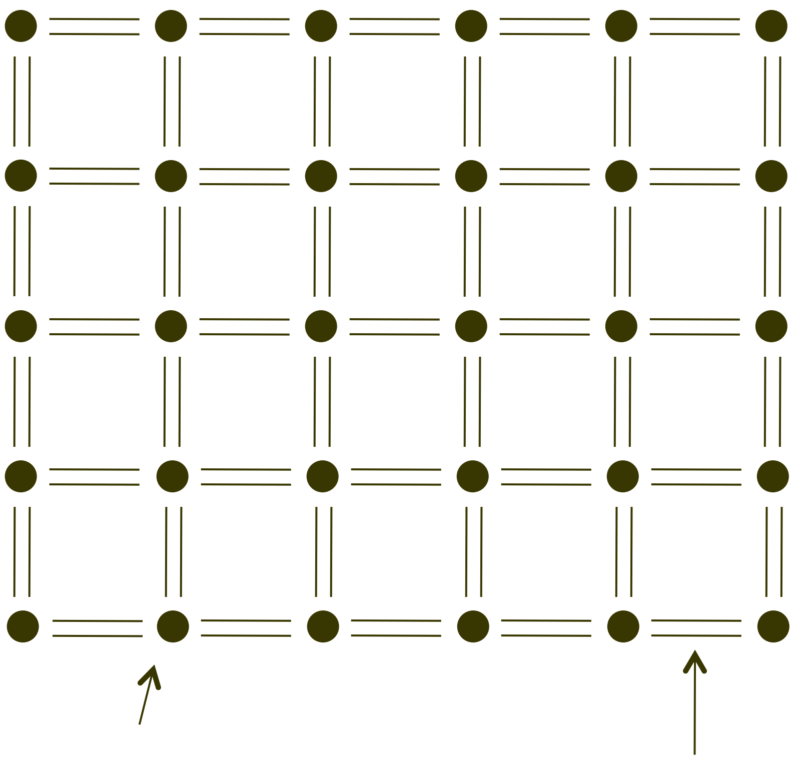
Lecture 5

- Holes
- Conduction in Intrinsic Semiconductors
- Comparison Intrinsic Semiconductors / Metals

Semiconductor Materials



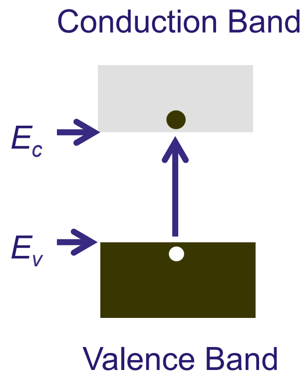
Si Atom cores

Bonds with 2 shared electrons

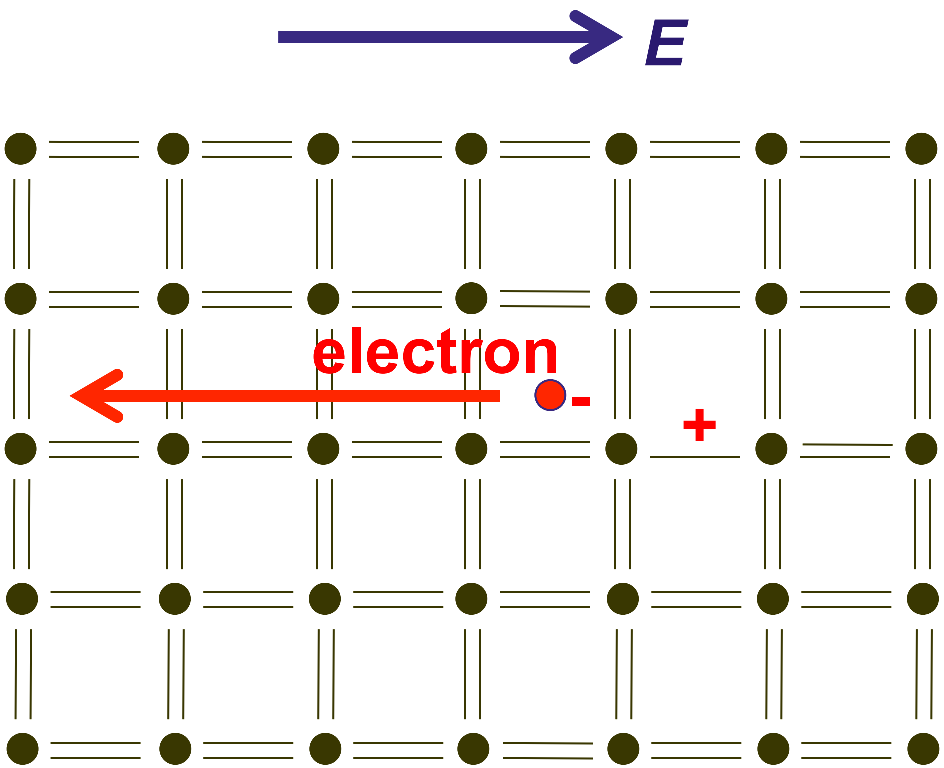
- Semiconductors generally covalently bonded

- This means for Si – 4 outer electrons “shared” with neighbours to fill the electronic shell (and minimise energy)

Note: 3D shape (2D representation for paper/screen!)



Conduction Processes



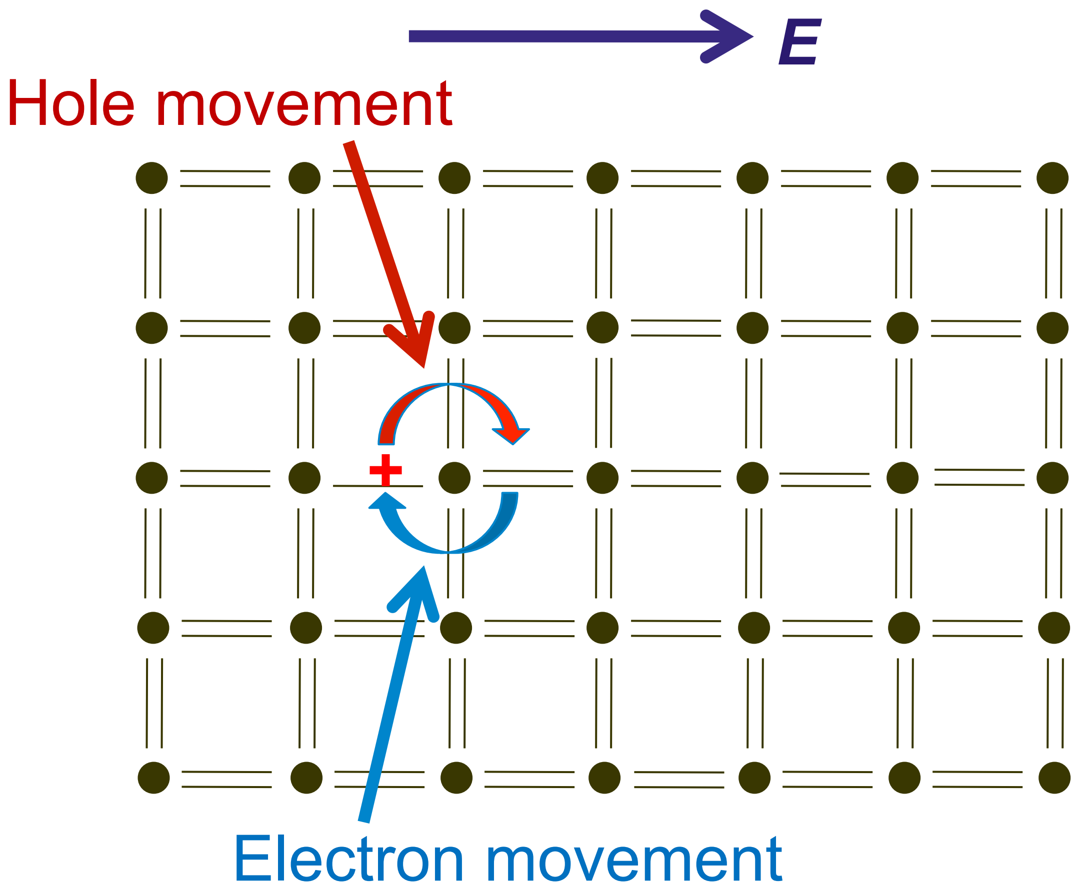
- A bond can be broken by a photon (light) or phonon (heat) producing a free conduction electron (see above)

- This electron has a negative charge and can move through the crystal under an ***E***-field

- Charge must be conserved so it leaves a +ve “hole” – which is an unfilled electron state or “missing” electron from the bond

What about the “Hole”?

- can it move in the electric field?



- An electron at an unbroken neighbouring bond can move to the empty state due to the ***E*** –field (shown in blue)

- The positive charge (hole) moves in the same direction as the ***E***-field and opposite to the electron (shown in red)

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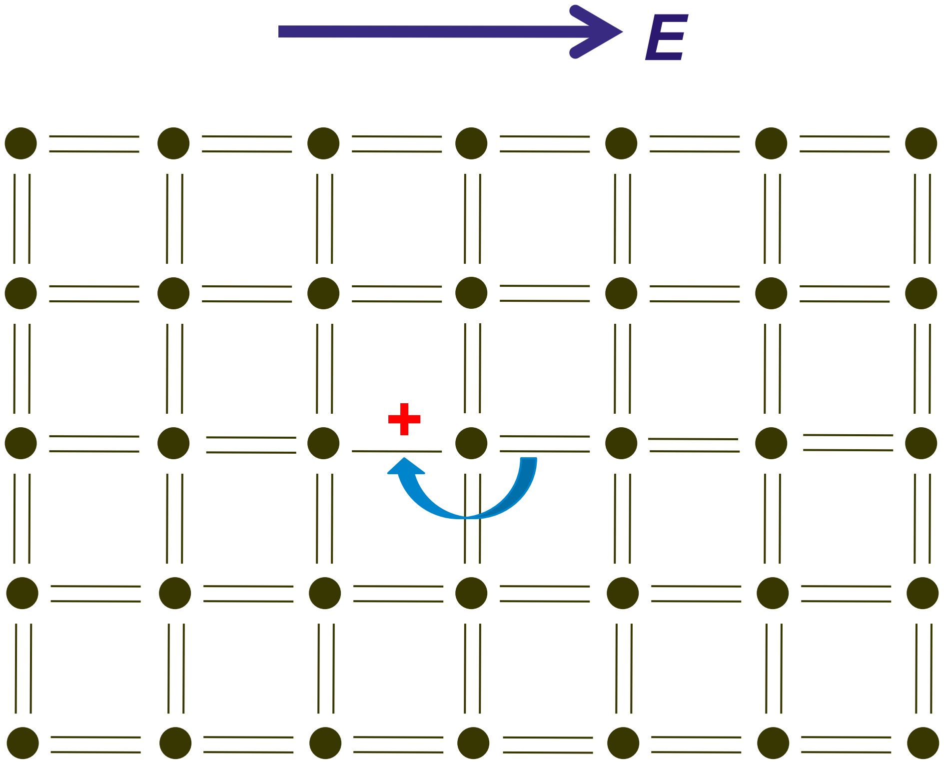

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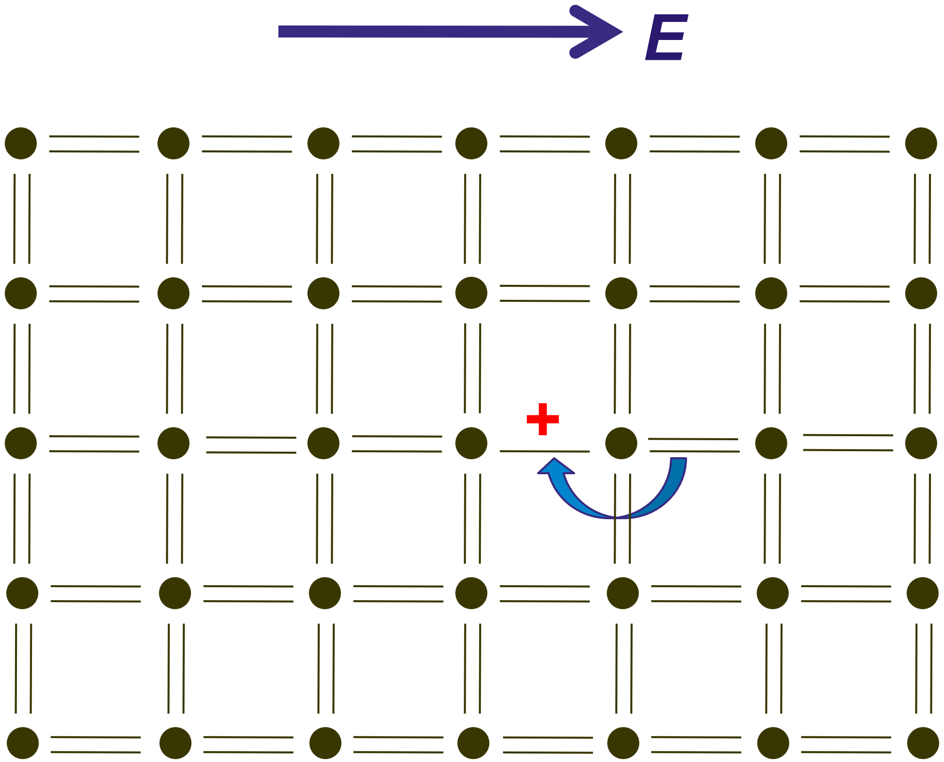

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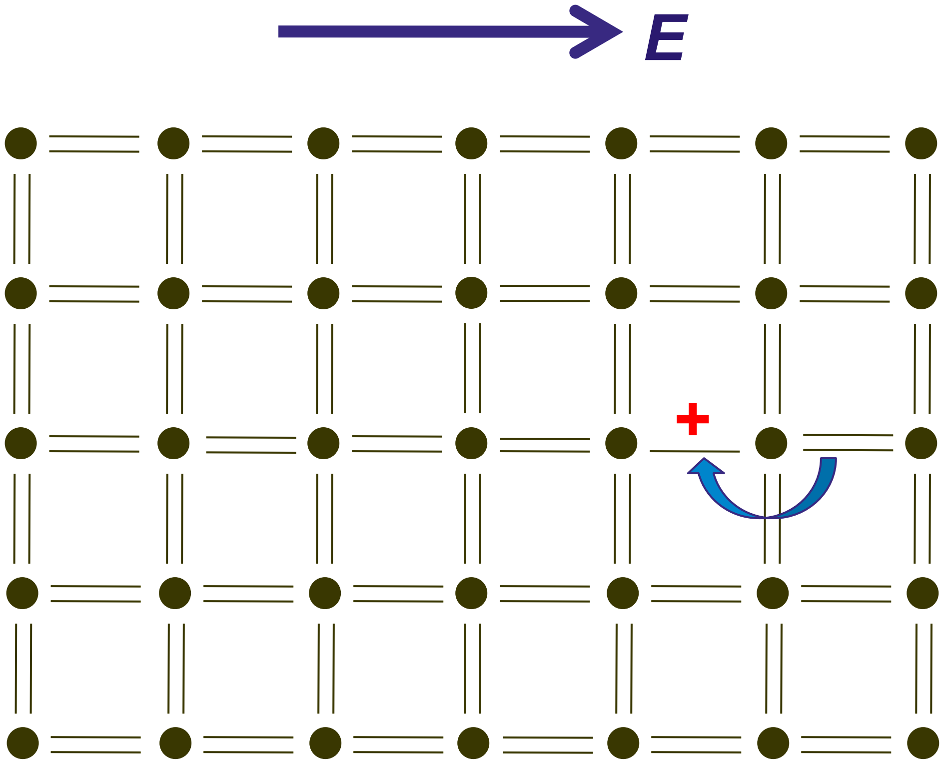

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Holes

- It is *convenient* to consider the motion described previously as a single particle called a hole, with charge +e moving through the semiconductor
- Motion is similar to that described for electrons – it has an effective mass, m^*_h, and a mobility, μ_h,
- When electrons and holes are present we need to specify m^*_e, m^*_h, μ_e , μ_h
- The motion of hole is opposite to the electron under an ***E***-field – hence electron and hole current flows **add** to give the total current [this is very important]

Some things to note about holes

- It is a 'hole' in the electronic state of the valence band – **it is not a physical hole or gap in the lattice**
- We have said it is *convenient* to consider the hole as the opposite of an electron, but it can be mathematically proven to be the case. It is a complicated calculation beyond the scope of this module.
- The effective mass and mobility of the holes, m^*_h, μ_h, is different to that of the single electron. This is because the hole represents the effect of **all the other electrons** in the valance band as well as the missing electron

Intrinsic (Pure) Semiconductors

- For a pure, intrinsic semiconductor, for every electron which breaks free from the bond (excited to the conduction band - free electron) there is a broken or incomplete bond left behind (free hole) giving

  $$n = p = n_i,$$

  where n = density of free electrons, p = density free holes - n_i is called the intrinsic carrier density
- Total density of free carriers is given by $n+p=2n_i$
- Conductivity for intrinsic semiconductor will be

$$\sigma = n_i e \mu_e + n_i e \mu_h$$

i.e. conductivity due to electrons and holes add

Intrinsic Carrier Density

- For a semiconductor with no thermal energy (absolute zero, 0 K) or other external energy influence – there are no conduction electrons
- If the temperature is increased, an electron can obtain enough energy to promote it to the conduction band (i.e. break free from the bond) and can move around the crystal
- The Number of such 'thermally excited' free electrons n_i is given by;

$$n_i = C\ T^{3/2} \exp\left(-\frac{W_g}{2\mathrm{k_B}T}\right)$$

where W_g is called the band-gap energy (equivalent to the energy required to break a bond), k_B is the Boltzmann constant , T is absolute temperature in Kelvin, C= Const

Conduction in Semiconductors

- From the formula, we can increase n_i by raising the temperature T. Also materials with a reduced band-gap energy $W_{g,}$ have a higher n_i
- For *metals*, which have effectively no bandgap they have ~1 conduction electron per atom (Note the density of atoms ~ 5×10^{28} Atoms/m^3)

  $n_i \sim 10^{28} \sim 10^{29}$ m^{-3} => very good conductors
- For a typical semiconductor like Silicon with a band-gap, at room temperature $n_i \sim 10^{16}$ m^{-3} => not very good conductors
- To get usable conductivity in a semiconductor we need a method to increase the the density of conducting electrons and/or holes in a semiconductor

Summary (1)

- In a semiconductor, atoms are covalently bonded in a regular array –each Si atom has a bond with each of 4 neighbours in a diamond-like lattice structure
- An electron with enough energy (e.g. from the ambient temperature) may be promoted to the conduction band and is no longer tied to this bond, leaving a +ve charge at the bond (an empty electronic state)
- The conduction electron and the hole are free to move around the crystal

Summary (2)

- The empty electronic state, or positively charged “hole” may also move around the crystal as a charge carrier similarly to the electron.
- The hole has effective mass, mobility, etc just like an electron
- Conduction in intrinsic (pure) semiconductors is made up of *both* electron and hole transport
- Intrinsic semiconductors typically have low carrier densities