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EEE105
“Electronic Devices”

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Lecture 11 - Midpoint 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

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Background Stuff

Potential and E-field

$$V = -\int E.\,dx \qquad E = -\frac{dV}{dx}$$

Poisson's Equation

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon} \qquad \frac{dE}{dx} = \frac{\rho}{\varepsilon}$$

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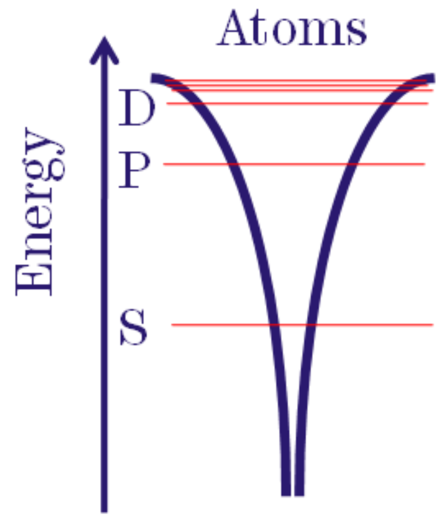
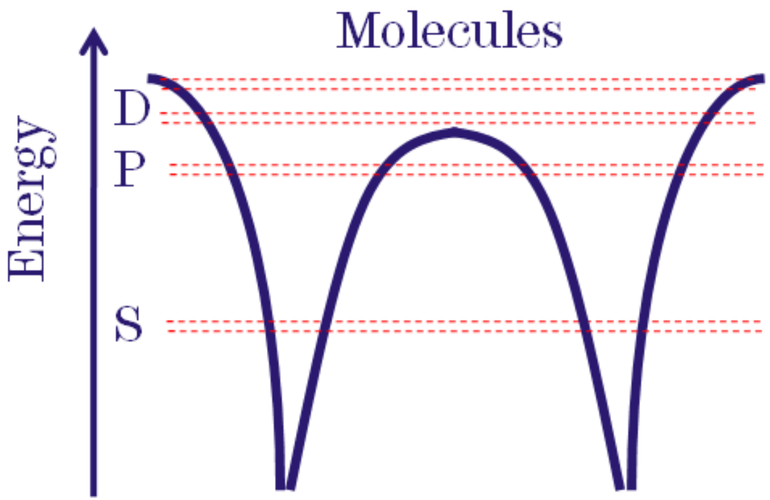
Band-Gap

In atoms, electrons are in well defined energy levels, given by quantum mechanical treatment of the atomic system. The electrons can only exist with these energies.





If two atoms are brought together, the discrete energy levels are split (again due to quantum mechanics)

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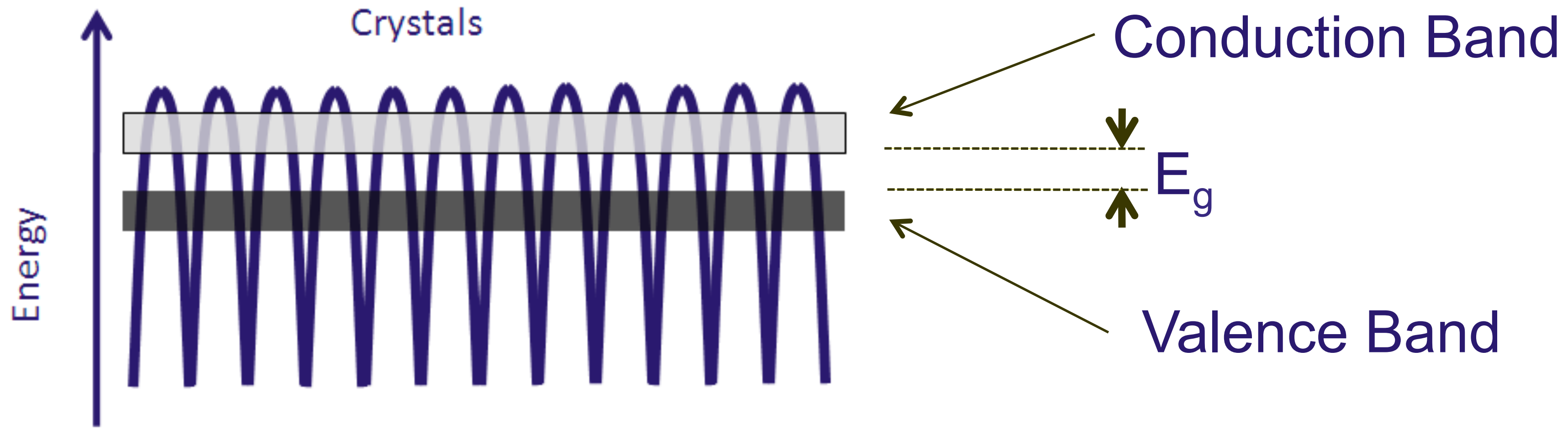
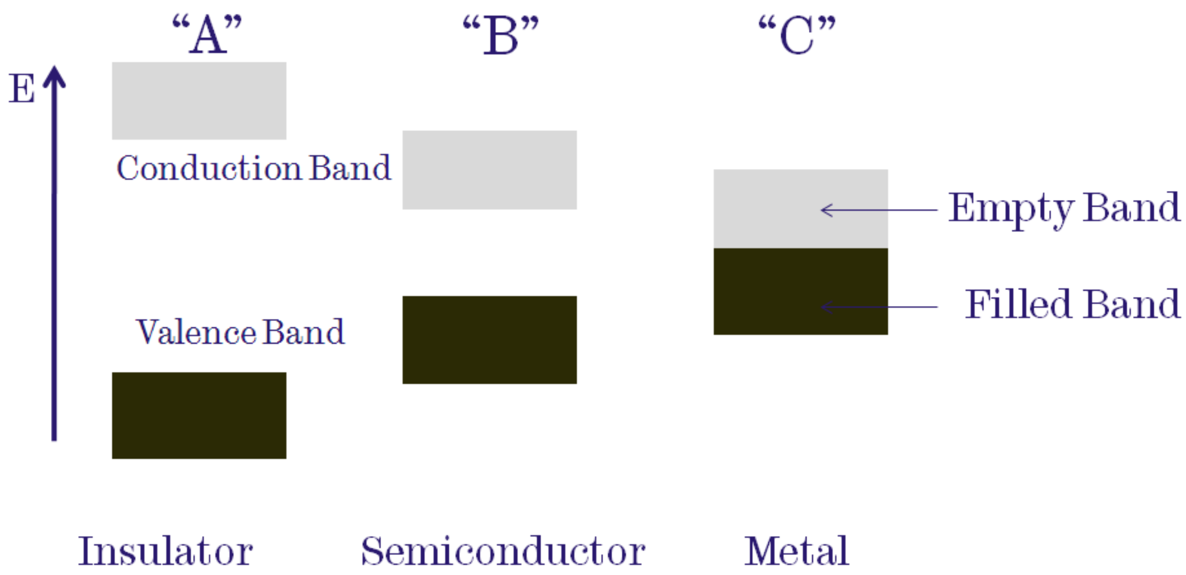
Band-Gap (2)

If we extend this to packing many atoms closely together, bands of allowed energy states can be formed. We are not concerned with full, core shells, only the outer shell which is not filled.
A band of filled states (valence band) and empty states (conduction band) can be formed with an energy gap (E_g) between them. The size of W_g can be zero, or very large compared to the thermal energy.



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).

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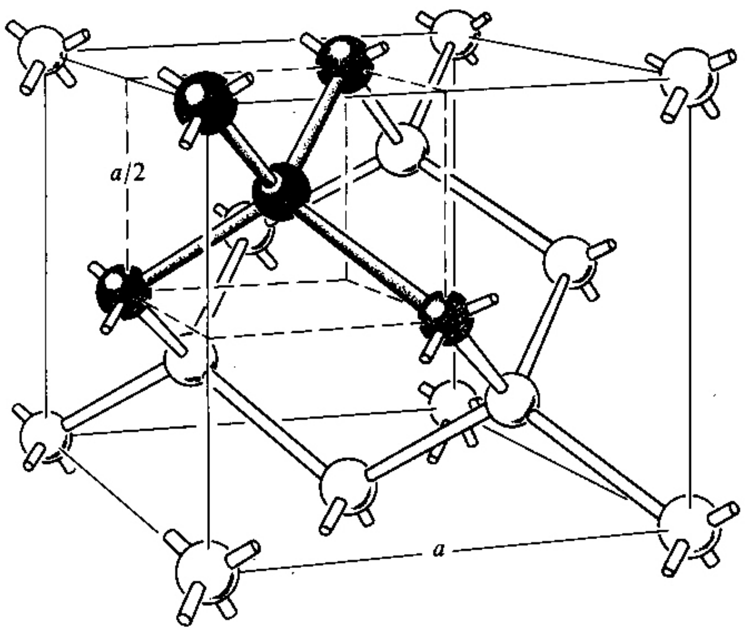
Crystals & Phonons



Crystals are made up of atoms bonded together.

The configurations are complex. The periodic structure is made up of a “unit cell” repeated to reproduce the whole crystal. The unit cell has a lattice constant and consists of a number of atoms.

Thermal energy acts to vibrate the atoms. This vibration is quantized and we treat these as particles with energy and momentum called phonons.

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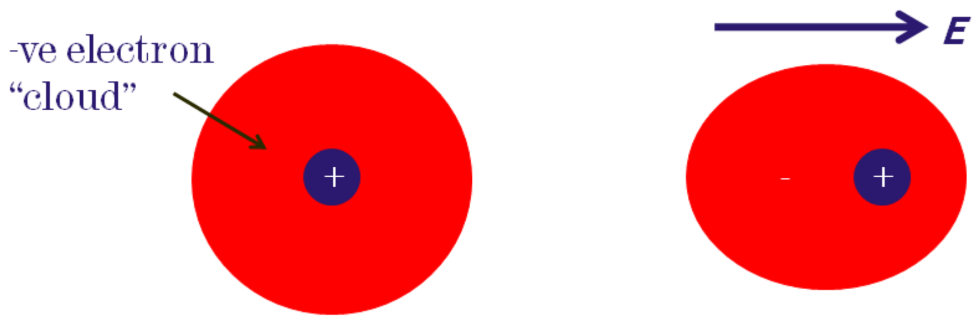
Insulators

- For insulators charge is not free to move around the crystal. However, a dipole can be formed on the application of an electric field. Such materials are termed *dielectric* materials and are described by a *relative permittivity*.
- Such materials are used in capacitors.



Crystals

$$\text{Density} = \frac{\left(\frac{\text{Atoms}}{\text{Vol}}\right)\left(\frac{\text{Kg}}{\text{Mole}}\right)}{\left(\frac{\text{Atoms}}{\text{Mole}}\right)}$$

Remember 8 atoms per unit cell for most semiconductors

Dielectrics

Capacitance

$$C = \frac{\varepsilon A}{d}$$

$$\text{where } \varepsilon = \varepsilon_0 \varepsilon_r$$

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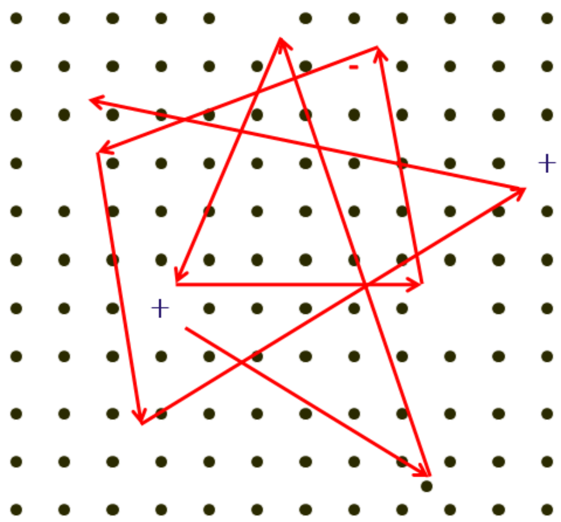
Motion of Electrons In Solids



- If an electron is free to move in the crystal, it occupies an electronic state of the crystal.
- If the electron has thermal energy, it will move around the crystal until scattered by *imperfections* of the crystal lattice
- The presence of the crystal potential alters the apparent or *effective mass* of the electron.

Drift Current

- **An electric potential gradient dV/dx (i.e. an 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 allows the average drift velocity to be deduced in terms of the effective mass, electron charge, electric field and the average time between scattering events.

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

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Drift Velocity & Ohm's law

- This may be subsequently simplified to relate the average drift velocity to the product of the mobility and the electric field.

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

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

$$J = n\,q\,\mu\,E \longrightarrow J = \sigma E$$

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Conductors

- n.b. Discussing electrons (majority carriers and no carrier concentration gradients...)

Conduction - Drift Velocity → mobility

$$\langle v_d \rangle = -\frac{qE\tau}{m^*} \qquad \langle v_d \rangle = -\mu E \qquad \mu = \frac{q\tau}{m^*}$$

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Conductors (2)

Drift Current - simplification

$$J_{Drift} = n\,q\,\mu\,E \qquad J = \sigma E \qquad \sigma = nq\mu$$

Resistivity and Conductivity $\rho = \dfrac{1}{\sigma}$

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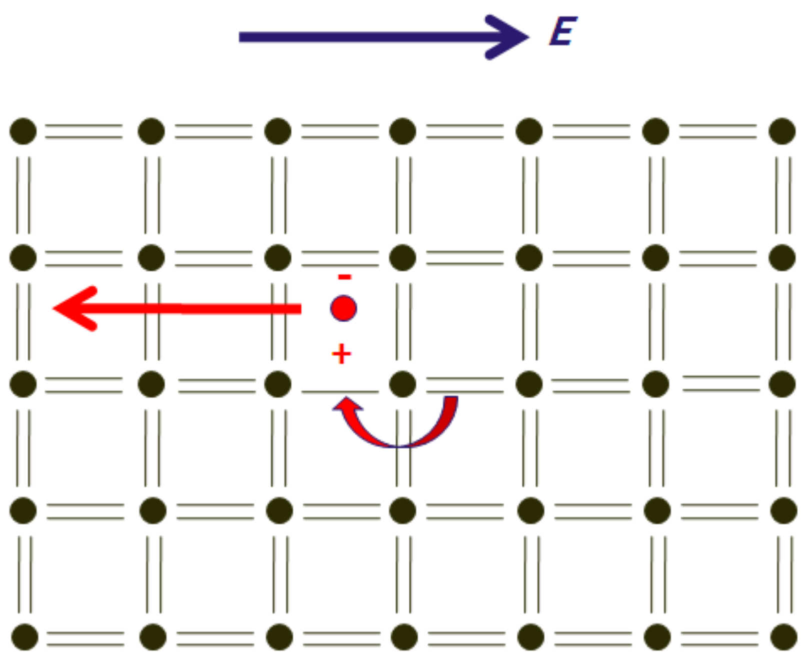
Conduction in Semiconductors



In semiconductors, electrons promoted to the conduction band, and the absence of electrons in the valence band (a *hole*) may contribute to conduction.

There are two possible charge carriers of opposite sign.

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

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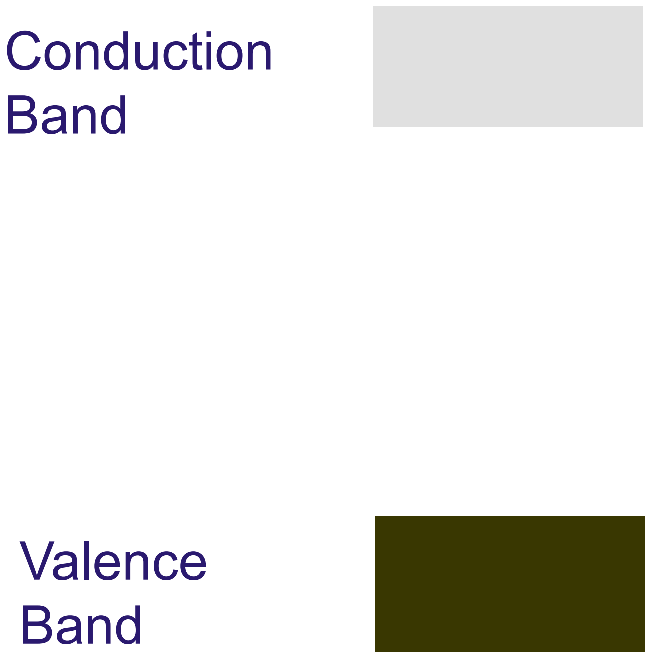
Intrinsic Semiconductors



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

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

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

The total number of free carriers is $2n_i$

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Semiconductors

Recombination $$R = B\,n\,p$$

Intrinsic Semiconductors

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

$$n_i = p_i$$

Where intrinsic carrier concentration is

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

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Semiconductors (2)

- Extrinsic Semiconductors - need to be careful with subscripts
- Have minority and majority carriers – could be n or p as majority – put subscript if minority

$$n_i^{\,2} = p_p n_p \qquad\qquad n_i^{\,2} = n_n p_n$$

majority

minority

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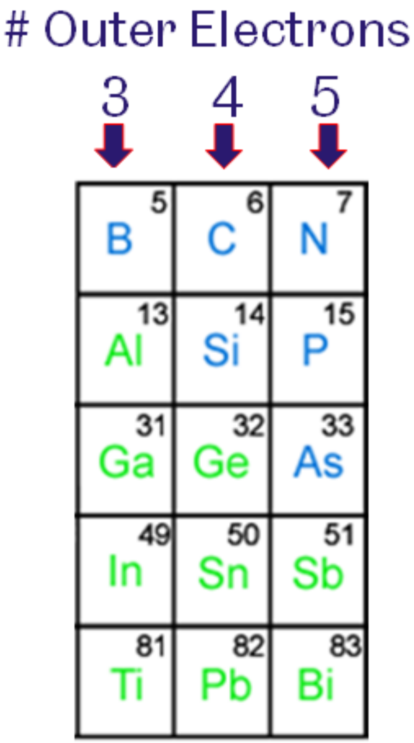
Doped Semiconductors



By introducing a small density of atoms (*doping*) with different valency, the number of free electrons (using *donors*) or free holes (using *acceptors*) in a semiconductor can be increased. The doped atom introduces a localized sate within the band-gap. These levels localize carriers at low temperature. At room temperature most states are emptied, providing one free carrier per dopant atom. The dopant atoms are charge (*ionized*).

The doping makes one carrier type of higher concentration (*majority carrier*) compared to the other (*minority carrier*).

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Minority Carrier Lifetime & Diffusion Length

$$\partial n(t) = \partial n_0 \exp\left(-\frac{t}{\tau_e}\right)$$

$$\tau_e = \left(\frac{1}{Bp}\right)$$

$$\partial n(x) = \partial n_0 \exp\left(-\frac{x}{L_e}\right)$$

$$L_e = \left(D_e \tau_e\right)^{1/2}$$

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Diffusion Current

- **An electron density gradient dn/dx**

A change in concentration or density brings about diffusion, and is governed by Fick's Law.

$$\varphi(x) = -D\frac{dn}{dx}$$

Concentration (dn)

Distance (dx)

Flux ($\varphi(x)$)

Diffusion Coefficient (D)

$$D_{e,h} = \frac{k_B T \mu_{e,h}}{q}$$

Drift & Diffusion

- For drift currents – minority carriers may often be ignored
- Combination of both drift and diffusion currents shows (e.g. For holes)

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

- As diffusion current is proportional to the *gradient* of carrier concentration, minority carrier diffusion currents can therefore be large
- As net current must be zero with no applied E-field – non uniform carrier concentrations bring about internal fields

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Diffusion & Drift Current

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

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

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

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Generation & Recombination

- Under equilibrium, we have a balance of the thermal generation of carriers and their recombination
- Comparing this for intrinsic and doped semiconductor shows the minority carrier density is lower than the intrinsic carrier density – it is suppressed by recombination with the majority carriers
- Perturbing the equilibrium temporally and spatially brings about the concept of a minority carrier lifetime and minority carrier diffusion length, respectively.

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