# TEMARIO DEL CURSO DE FUNDAMENTOS DE DISPOSITIVOS ELECTRONICOS

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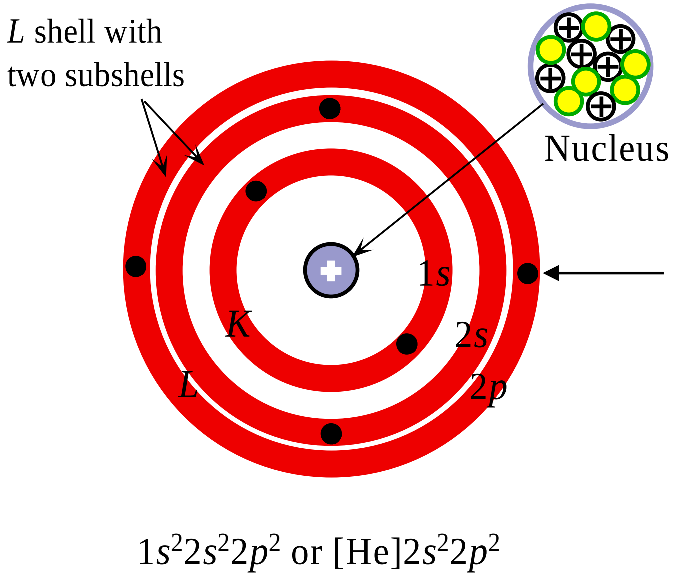
This section discusses the *specific mechanisms by which current flows in a solid*, thus lying the basis to understand why some materials are good conductors of electric current and others not.

## Shell model of the atom

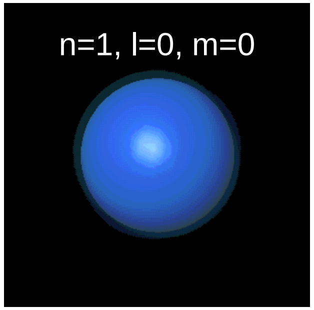
| n | Shell |
|---|---|
| 1 | K |
| 2 | L |
| 3 | M |
| 4 | N |

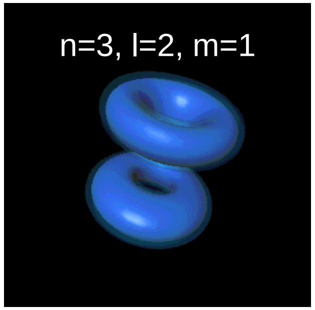


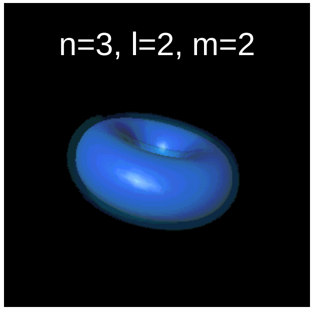

electrons are restricted to sets of ***discrete energy levels*** within atoms.

Fig. 1.1: The shell model of the atom in which the electrons are confined to live within certain shells and in subshells within shells.

From *Principles of Electronic Materials and Devices, Second Edition*, S.O. Kasap (© McGraw-Hill, 2002) http://Materials.Usask.Ca



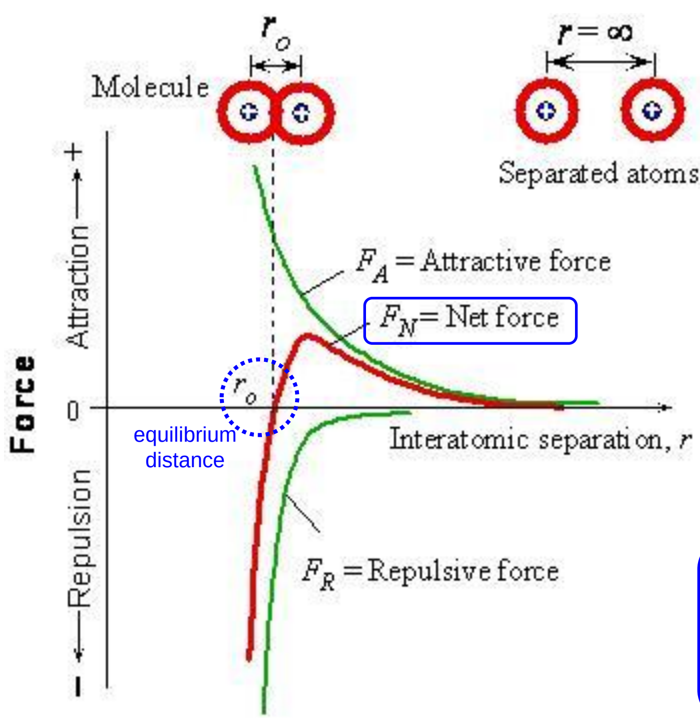



# Bonding Forces and Energy Bands in Solids

The influence of neighboring atoms on the energy levels of a particular atom gives rise to ***shifting and splitting of energy states into energy bands***. This interaction of electrons in neighboring atoms of a solid serves to hold the crystal together.

When 2 atoms are brought together, the valence electrons interact with each other (*repulsive forces* $F_R$) and with the neighbor's positively charged nucleus (*attractive forces* $F_A$).The result of this interaction is often the formation of a bond between the 2 atoms, producing a molecule.




$\Delta E=W$

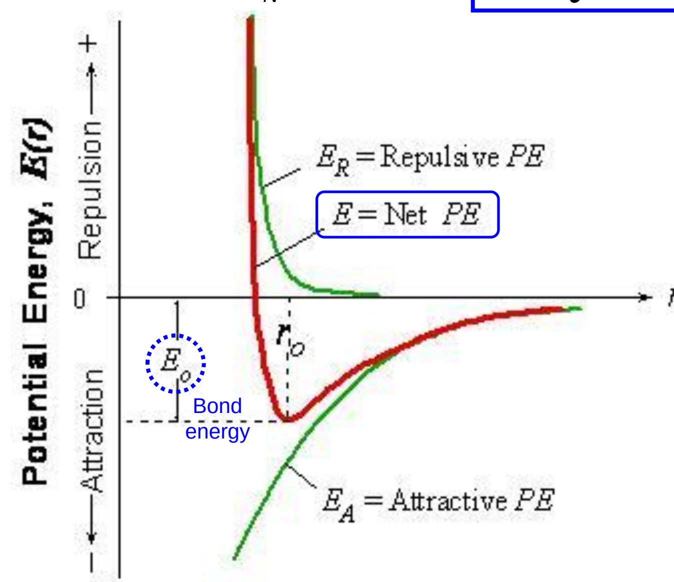
$\Delta E=F\cdot r$

$F_N=dE/dr$

$dE=F_N dr$

$$\boxed{E=\int F_N dr}$$

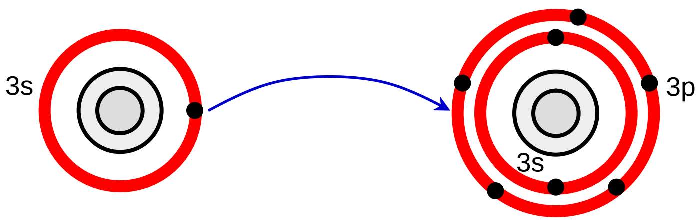
Once the atoms are held together, a *bond length* $r_0$ and *bond energy* $E_0$ develops in the solid.

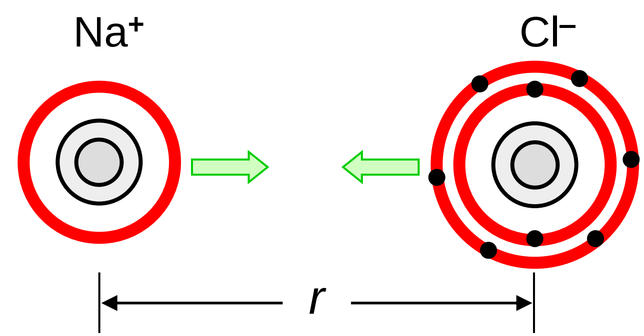


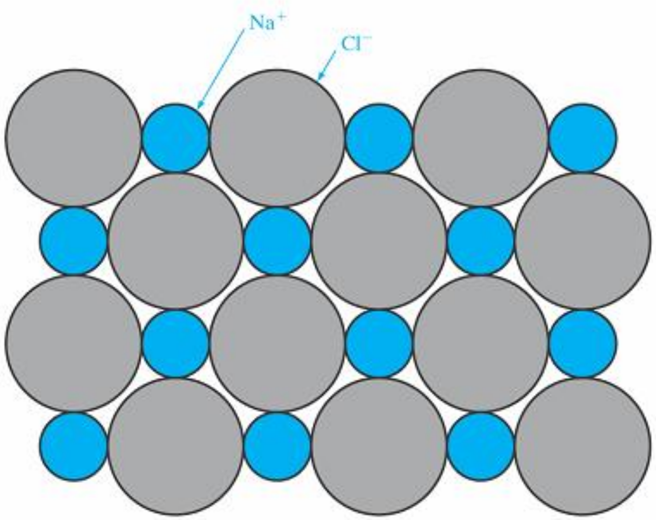
# Ionically Bonded Solids

Ionic bonding is frequently found in materials that normally have a metal and a nonmetal as the constituent elements. ***Transfer of valence electrons between the 2 elements results in 2 oppositely charged ions called cation and anion***.

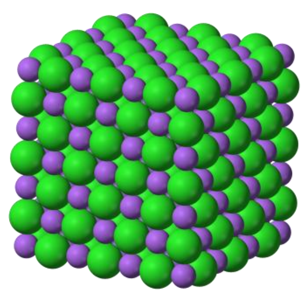
Na= [Ne] $3s^1$ Cl = [Ne] $3s^2$ $3p^5$

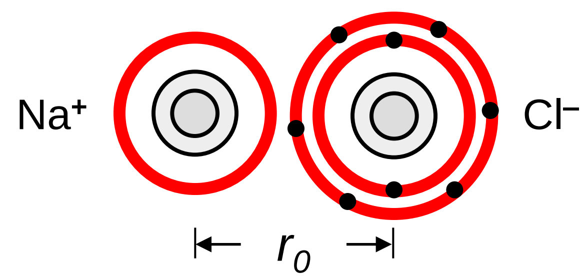



(a)



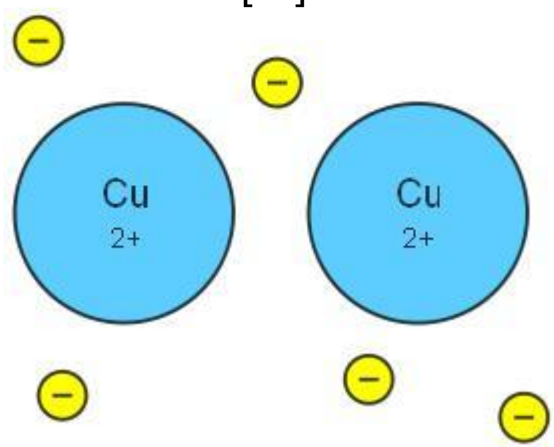


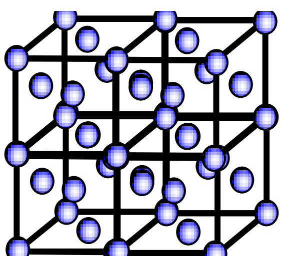

Once the electron exchanges have been made, the outer orbits of all atoms are completely filled and *there are no bound electrons to participate in current flow*.

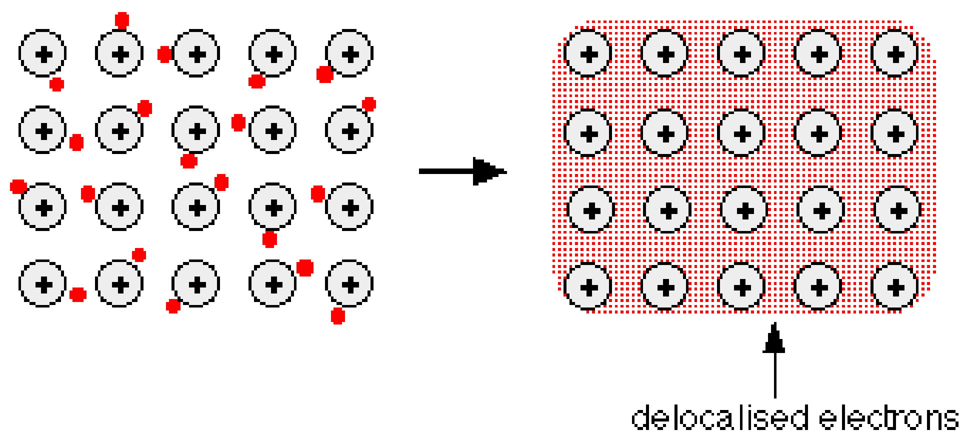
# Metallically Bonded Solids

Metal atoms have only a few valence electrons, which are not very difficult to remove. When many metal atoms are brought together to form a solid, these valence electrons are lost from individual atoms and become collectively shared by all the ions. ***The valence electrons become delocalized and form an electron gas or electron cloud, permeating the space between the ions***.

Cu = [Ar] $3d^{10}$ $4s^{1}$





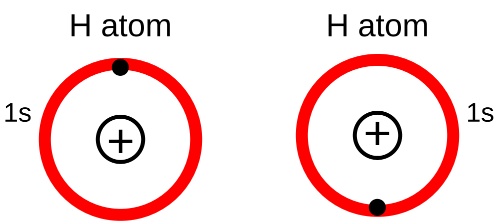

The bonding in a metal is essentially due to the attraction between the stationary metal ions and the freely wandering electrons between the ions. *These electrons are free to move about the crystal under the influence of an electric field*.

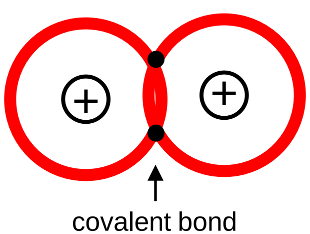
# Covalently Bonded Solids

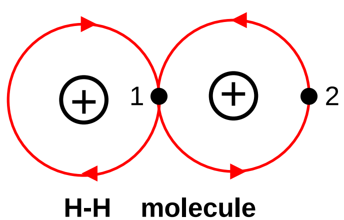
2 atoms can form a bond with each other by ***sharing some or all of their valence electrons*** and thereby reducing the overall potential energy of the combination.

The covalent bond results from the *sharing of valence electrons* to complete the subshells (saturate the valence) of each atom.

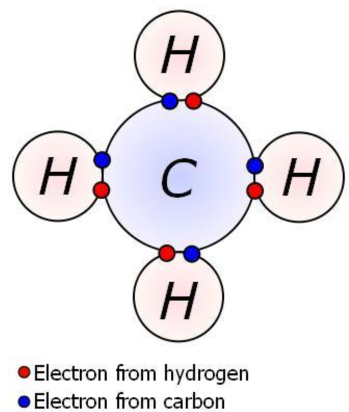
The covalent bond can also be found for more complex structures like CH4, C, Si, etc. *The covalent bond energy is usually the highest for all bond types*: high Tm, hardness, etc.

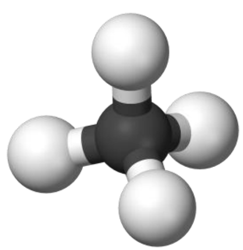


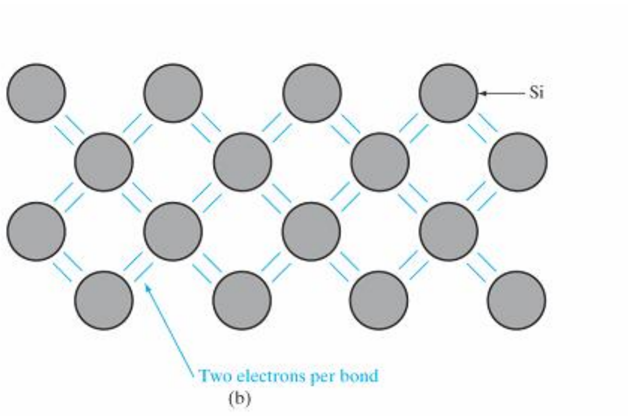



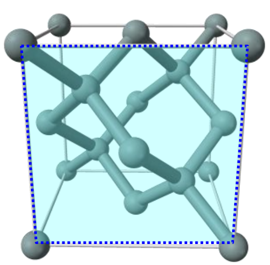

[He] $2s^2$ $2p^2$ + 4H = $\mathbf{CH_4}$



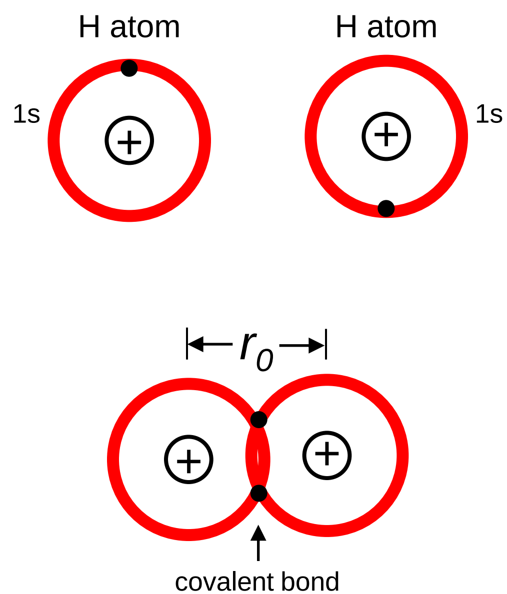
[Ne] $3s^2$ $3p^2$

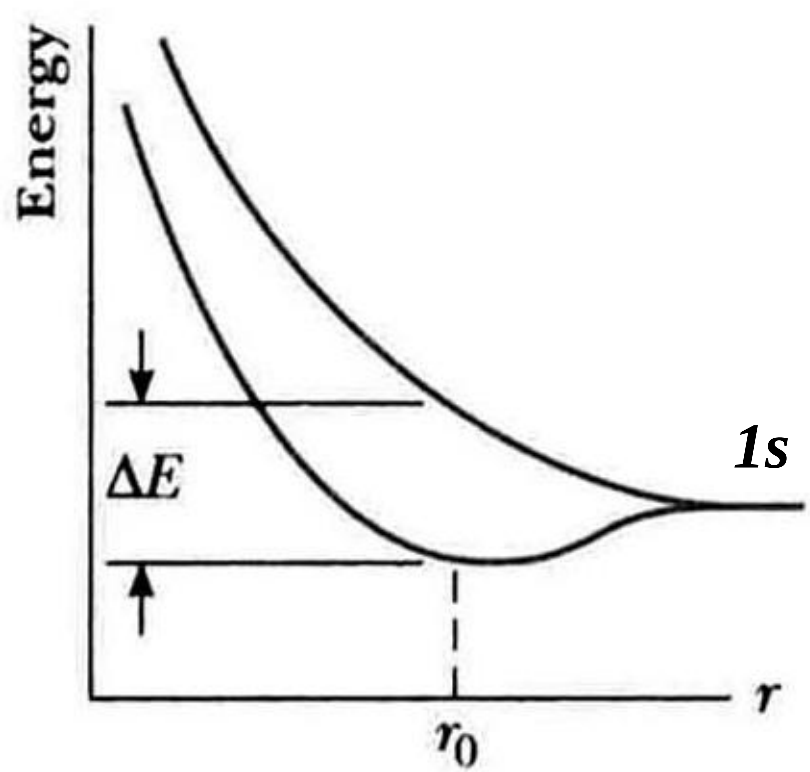


# Energy Bands

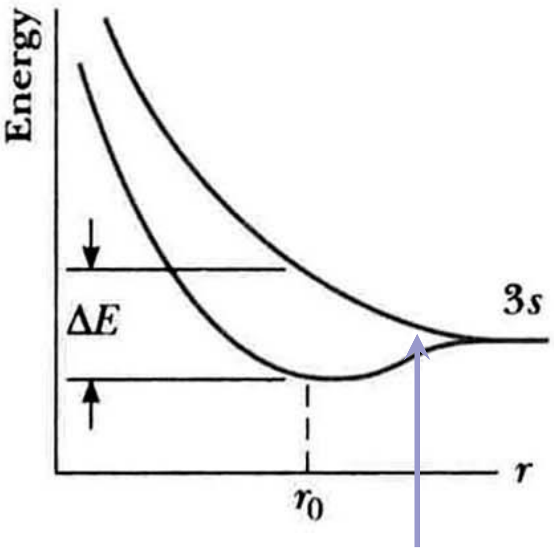
As isolated atoms are brought together to form a solid, various interactions occur between neighboring atoms. The forces of attraction and repulsion between atoms will find a balance at the proper interatomic spacing of the crystal. In the process, ***important changes occur in the electron energy level configurations, which result in the varied electrical properties of solids***.



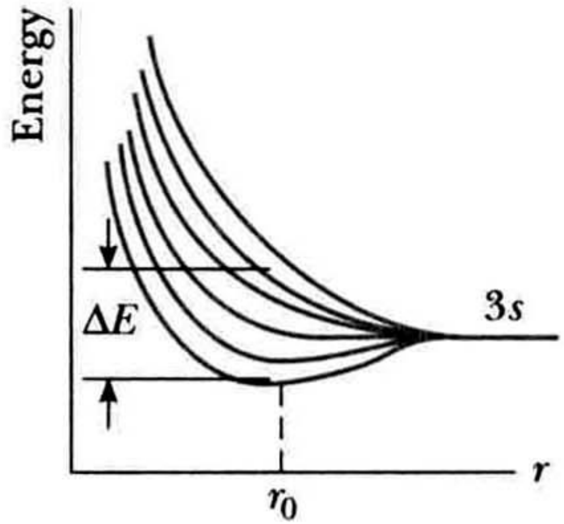



Na = [Ne] $3s^1$

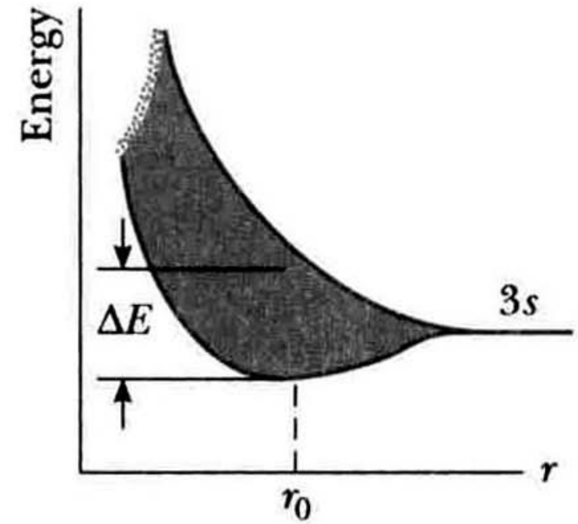
**Two atoms**




**Six atoms**




**Solid of $1X10^{22}$ atoms**

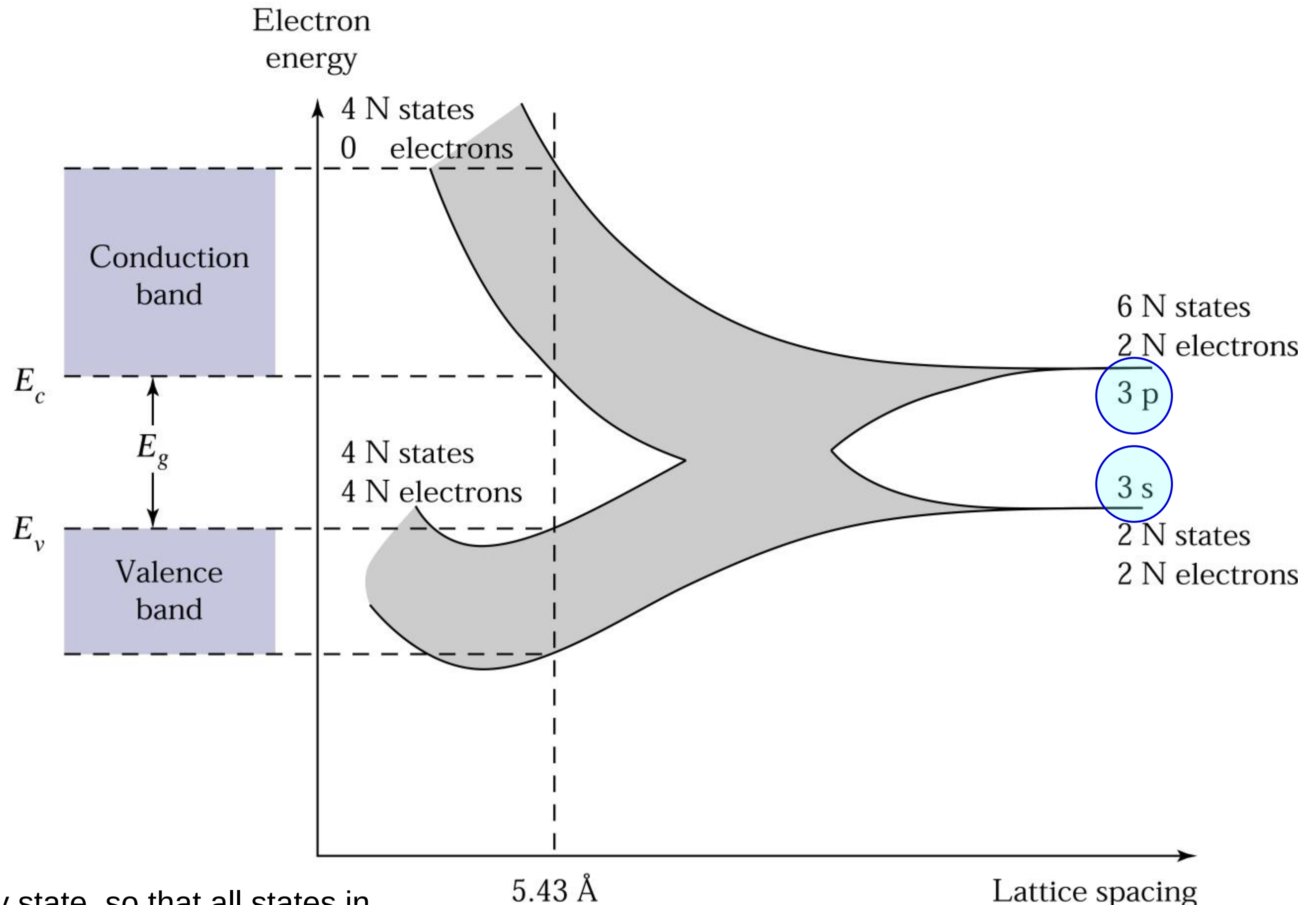



Electrons must occupy different energies due to Pauli Exclusion principle.

Si = [Ne] $3s^2\ 3p^2$

$E_g$ (Si) = 1.12 eV

$E_g$ (GaAs) = 1.42 eV




- At 0K, electrons are in the lowest energy state, so that all states in the lower band (valence band) will be full, and all states in the upper band (conduction band) will be empty.

- Thermal excitations in semiconductors above 0K allow electrons to cross the energy gap from the valence to the conduction band. This is essentially the energy required to break a valence bond

*The formation of these energy bands is directly related to the electrical characteristics of the crystal*.

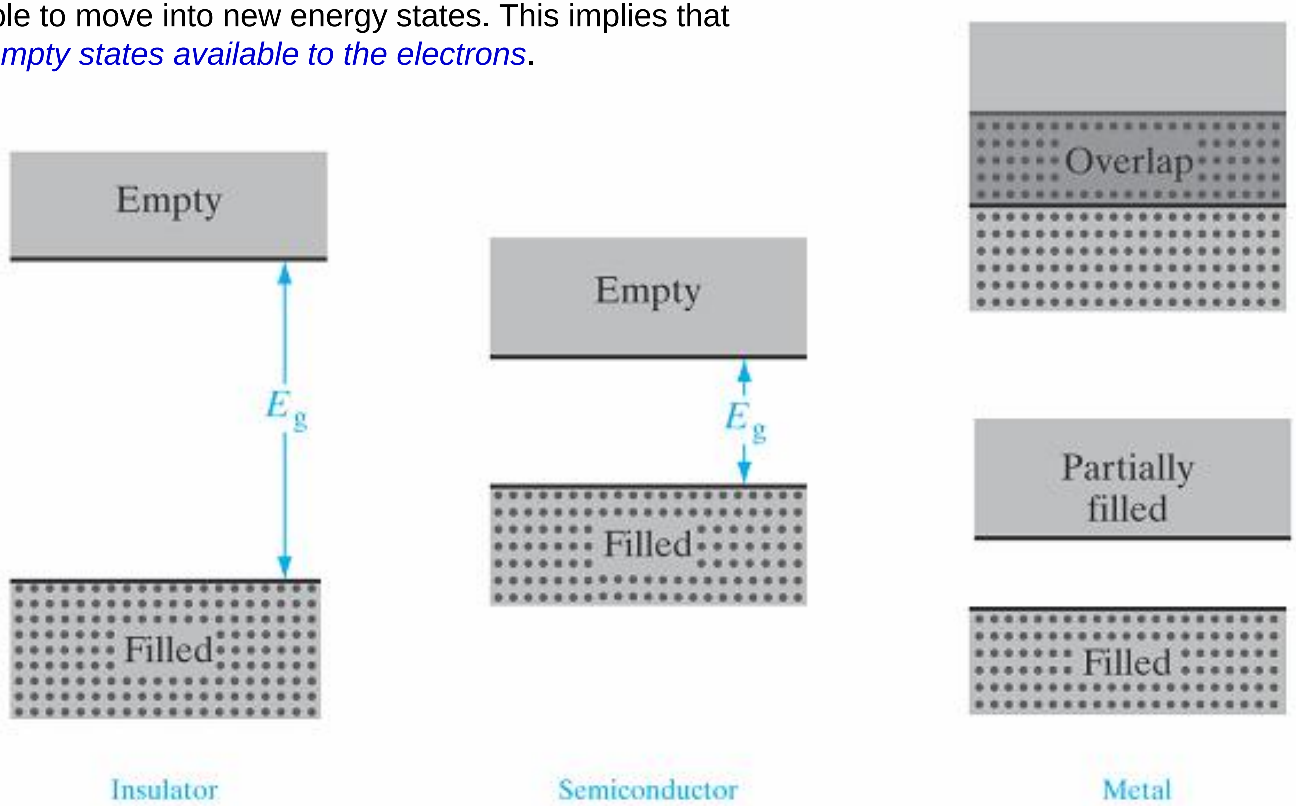
# Insulators, Semiconductors and Metals

For electrons to experience acceleration in an applied electric field, they must be able to move into new energy states. This implies that *there must be empty states available to the electrons*.

Eg ($SiO_2$) ~ 9 eV

$E_g$ (C) = 5 eV

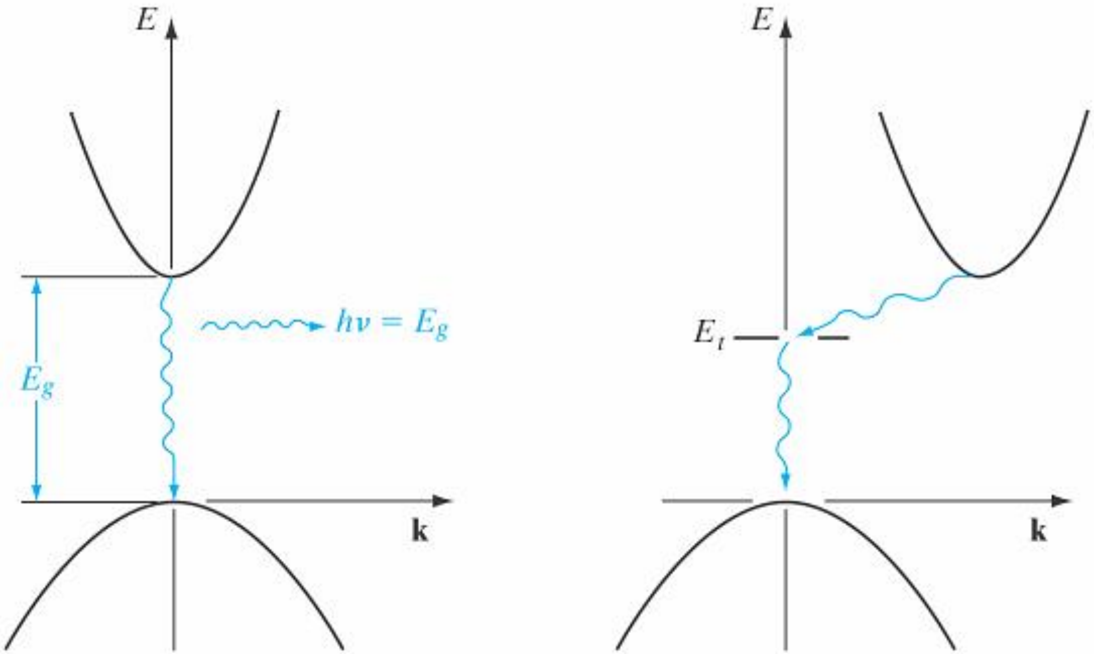
$E_g$ (Si) = 1.12 eV




The most important result of application of quantum mechanics to description of electrons in a solid is that the ***allowed energy levels of the electrons will be grouped into two bands and they are separated by regions of energy in which the electrons cannot exist***.

# Direct and Indirect Semiconductors

Since the periodicity of most lattices is different in various directions, the (E, **k**) diagram must be plotted for the various crystal directions.

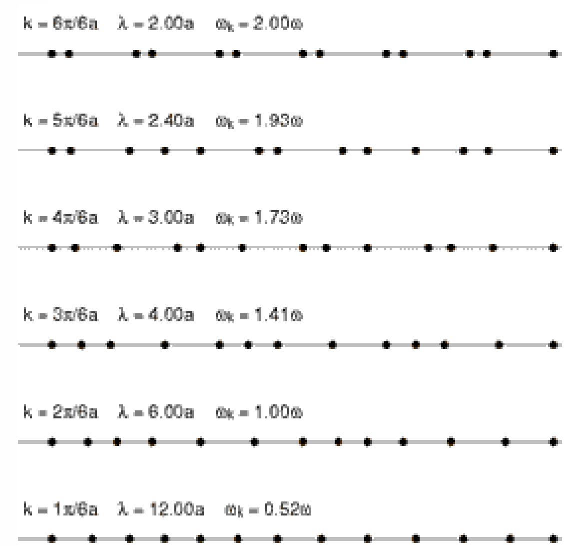



**Direct bandgap (GaAs)**
No change in momentum required
(useful for photonic devices)

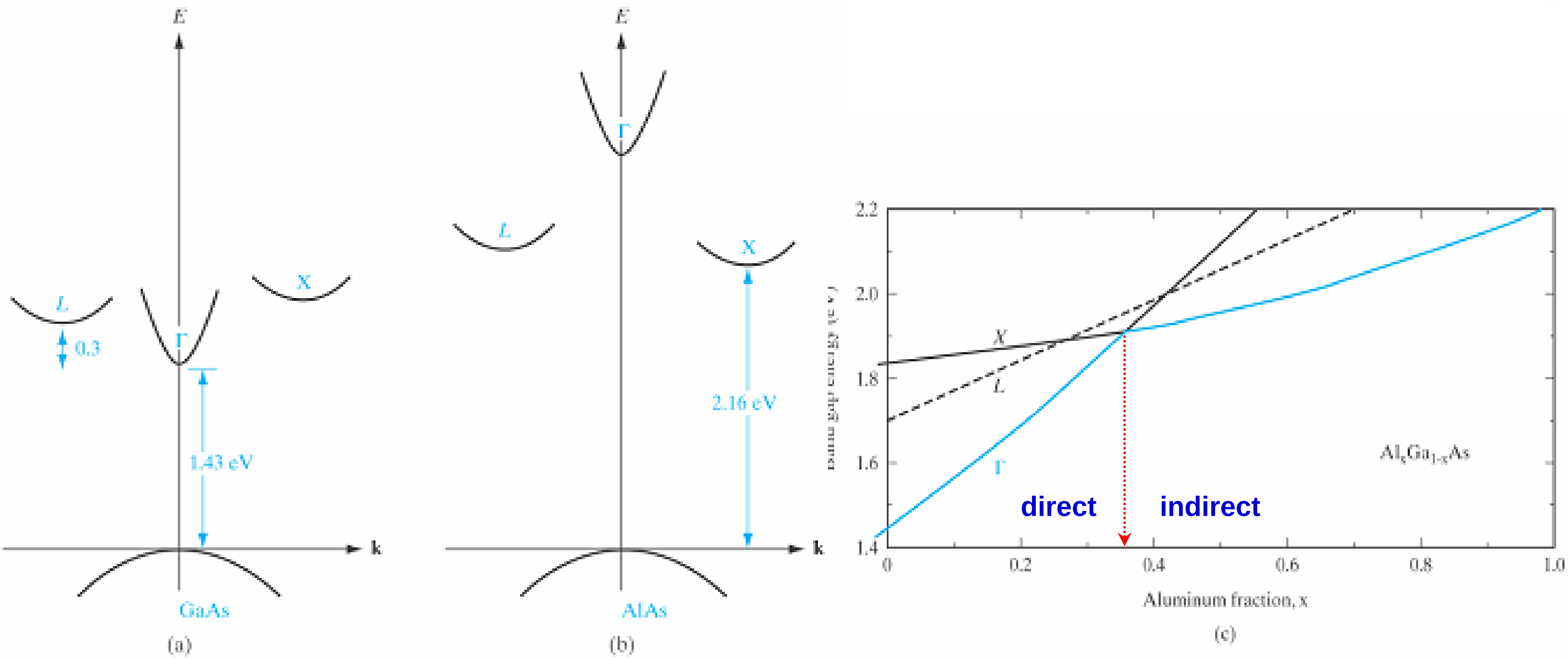
**Indirect bandgap (Si)**
Change in momentum required

Direct and indirect electron transitions in semiconductors: (a) direct transition with accompanying photon emission; (b) indirect transition via a defect level.

*Phonon*: quantized mode of vibration occurring in a rigid crystal lattice (heat)

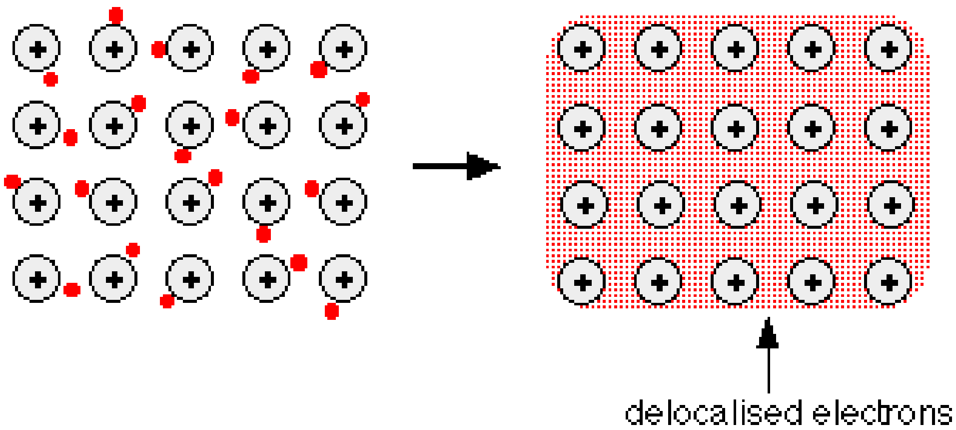


# Variations of Energy Bands with Alloy Composition



# Charge Carriers in Semiconductors

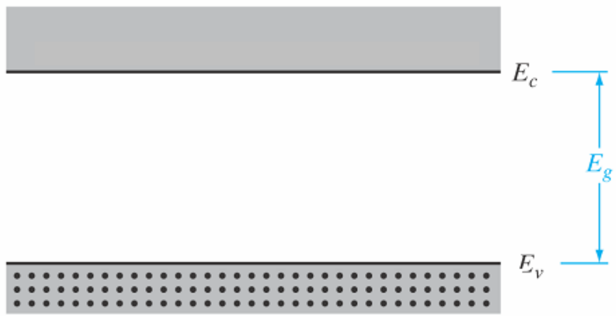
- The mechanism of current conduction is relatively easy to visualize in the case of a metal; the metals atoms are imbedded in a “sea” of relatively free electrons, and these electrons can move as a group under the influence of an electric field.



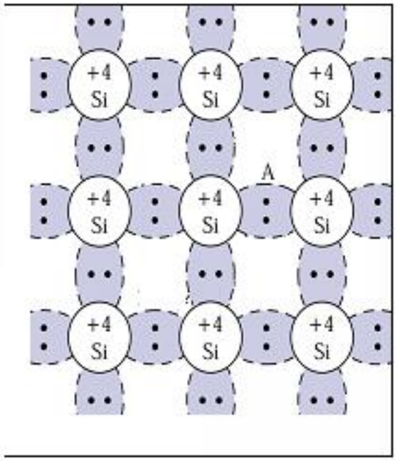

- However, we cannot account for all the electrical properties of semiconductors in this way. Because these properties are strongly *dependent of temperature, doping, electric, optical and magnetic fields*.

# Electrons and Holes

At T=0K all bonds remain intact resulting in a highly insulating material.

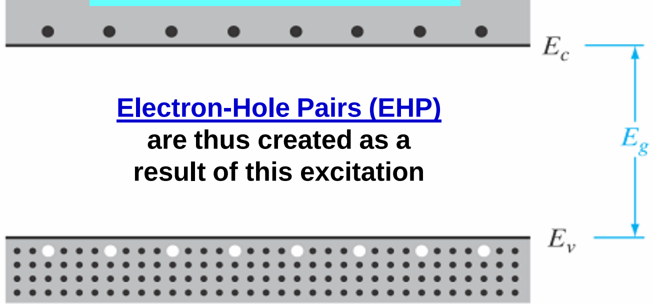



T = 0 K




At T>0K thermal excitations may cause bonds to break resulting in free electrons and ‘holes’: conducting solid.

**Few electrons in the conduction band are free to move about via the many available empty states**

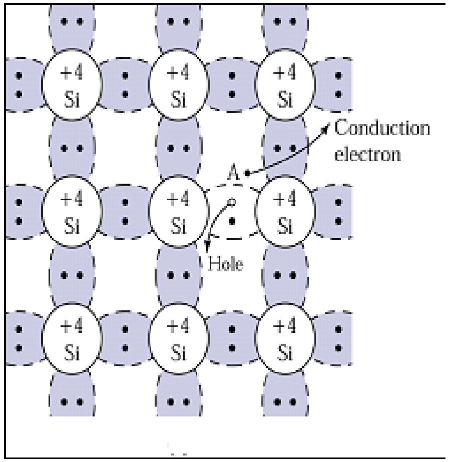



**Electron-Hole Pairs (EHP) are thus created as a result of this excitation**

**An empty state in the valence band is referred as a hole**

T > 0 K

In all the following discussions we shall concentrate on the electrons in the conduction band and on the holes in the valence band. **The current flow in a semiconductor is done by the motion of these 2 types of charge carriers**.



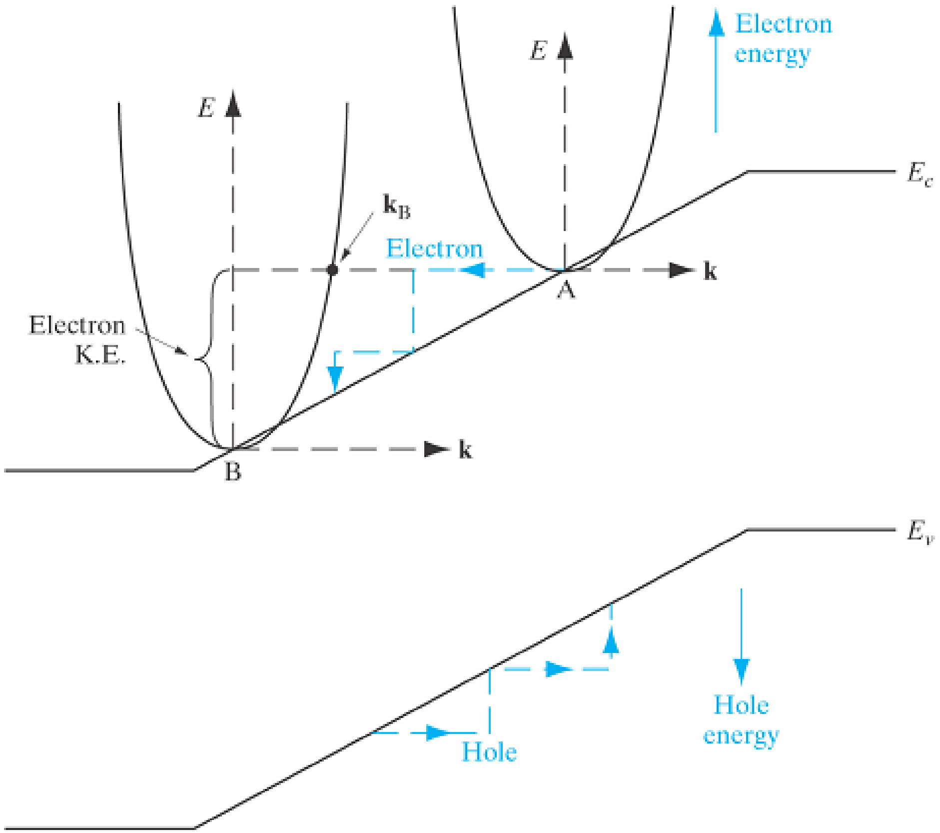
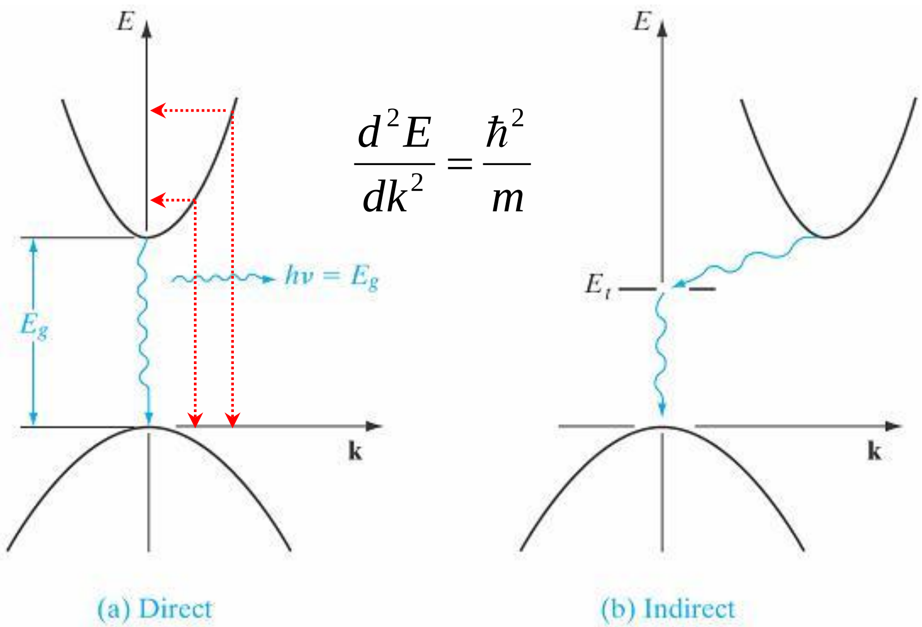


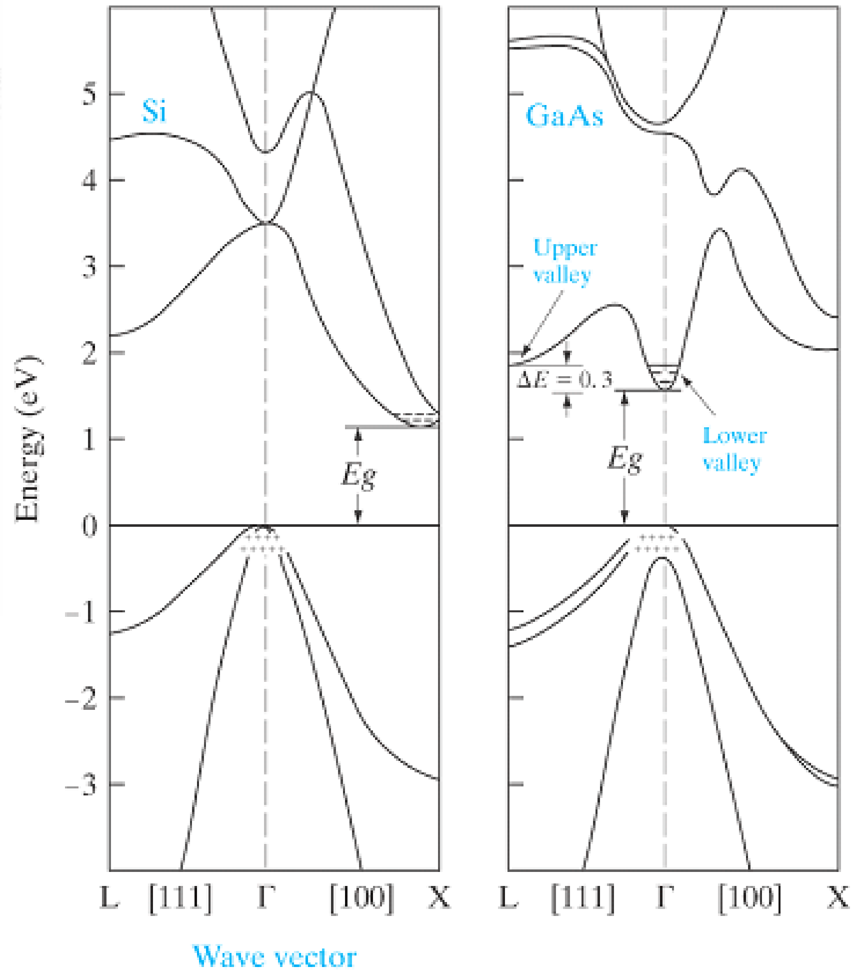

Figure 3.9

Superimposition of the ($E$,$\mathbf{k}$) band structure on the $E$-versus-position simplified band diagram for a semiconductor in an electric field. Electron energies increase going up, while hole energies increase going down. Similarly, electron and hole wave vectors point in opposite directions and these charge carriers move opposite to each other, as shown.

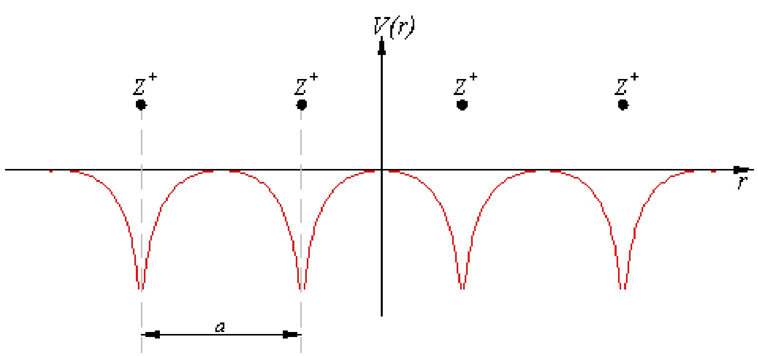
# Ideal and realistic band structures in semiconductors




$$\frac{d^2E}{dk^2} = \frac{\hbar^2}{m}$$

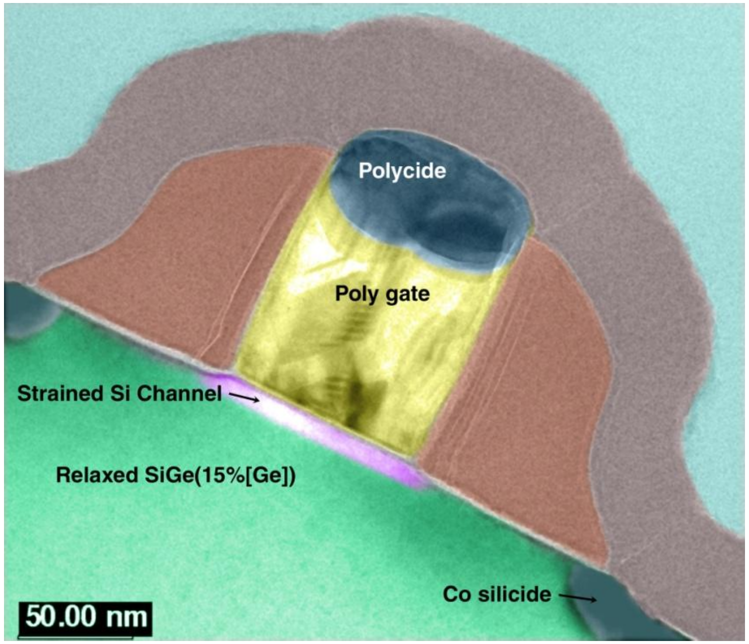


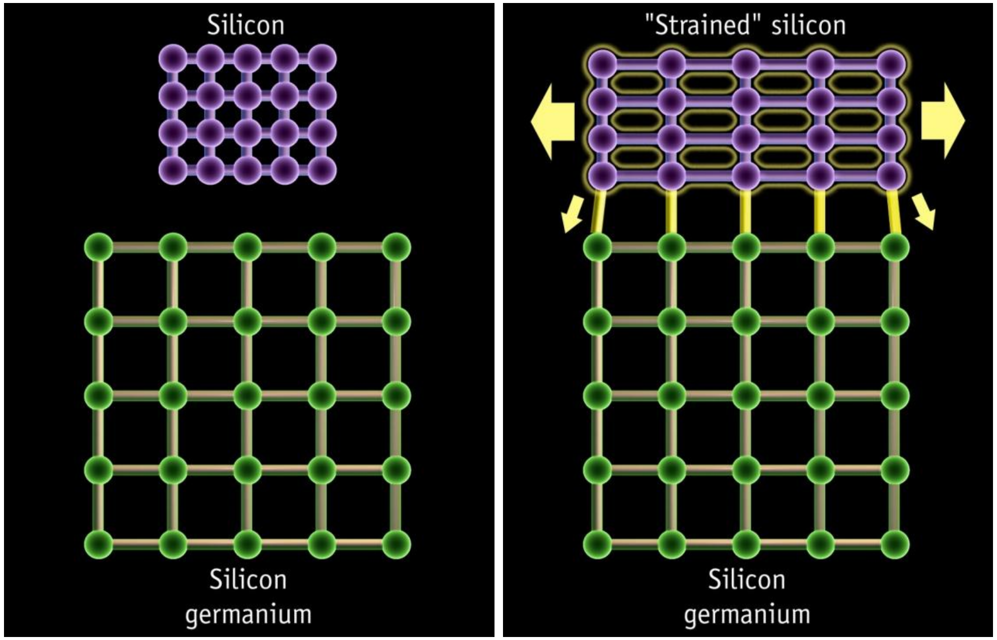

**The electrons in a crystal are not completely free, but instead interact with the periodic potential of the lattice.**



# Strained-silicon based MOSFETs

Strained silicon is a layer of silicon in which the silicon atoms are stretched beyond their normal interatomic distance. This can be accomplished by putting the layer of silicon over a substrate of silicon germanium (SiGe), where the atoms are farther apart. The linking of the silicon atoms with the SiGe substrate become stretched - thereby leading to strained silicon.




The silicon is "stretched out" because of the natural tendency for atoms inside compounds to align with one another. When silicon is deposited on top of a substrate with atoms spaced farther apart, the atoms in silicon stretch to line up with the atoms beneath, stretching -- or "straining" -- the silicon ***… without having to shrink the size of transistors.***