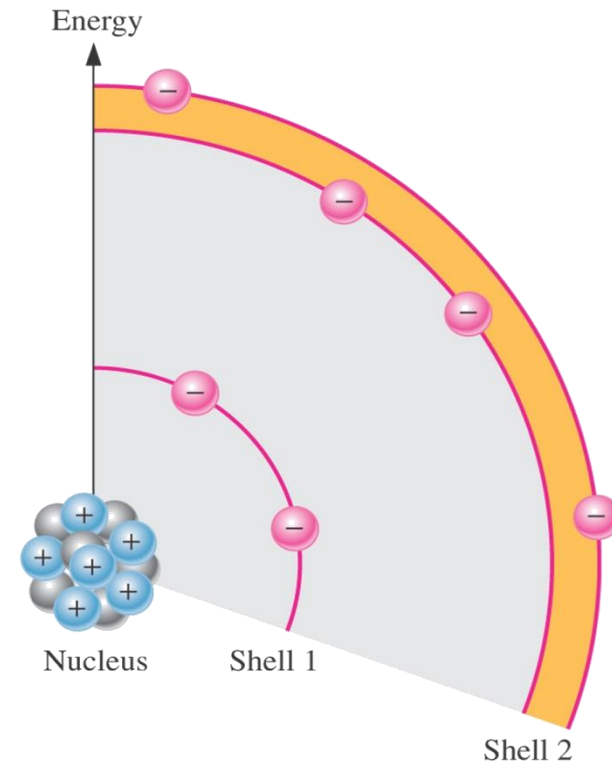


Atomic Structure

- Electrons go around the nucleus in their **orbits**
- Each orbit has some energy level
- Group of orbits called **shell**
- Electrons on the same shell have similar energy level
- Number of electrons (N) on each shell (n)

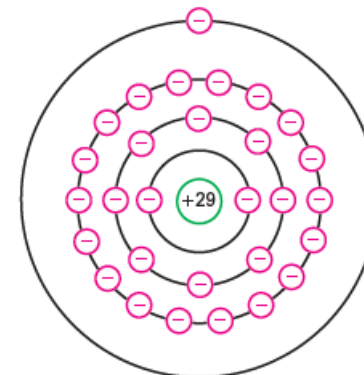
$$N = 2n^2$$

- First shell has 2 electrons
- Second shell has 8 electrons

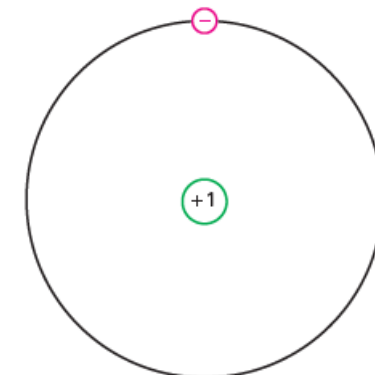


Valence Shell

- Atoms are made of **valence shell** and **core**
- **Valence shell** is the outermost shell
- Valence shell has **valence electrons** ready to be freed
- This orbit **controls the electrical properties** of the atom.
- **Core** of an atom is the **nucleus and all the inner orbits**
- When an atom has more of one particle than the other the atom acquires the charge of the greater.
 - **+ Ion**, Has more **Protons** than Electrons,
 - **- Ion**, Has more **Electrons** than Protons.



Copper atom.



Core diagram of copper atom.



Solid-state electronic materials

- Electronic materials fall into three categories with respect to **resistivity**
 - Insulators $\rho > 10^5 \Omega\text{-cm}$ (diamond $\rho = 10^{16}$)
 - Semiconductors $10^{-3} < \rho < 10^5 \Omega\text{-cm}$
 - Conductors $\rho < 10^{-3} \Omega\text{-cm}$ (copper $\rho = 10^{-6}$)
- In order of conductivity:
 - Conductors
 - Semiconductors
 - Insulators



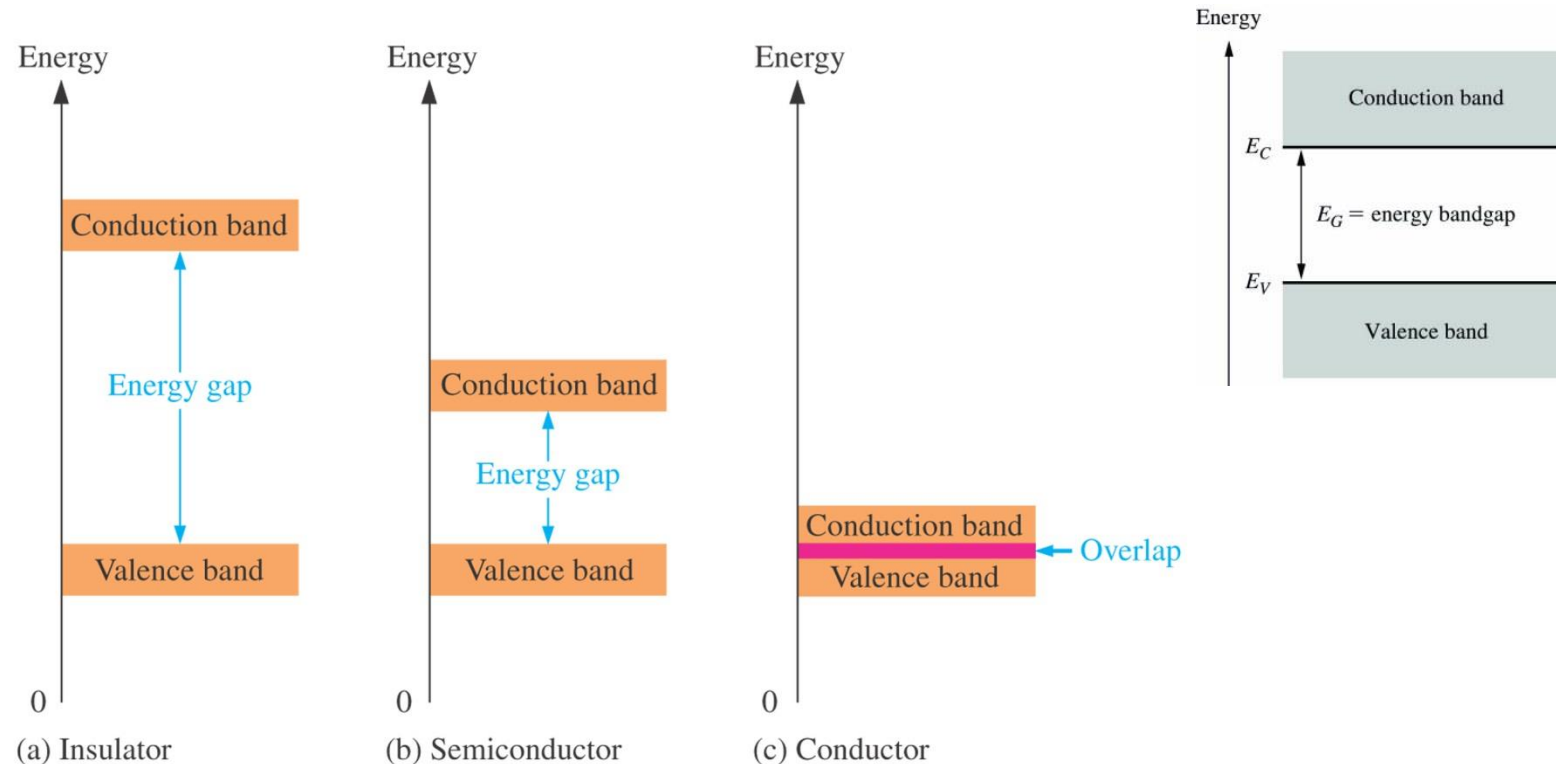
Solid-state electronic materials

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Solid-state electronic materials

- Bandgap is an energy range in a solid where no electron states can exist.
- It refers to the energy difference between the top of the valence band and the bottom of the conduction band



Conductors

- Material capable of carrying electric current, i.e. material which has “**mobile charge carriers**” (e.g. electrons, ions..)
- Has **loosely bound electrons in its outer or Valence shell**, they are easily displaced
- Have a high concentration of electrons in **conduction bands** e.g. metals, liquids with ions (water, molten ionic compounds)
- Current is carried by a single type of mobile charge, the free electron (current carrier).
- There is relatively large density of mobile charge carriers.



Insulators

- Materials with **no or very few free charge carriers**
- Has **tightly bound electrons** in its outer or Valence ring, they are not easily displaced.
- Have virtually zero electrons in bands
 - conduction band energy is too high
 - all the electrons are stuck in *valance bands*
- Eg: quartz, most covalent and ionic solids, plastics



Semiconductors

- Elemental semiconductors are formed from a single type of atom of column IV, typically Silicon.
- Compound semiconductors are formed from combinations of elements of column III and V or columns II and VI.

Periodic Table of the Elements

Representative (main group) elements		Transition metals										Representative (main group) elements							
1A												IIIA	IVA	VA	VIA	VIIA	VIIIA		
1	H 1.0079											5	6	7	8	9	10		
2	Li 6.941	Be 9.012											B 10.811	C 12.011	N 14.007	O 15.999	F 18.998	Ne 20.180	
3	Na 22.990	Mg 24.305	IIIB	IVB	VB	VIB	VIIIB	VIII B			IB	II B	13	14	15	16	17	18	
4	K 39.098	Ca 40.078	Sc 44.956	Ti 47.88	V 50.942	Cr 51.996	Mn 54.938	Fe 55.845	Co 58.933	Ni 58.69	Cu 63.546	Zn 65.39	Ga 69.723	Ge 72.61	As 74.922	Se 78.96	Br 79.904	Kr 83.8	
5	Rb 85.468	Sr 87.62	Y 88.906	Zr 91.224	Nb 92.906	Mo 95.94	Tc 98	Ru 101.07	Rh 102.906	Pd 106.42	Ag 107.868	Cd 112.411	In 114.82	Sn 118.71	Sb 121.76	Te 127.60	I 126.905	Xe 131.29	
6	Cs 132.905	Ba 137.327	La 138.906	Hf 178.49	Ta 180.948	W 183.84	Re 186.207	Os 190.23	Ir 192.22	Pt 195.08	Au 196.967	Hg 200.59	Tl 204.383	Pb 207.2	Bi 208.980	Po 209	At 210	Rn 222	
7	Fr 223	Ra 226.025	Ac 227.028	Rf 261	Db 262	Sg 263	Bh 262	Hs 265	Mt 266	Uun 272	Uuu 272	Uub 277							
			Rare earth elements																
Lanthanides			58	59	60	61	62	63	64	65	66	67	68	69	70	71			
			Ce 140.115	Pr 140.908	Nd 144.24	Pm 145	Sm 150.36	Eu 151.964	Gd 157.25	Tb 158.925	Dy 162.5	Ho 164.93	Er 167.26	Tm 168.934	Yb 173.04	Lu 174.967			
Actinides			90	91	92	93	94	95	96	97	98	99	100	101	102	103			
			Th 232.038	Pa 231.036	U 238.029	Np 237.048	Pu 244	Am 243	Cm 247	Bk 247	Cf 251	Es 252	Fm 257	Md 258	No 259	Lr 262			

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Semiconductor Materials

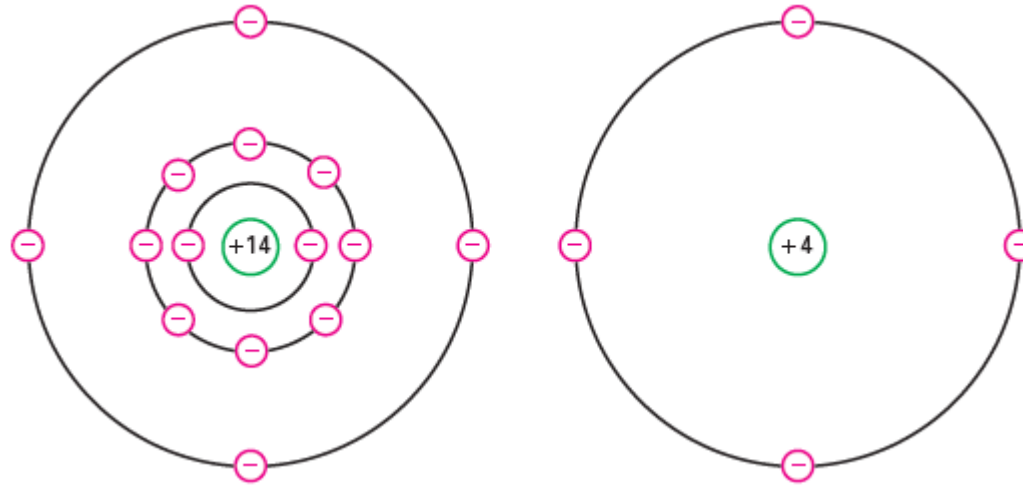
Semiconductor	Bandgap Energy E_G (eV)
Carbon (diamond)	5.47
Silicon	1.12
Germanium	0.66
Tin	0.082
Gallium arsenide	1.42
Gallium nitride	3.49
Indium phosphide	1.35
Boron nitride	7.50
Silicon carbide	3.26
Cadmium selenide	1.70

	IIIA	IVA	VA	VIA
5	10.811 B Boron	6 12.01115 C Carbon	7 14.0067 N Nitrogen	8 15.9994 O Oxygen
13	26.9815 Al Aluminum	14 28.086 Si Silicon	15 30.9738 P Phosphorus	16 32.064 S Sulfur
30	65.37 Zn Zinc	31 69.72 Ga Gallium	32 72.59 Ge Germanium	33 74.922 As Arsenic
48	112.40 Cd Cadmium	49 114.82 In Indium	50 118.69 Sn Tin	51 121.75 Sb Antimony
80	200.59 Hg Mercury	81 204.37 Tl Thallium	82 207.19 Pb Lead	83 208.980 Bi Bismuth
				84 (210) Po Polonium



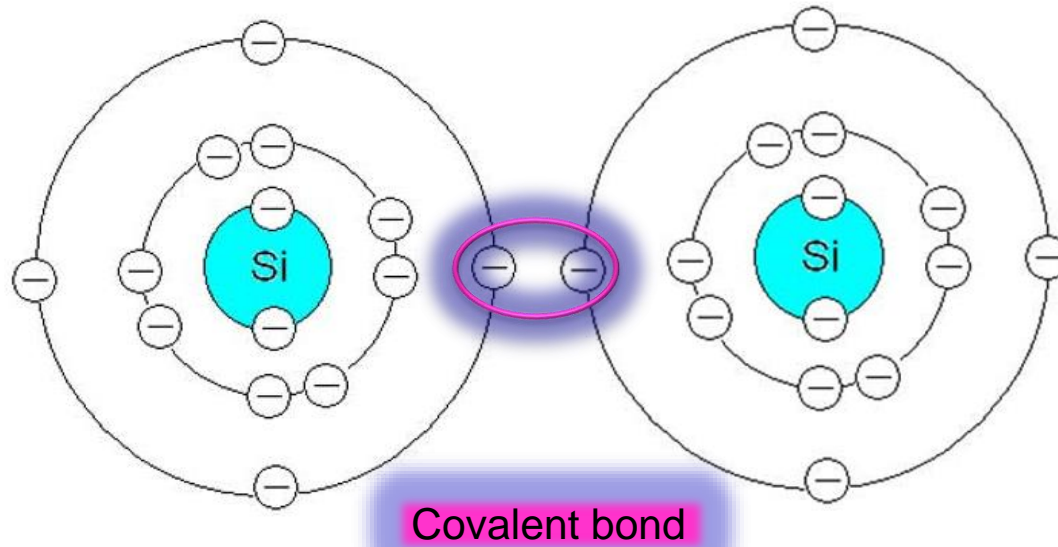
Intrinsic Silicon

- Intrinsic refers to properties of pure materials.

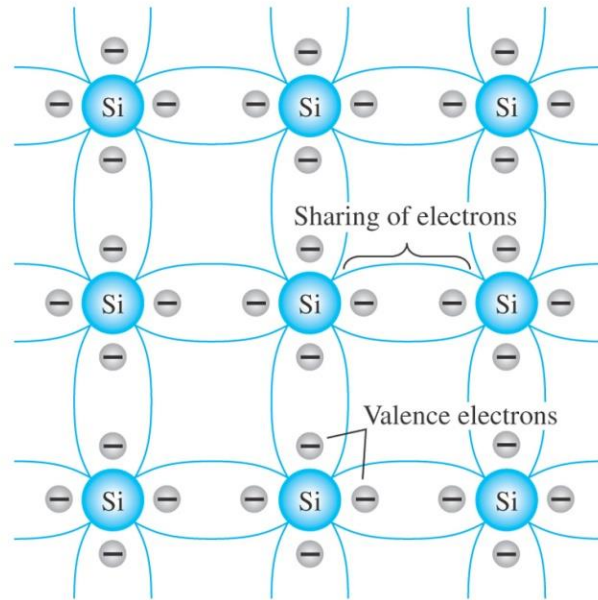


Intrinsic Silicon

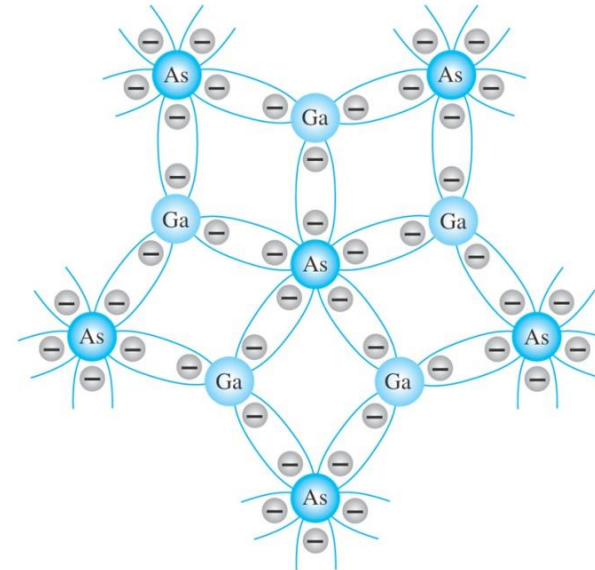
- Covalent Bonding



Covalent Bonding



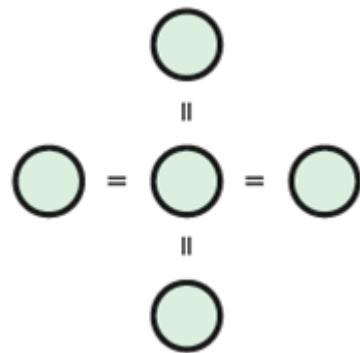
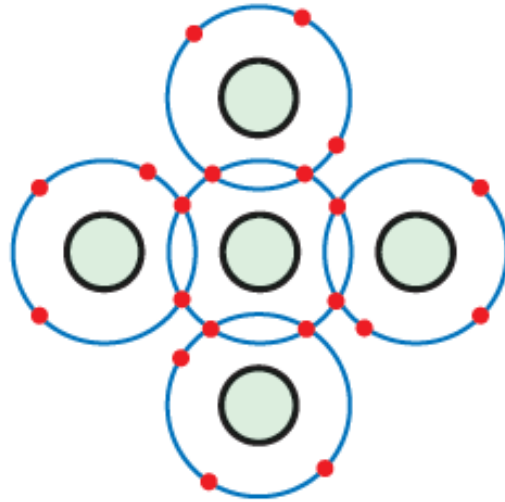
Covalent bonding of Si crystal



Covalent bonding of GaAs crystal

This bonding of atoms, strengthened by the sharing of electrons, is called covalent bonding

Intrinsic Silicon

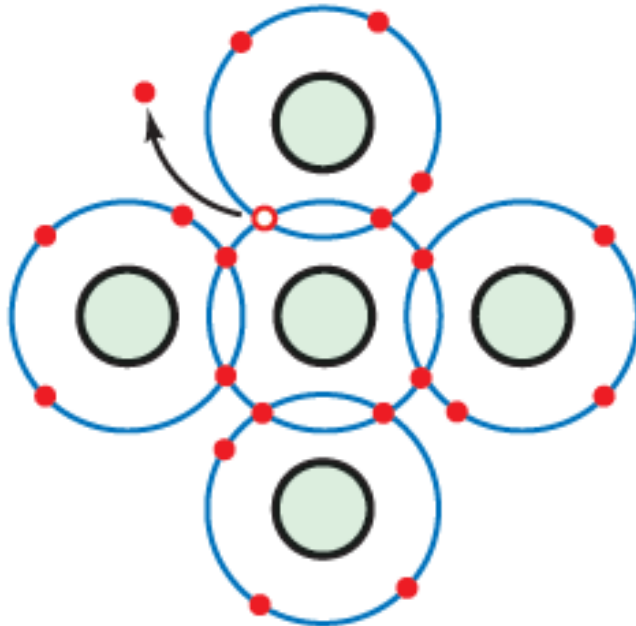


- Near absolute zero, all bonds are complete
- Each Si atom contributes one electron to each of the four bond pairs
- The outer shell is full, no free electrons, silicon crystal is an insulator

- What happens as the temperature increases?

Intrinsic Silicon

When temperature increases



- Increasing temperature adds energy to the system and breaks bonds in the lattice, **generating electron-hole pairs**.
- The departure of the electron creates a vacancy in the valence orbit called a **hole**
- Some of the electrons can fall into the holes – **recombination**.
- **Recombination** is the merging of a free electron and a hole.

Intrinsic Semiconductors

- **intrinsic semiconductor** – is one which is **not doped**
 - One example is pure silicon.
- **generation** – is the process of free electrons and holes being **created**.
 - **generation rate** – is speed with which this occurs.
- **recombination** – is the process of free electrons and holes **disappearing**.
 - **recombination rate** – is speed with which this occurs.

Generation may be effected by **thermal energy**. As such, both generation and recombination rates will be a function of temperature.



Intrinsic Semiconductors

- **Thermal generation** – effects a **equal concentration** of free electrons and holes.
 - Therefore, electrons **move randomly** throughout the material.
- In thermal equilibrium, **generation and recombination rates are equal.**
- **Concentration of free electrons is equal to the concentration of holes**



Intrinsic carrier concentration

- Concentration of free electrons is equal to the concentration of holes

$$n = p = n_i$$

$$n_i = BT^{3/2} e^{-E_g/2kT}$$

- n_i = number of free electrons and holes in a unit volume for intrinsic semiconductor
- B = parameter which is $7.3 \times 10^{15} \text{ cm}^{-3} \text{ K}^{-3/2}$ for silicon
- T = temperature (K)
- E_g = bandgap energy which is 1.12 eV for silicon
- k = Boltzman constant ($8.62 \times 10^{-5} \text{ eV/K}$)



Electron-Hole Concentration

- The electron density is n
- Hole density is represented by p .
- For intrinsic silicon, $n = n_i = p$.
- The product of electron and hole concentrations is

$$pn = n_i^2$$

- The pn product above holds when a semiconductor is in **thermal equilibrium** (not with an external voltage applied).



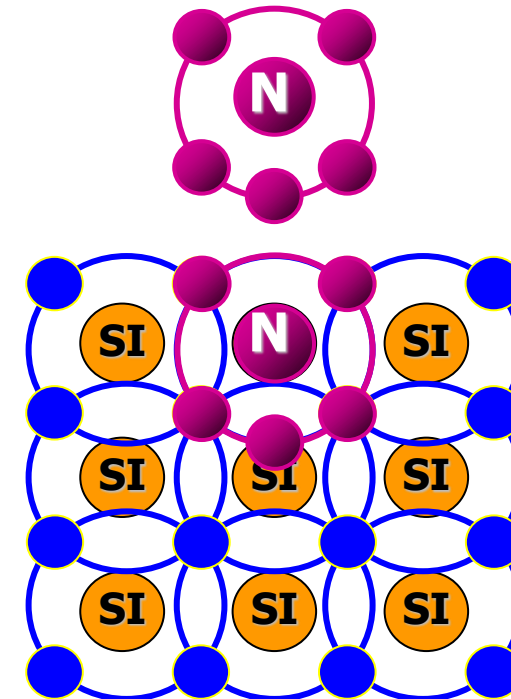
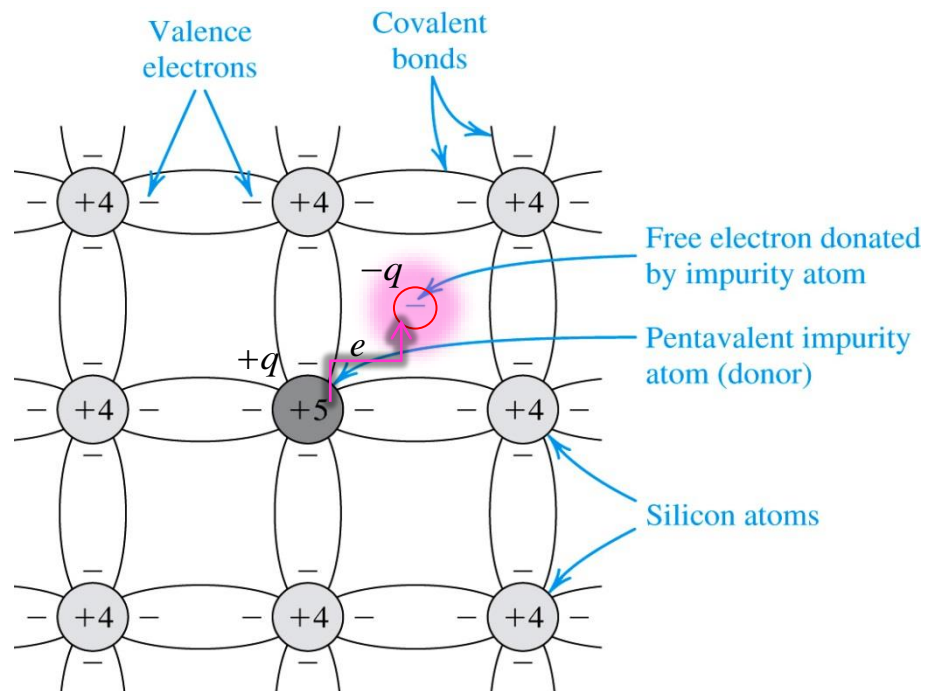
Semiconductor doping

- Doping is the process of adding very small well controlled **amounts of impurities into a semiconductor**.
- Doping enables the **control of the resistivity** and other properties over a wide range of values.
- Increase conductivity of a semiconductor
- For silicon, impurities are from **columns III and V** of the periodic table.
- **Extrinsic** - Impure semiconductors obtained by adding impurities



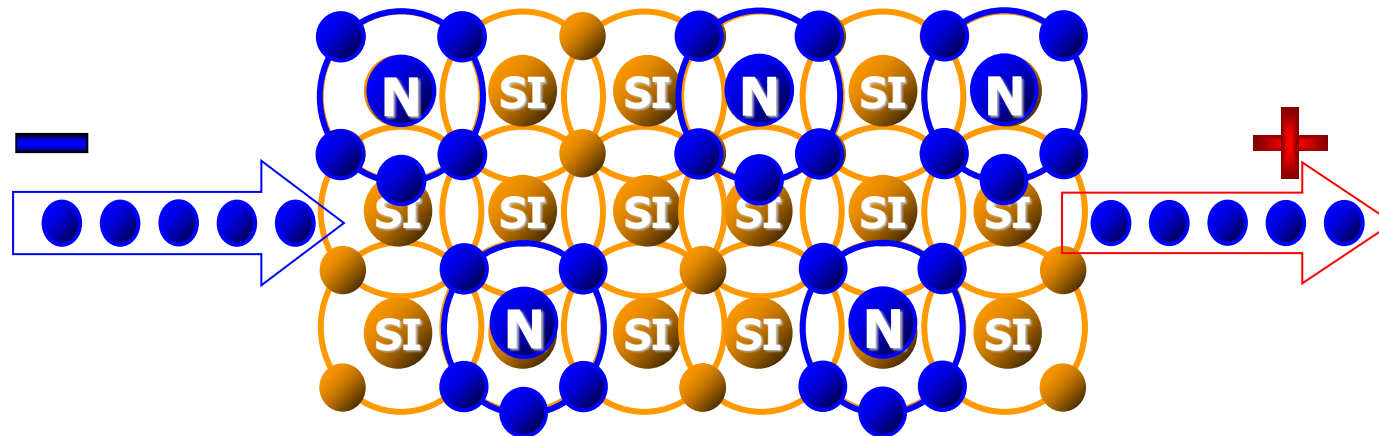
Donor Impurities in Silicon

- Pentavalent Doping – Donor Material
- Pentavalent material have **five outer shell electrons**, there is now an ‘extra’ electron in the structure
- Increases concentration of electrons
- Group V elements - Phosphorous, Arsenic, and Antimony



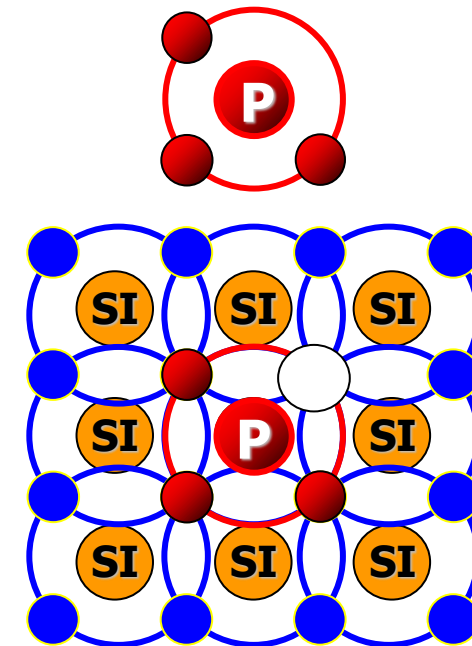
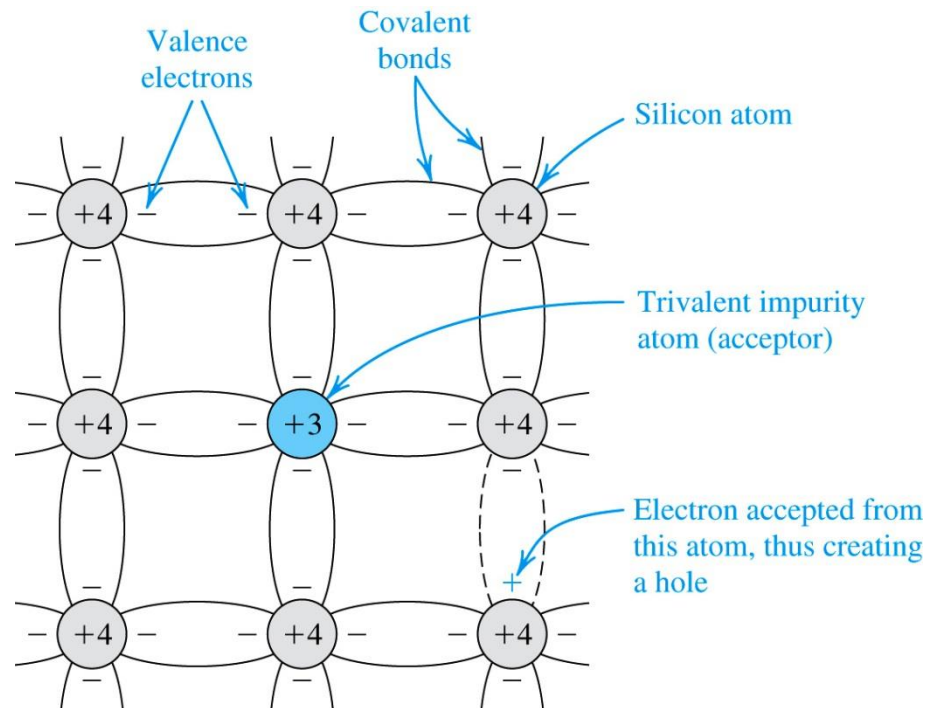
N-type Semiconductor

- Free electrons outnumber the holes in an n-type semiconductor
- **Free electrons** are called **majority carriers**
- **Holes** are called **minority carriers**
- Negative charge



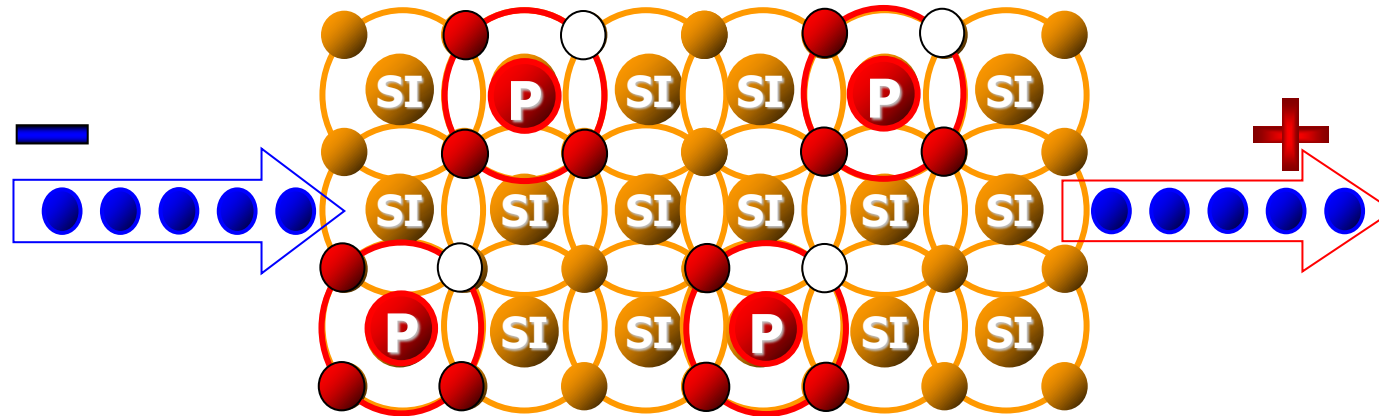
Acceptor Impurities in Silicon

- Trivalent Doping - Acceptor Material.
- Trivalent atoms have only **three valence electrons** – there is one ‘hole’ in the structure
- Increases concentration of holes
- Group III elements - Boron, Aluminum, and Gallium



P-type Semiconductor

- Holes outnumber free electrons
- **Holes** are referred to as the majority carriers
- **Free electrons** are known as the minority carriers
- Positive charge



Summary

- In doped material, the electron and hole concentrations are no longer equal.
- If $n > p$, the material is ***n*-type**.
- If $p > n$, the material is ***p*-type**.
- Carrier with largest concentration is **majority carrier**
- Carrier with smallest concentration is **minority carrier**

