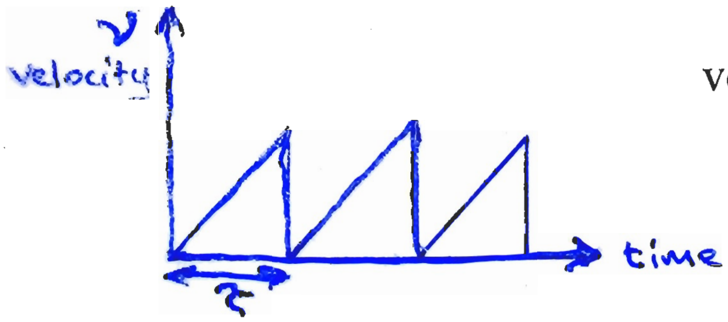
EEE 207 Semiconductors for Electronics and Devices

Revision: Electron mobility in a semiconductor.
Electron in an electric field undergoes acceleration and then collides every τ seconds with phonons (lattice vibrations), defects, impurities etc. $\tau \sim 10^{-14}$ sec.

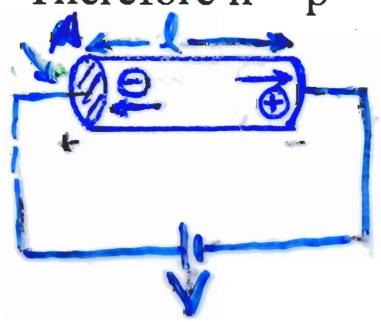


Force $F = eE$
velocity (v) = acceleration x time
acceleration = eE/m
$v = eE/m$ x time
$v_{max} = eE\tau/m$

$v_{ave} = \frac{1}{2}(0 + eE\tau/m) = eE\tau/2m$

Since definition of mobility is $v = \mu E$, this implies that
$\mu = e\tau/2m$
This is a simplification – **in reality, $\mu = e\tau/m$.**
(see Allison pg.72-74 for detailed treatment)

Intrinsic (pure) semiconductors have equal number of electrons and holes as when bonds are broken we have one electron and one hole created.
Therefore $n = p = n_i$ (number per unit volume)



Field (E) = V/l
Time for electrons to move distance $l = l/v$
Since $v = \mu_e E$, time = $l/\ \mu_e E$
Similarly for holes, time = $l/\ \mu_h E$

Current (I) = charge/unit time

$$I = \frac{lAne\mu_e E}{l} + \frac{lApe\mu_h E}{l}$$

Current density (J) = I/A

$$J = eE(n\mu_e + p\mu_h) = \sigma E$$

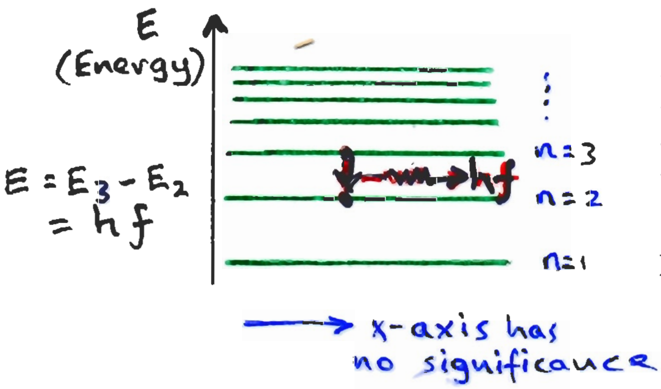
where

$$\sigma = e(n\mu_e + p\mu_h)$$

Energy Band Model for Electrons in Solids

Individual atom: Consider hydrogen atom as it is the simplest. In 1913 Bohr postulated that to explain the discrete sharp lines in the radiation spectrum we must have

i) Fixed orbitals
ii) Quantised electron energy levels



$E_n = -13.6/n^2$ eV, where n = principal quantum numbers, 1,2,3,…..etc. The x-axis has no significance.

A transition between two levels results in emission of radiation hf, where h = Planck's constant and f = frequency. (For more background see Allison, pg. 7-10)

Actual picture is more complicated as there are 3 other quantum numbers: l (gives allowed angular momentum), m (magnetic quantum number – angle of spin axis w.r.t. B-field), s (spin – either +1/2 or –1/2).

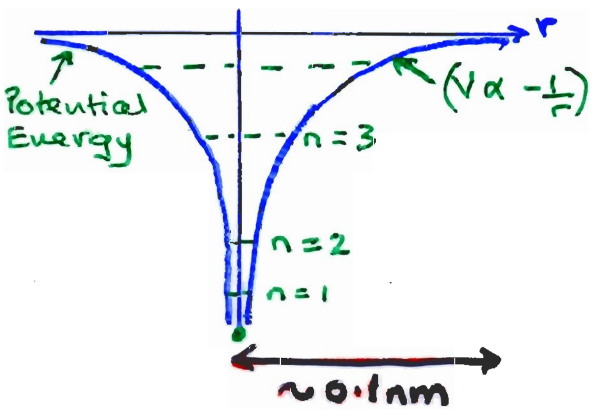
Electrons in solids also obey 2 other rules:

i) Usually occupy **lowest** available energy level

ii) Obey **Pauli Exclusion Principle** – only 1 electron is allowed in any particular quantum state, i.e. only 1 electron with particular (n,l,m,s) values.

2 electrons cannot exist at the same place with the same energy....

Often radius of orbitals is included in the model:



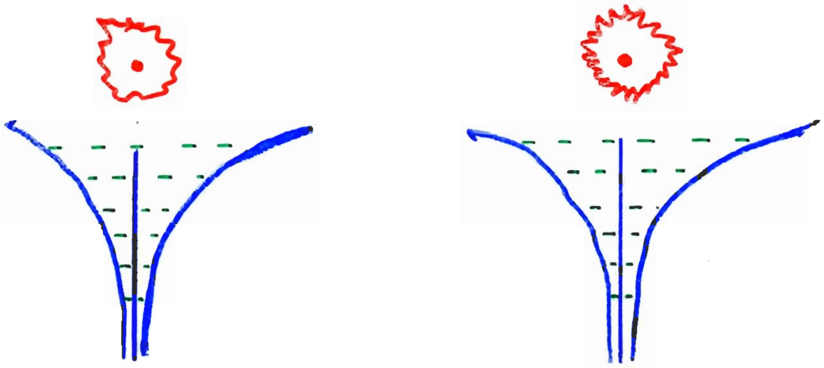
2-D model of electron energy in atom

Potential energy barriers bind electrons to nucleus.

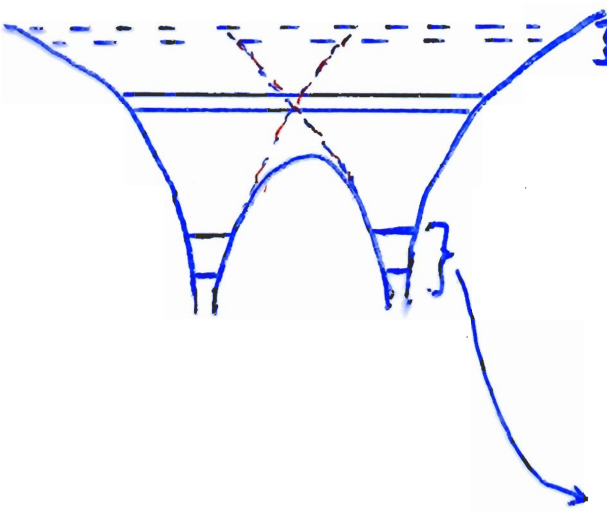
Electrons in the lower states are more strongly bound to nucleus.

Atoms and Electrons in Solids

a) When atoms are far apart – as in a gas – no interaction between atoms, no interaction between atoms, no overlap of orbitals, so electrons **can** have the same energy levels.



b) As soon as atoms are brought together in a solid, electron orbitals overlap, so their corresponding energy levels change slightly (‘split’) to avoid contravening the Pauli exclusion principle.

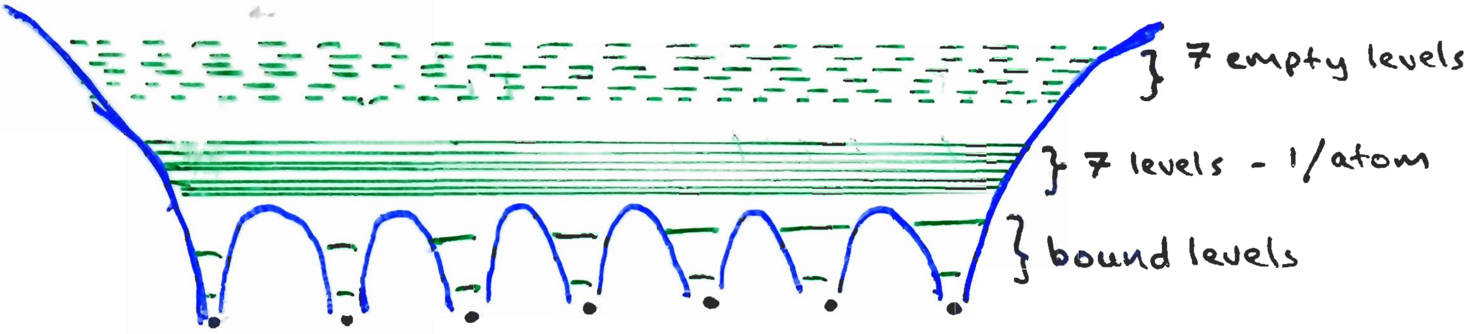


Levels split to avoid contravening Pauli

Lowered energy barrier – potential energy of barriers add – both are –ive – allows for attraction of other +ive nuceleus.

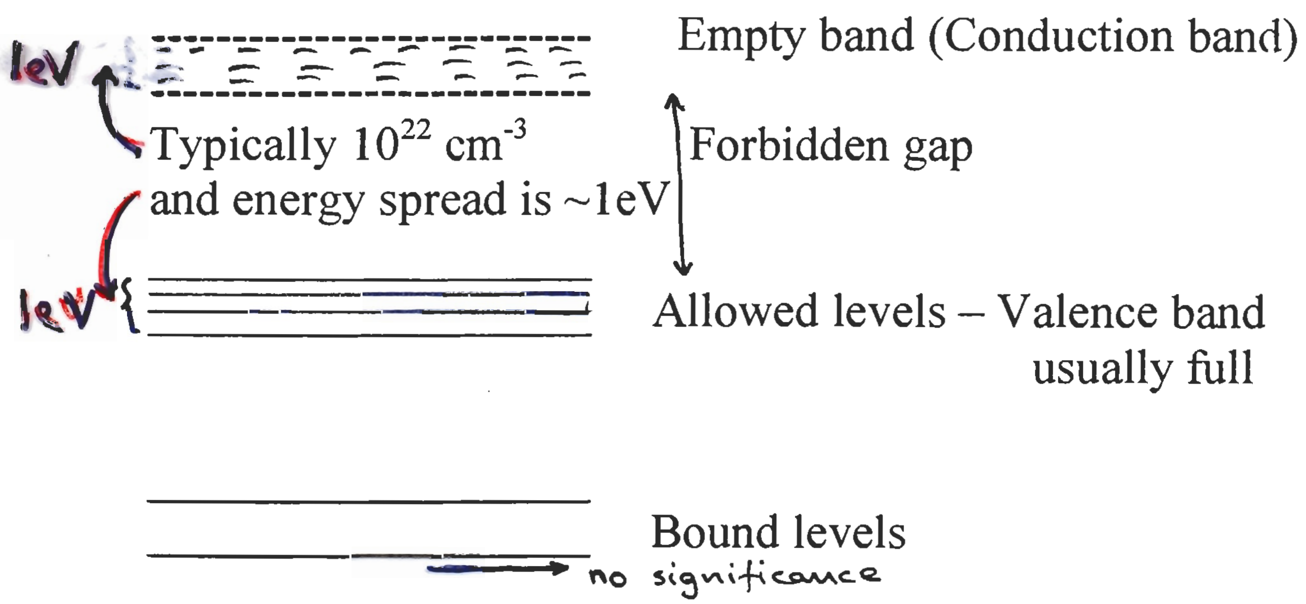
Orbitals of bound electrons do not overlap – so no ‘splitting’.

e.g. 7 atom solid



As 7 atoms interact to form the 'solid', outer overlapping electron levels each split 7 ways, so as to obey Pauli's exclusion principle.

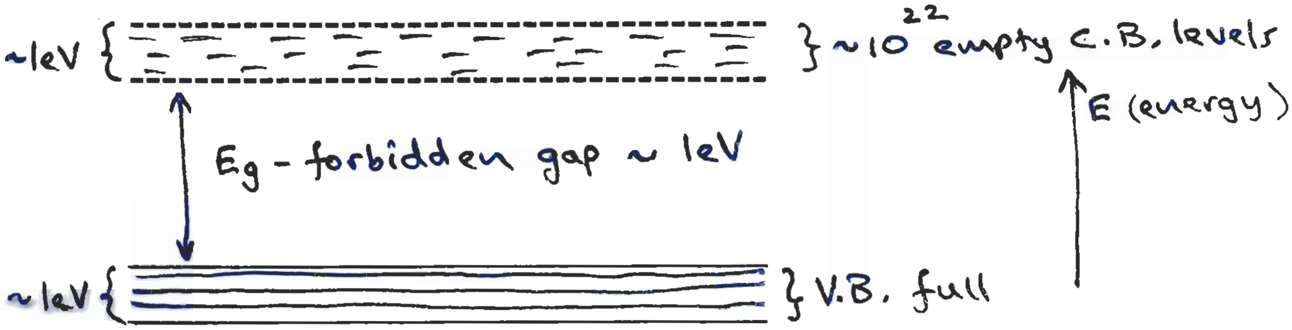
Hence real solid can be represented by:-



The levels are 10^{-22}eV apart – so quasi-continuous allowed band of energies.

Bound levels do not affect electrical properties – hence omit them.
Also empty allowed band ≡ excited levels in atom :
these allow valence band electrons gaining energy from an electric field to fill these levels, called conduction band.
Forbidden energy gap ≡ forbidden energies (levels).

Hence possible band model of solid:



Metals, Insulators & Semiconductors : Energy band Descriptions

For conduction in a band;

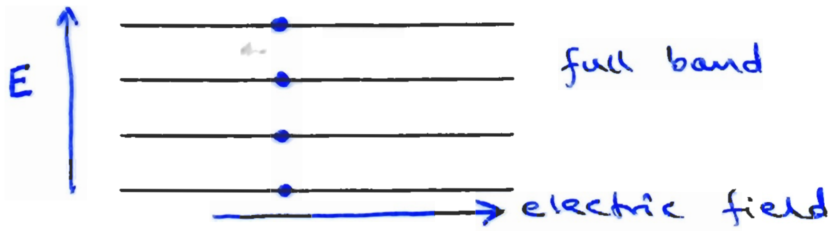
i) **free** electron must be there, i.e. no conduction in an empty C.B.

iii) If carriers are to gain energy from electric field, there must exist a higher empty energy-level to move into (- otherwise Paulis's exclusion principle violated).

Consequences:

(a) an empty C.B. cannot support conduction

(b) a completely full band cannot support conduction (not obvious!) – no empty energy levels for electrons to move into.

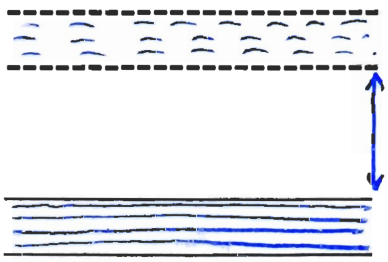


(b) for conduction, need partially filled band

If an electric field is applied, electrons gain energy and can move into higher empty levels.

Insulators:

Outermost energy bands determine electrical properties. These have a filled valence band, separated by a large energy gap, from an empty conduction band.



C.B. empty – no conduction

Large forbidden gap ~5eV

full V.B.- no conduction

Electrons in V.B. cannot acquire small energy as this would move them into the forbidden gap.

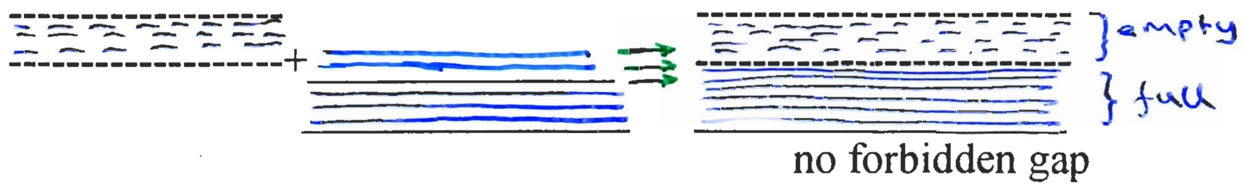
Conduction only if V.B. electrons can acquire >Eg (~5eV) energy to move into C.B.

Probability of this happening is small e.g. at room temperature, thermal energy of valence electrons

~kT=25meV, <<5eV! Therefore poor conductor at room temperature.

Metals(:good conductors)

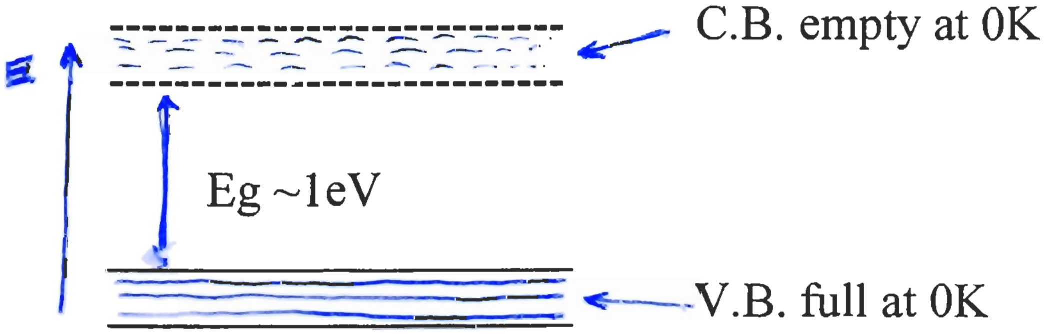
Distinguishing feature is that outer empty band overlaps next inner full band – forms a composite part-filled band.



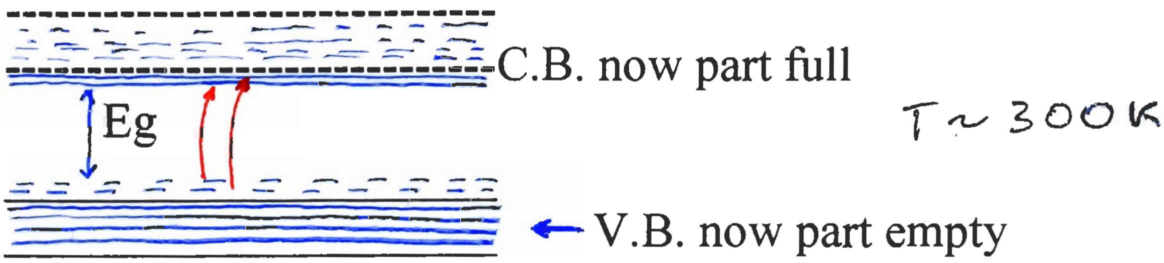
In a composite band, all levels up to the Fermi energy level are full at 0K, - levels above Fermi energy are empty at 0K (will cover Fermi levels later). Many electrons in band – all free to move in electric field to higher empty levels – easy, high conduction.

Intrinsic Semiconductors:

Have similar bands to insulator except energy gap is smaller.



Behaves as insulator at very low temperature – at room temperature (RT), kT still <Eg but there is now a finite possibility that some electrons in V.B. have sufficient energy (≥Eg) to move into the C.B. and for conduction to occur.

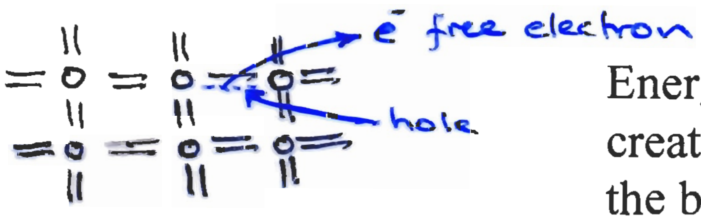


Subtle difference in conduction in a semiconductor and a metal -
Each electron elevated into C.B. leaves behind one vacant level in V.B. Conduction due to

(i) electrons in part-filled C.B., and
(ii) electrons in part filled V.B. moving into levels vacated by electrons 'elevated' into C.B. – hole conduction i.e. movement of bound electrons.

Since each elevated electron leaves behind one vacant level,
number of electrons m^{-3}, n = number of ~~electrons~~ holes m^{-3}, p

In intrinsic material, $\mathbf{n = p = n_i}$



Energy to break bond to create e-h pair has to be ≥Eg, the band-gap energy.