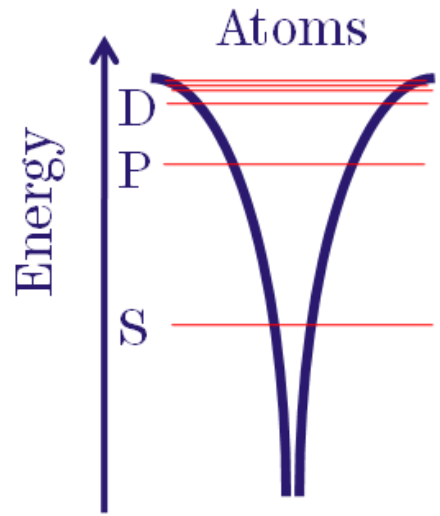
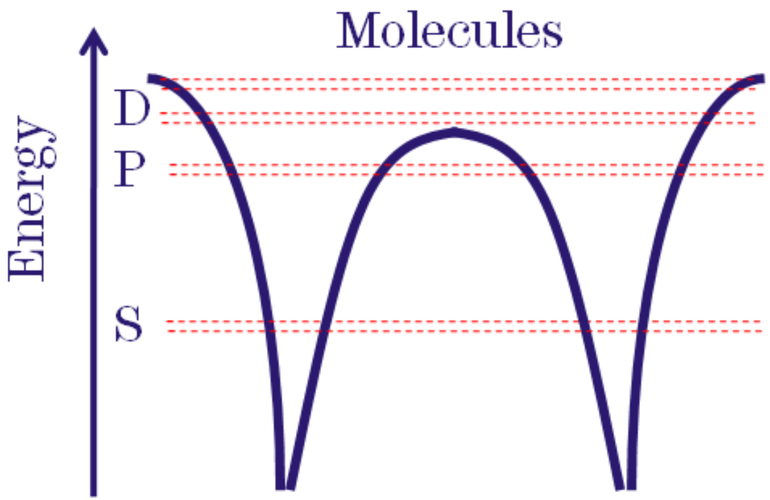
Lecture 9 - Review

- Band-gaps
  - Insulators, Semiconductors, Metals
- Insulators – Capacitors
- Metals – Conduction – Drift Velocity, Ohm's Law, Mobility
- Semiconductors – Electrons & Holes, Doping, Diffusion and Drift Currents, Carrier Generation & Recombination

Energy Band-Gap



In atoms, electrons are in a confining potential well with *defined energy levels* - the electrons can only exist with these energies.

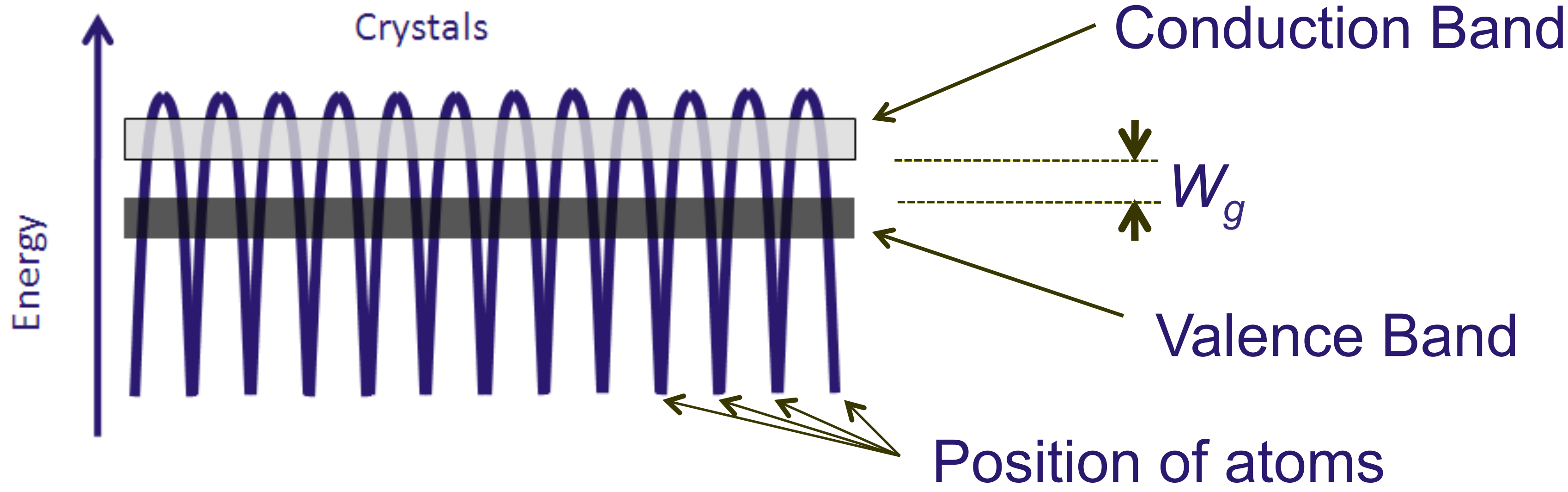


If two atoms are brought together, the discrete energy levels are split (due to quantum mechanics) and some *electrons can be shared*.

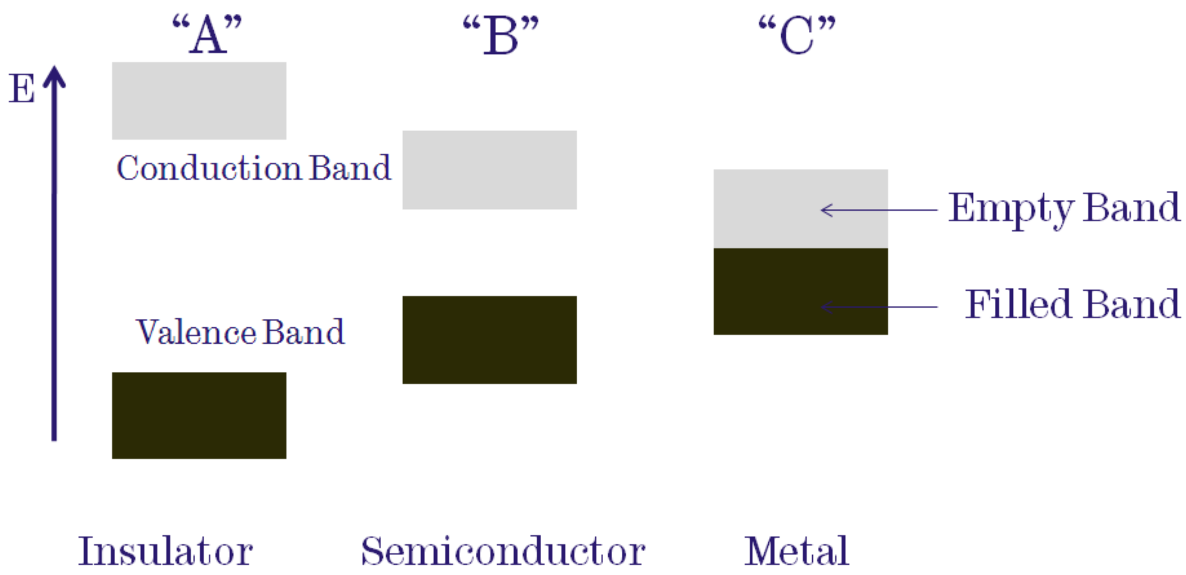
Energy Band-Gap (2)

If we extend this to packing many atoms closely together in a crystal, *bands of allowed energy states* can be formed.

A band of *filled energy states (valence band)* and (almost) *empty energy states (conduction band)* can be formed with an *energy gap (W_g)* between them. The size of W_g can be zero (metal), or very large compared to the thermal energy (insulator).



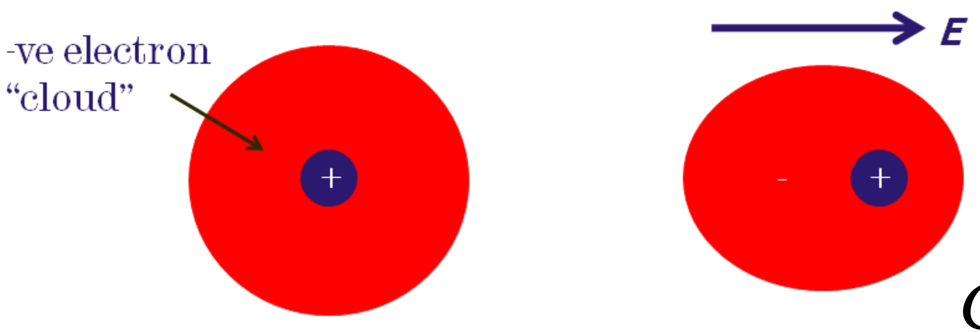
Classification of Solids



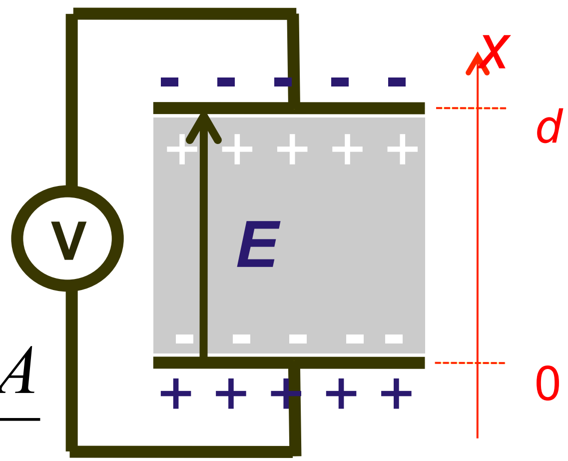
We classify solids as metals (zero band-gap), insulators (large band-gap compared to thermal energy) and semiconductors (moderate band-gap compared to thermal energy).

Insulators

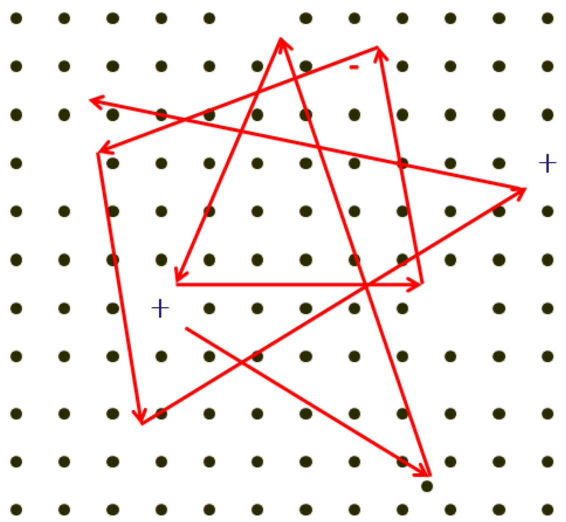
- For insulators, electrons are tightly bound into the atoms of the crystal and are not free to move around. However, a dipole can be formed on the application of an electric field – called polarization. Such materials are termed *dielectric* materials and the degree of polarization is described by the *relative permittivity*, ε_r.
- Such materials are used in capacitors.



$$C = \frac{\varepsilon_r \varepsilon_o A}{d}$$



Motion of Electrons In Solids



- A conduction electron is free to move in the crystal
- The thermal energy of the electron will cause it to move around the crystal until scattered by *imperfections* of the crystal lattice
- The presence of the crystal is taken care of by the use of *effective mass* of the electron

Drift Current

- Drift current results from the action of an electric potential gradient *dV/dx* (i.e. an electric field or ***E***-field)
- A statistical analysis of the electron population under steady state, where *the momentum gain of the electrons due to acceleration under an E-field is equated to the loss of momentum due to scattering* which allows the average drift velocity to be deduced in terms of the effective mass, *m*,* electron charge, e, electric field, ***E****,* and the average time between scattering events, τ.

$$\langle v_d \rangle = -\frac{e\tau E}{m^*}$$

Drift Velocity & Ohm’s law

- The previous expression for drift velocity may be subsequently simplified to relate the average drift velocity to the product of the *mobility*, μ, and the electric field.

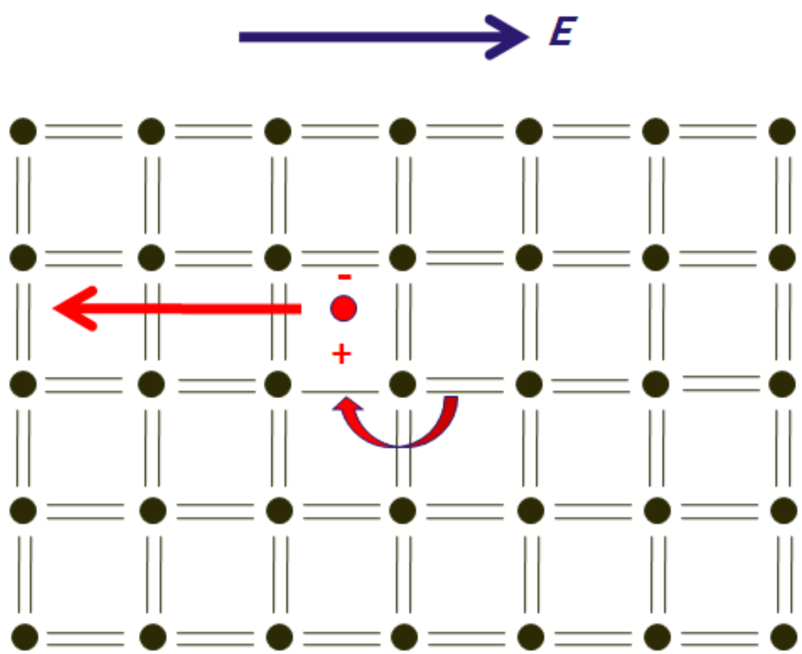
$$\langle v_d \rangle = -\mu E \qquad \text{where} \qquad \mu = \frac{e\tau}{m^*}$$

- Considering a rod of material, the current density may be derived for the electron density n, giving the *general form of Ohm’s law.*

$$J = ne\mu E \longrightarrow J = \sigma E$$

Conductivity $\sigma = ne\mu$ Resistivity $\rho = \dfrac{1}{\sigma}$

Conduction in Semiconductors

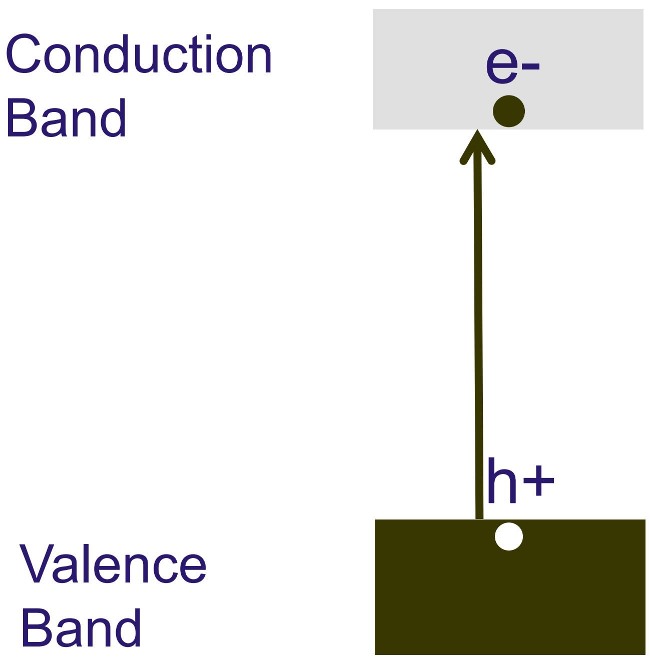


- In semiconductors, electrons can be promoted to the conduction band, and the absence of electrons in the valence band (a *hole* or broken bond) may also contribute to conduction

- Hence there are two possible charge carriers of opposite sign

- The equations for conduction in metals are modified to cope with these two charge carriers

Intrinsic Semiconductors



- For a pure, *intrinsic* semiconductor, the carrier density is given solely by the *thermal generation* of carriers

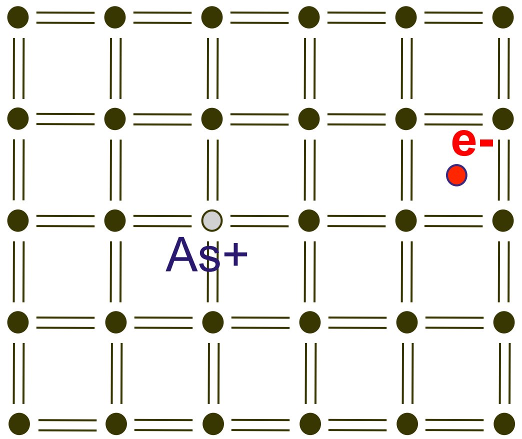
- The number of free holes and free electrons is equal and is given by;

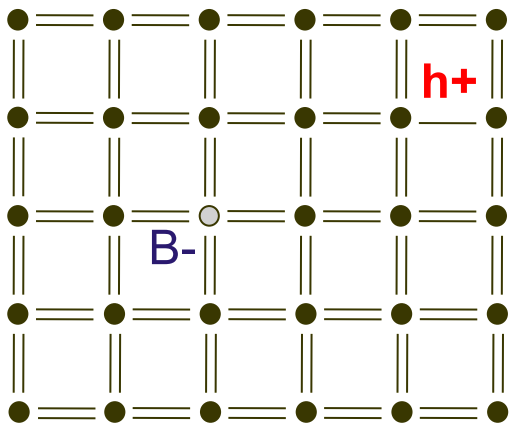
$$n_i = C \ T^{3/2} \exp\left(-\frac{W_g}{2k_B T}\right)$$

- The total number of free carriers is $2n_i$

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

Extrinsic (Doped) Semiconductors





- *Group 5 donor atoms* (5 outer electrons) *donate* 1 electron per atom to the lattice

- *Group 3 acceptor atoms* (3 outer electrons) *accept* 1 electron per atom from the lattice to produce 1 hole

- Dopant atoms are ionized (positive for donors, negative for electrons) at room temperature

- The doping process results in one carrier type of much higher concentration (*majority carrier*) compared to the other (*minority carrier*).

Equilibrium

- In equilibrium $G = R$, otherwise the electron and hole population will continue to rise indefinitely ($G>R$) or decrease to zero ($G<R$)
- For an Intrinsic Semiconductor this means:

$$G = R = Bn_i p_i = B\, n_i^{\,2} \ \text{since}\ n_i = p_i$$

- For Extrinsic Semiconductor, n-doped, $n>>n_i$ (G is constant)

$$G = R = Bnp_n = Bn_i^2 \qquad \Rightarrow n_i^{\,2} = np_n$$

p_n is hole concentration in the n-doped material

For p-type material $\quad n_i^{\,2} = pn_p$

Extrinsic Semiconductors

- Extrinsic Semiconductors - need to be careful with subscripts
- Have minority and majority carriers – could be n or p (can be written n_n or p_p) as majority – put subscript if minority

$$n_i^2 = p_p n_p \qquad n_i^2 = n_n p_n$$

$$p_p >> n_i >> n_p \qquad n_n >> n_i >> p_n$$

majority

minority

Disturbing The Equilibrium

- Consider exciting carriers *uniformly* in p-type material instantaneously with a light pulse
- The thermal generation rate, *G*, remains constant
- Our recombination rate increases and is now

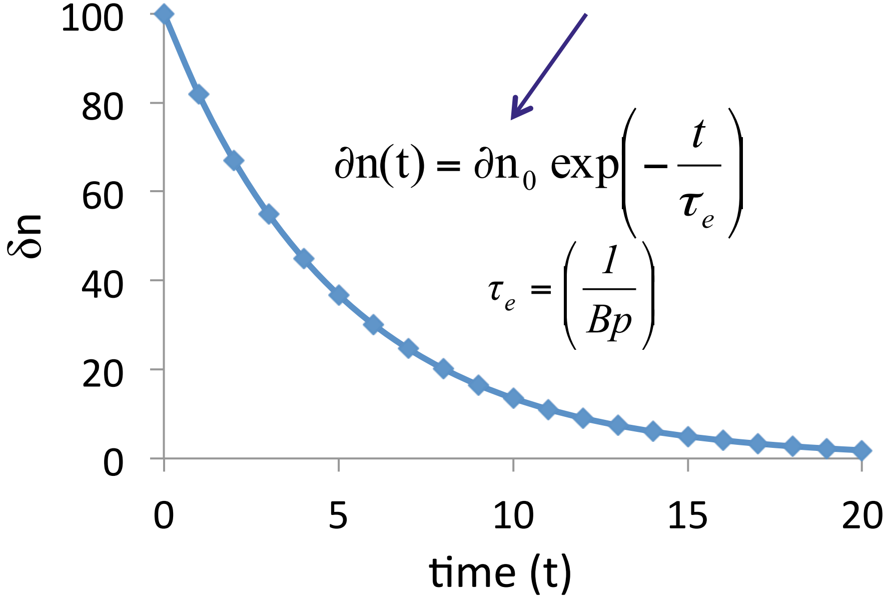
$$R = Bp(n_p + \partial n) > G = Bpn_p$$

$$\therefore \frac{dn}{dt} = G - R = G - \left[Bpn_p + Bp\partial n\right]$$

So $$\frac{dn}{dt} = -Bp\partial n$$ (first order differential equation)

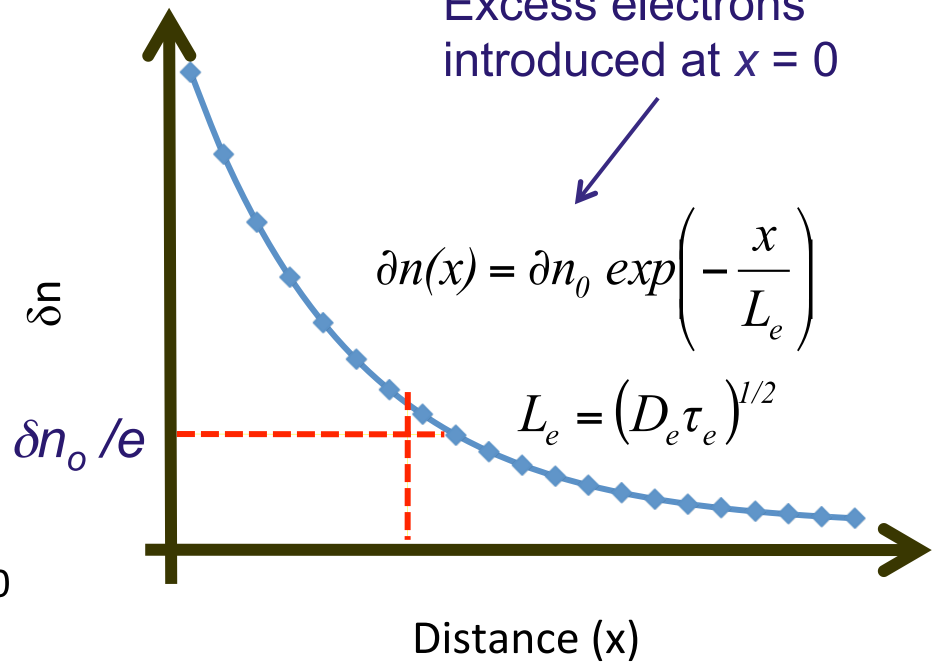
Time and distance dependence

Excess electrons introduced at *t* = 0



Solution to previous slide

Excess electrons introduced at *x* = 0



Distance variation

Diffusion & Drift Current

$$J_e = eD_e \frac{dn}{dx} \qquad J_h = -eD_h \frac{dp}{dx} \qquad D_{e,h} = \frac{k_B T \mu_{e,h}}{q}$$

$$J_e^{total}(x) = J_e^{drift} + J_e^{diffusion} = q\mu_e E_x n + qD_e \frac{dn}{dx}$$

$$J_h^{total}(x) = J_h^{drift} + J_h^{diffusion} = q\mu_h E_x p - qD_h \frac{dp}{dx}$$