7: Optical properties
7.1 Colour

- Caused by interactions of light waves with atoms - especially their electrons.
- It is the relative contributions of light of various wavelengths that determines the colour of a material. (Visible range: λ = 400 nm to λ = 700 nm)

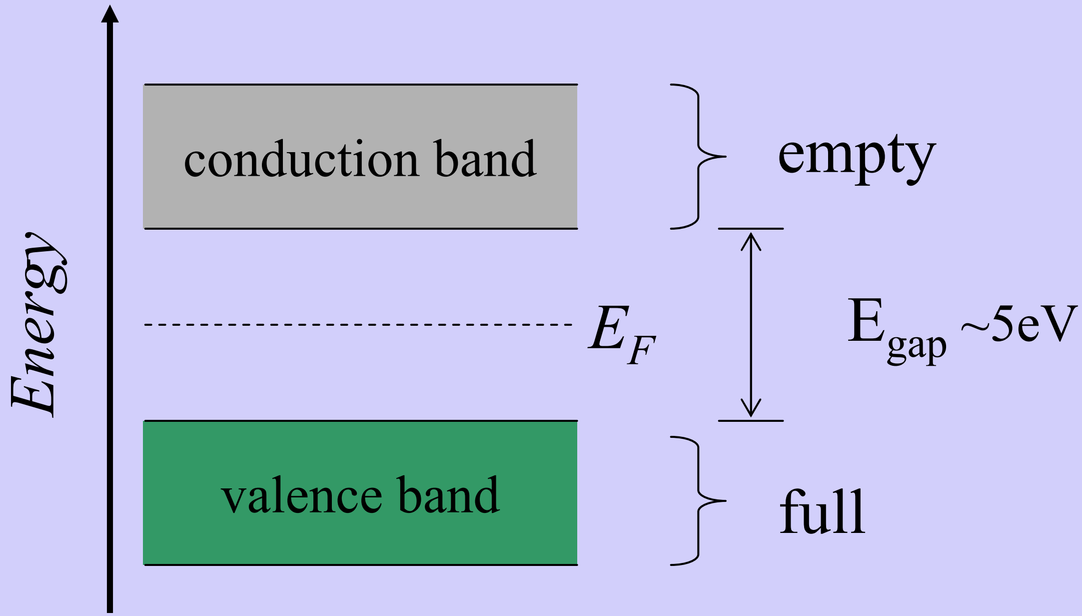
color	wavelength interval	E
red	~ 625–740 nm	~ 1.77 eV
orange	~ 590–625 nm	~ 2.00 eV
yellow	~ 565–590 nm	~ 2.14 eV
green	~ 500–565 nm	~ 2.34 eV
cyan	~ 485–500 nm	~ 2.52 eV
blue	~ 450–485 nm	~ 2.64 eV
violet	~ 380–450 nm	~ 2.95 eV

- Many different phenomena occur which affect material colour:

  emission, absorption, reflection, transmission, light scattering, dispersion, interference...
- We will limit ourselves to: absorption (and reflection) in metals and semi-conductors

Colour of insulators

- For insulators colour is mostly defined by absorption and re-emission of light, through excitation and de-excitation of electrons to higher levels.
- From band theory we know most levels are occupied, hence only limited wavelengths available.



Colour of metals

- Because a metal have a near continuum of excited energy levels (energies above the Fermi energy), a metal can absorb light of any wavelength, including visible. (If this were the only effect operable here, all metals would appear black).

- When an electron absorbs a photon, it is promoted to an excited state that has many other levels available for de-excitation (due to the virtual continuum of energy levels).

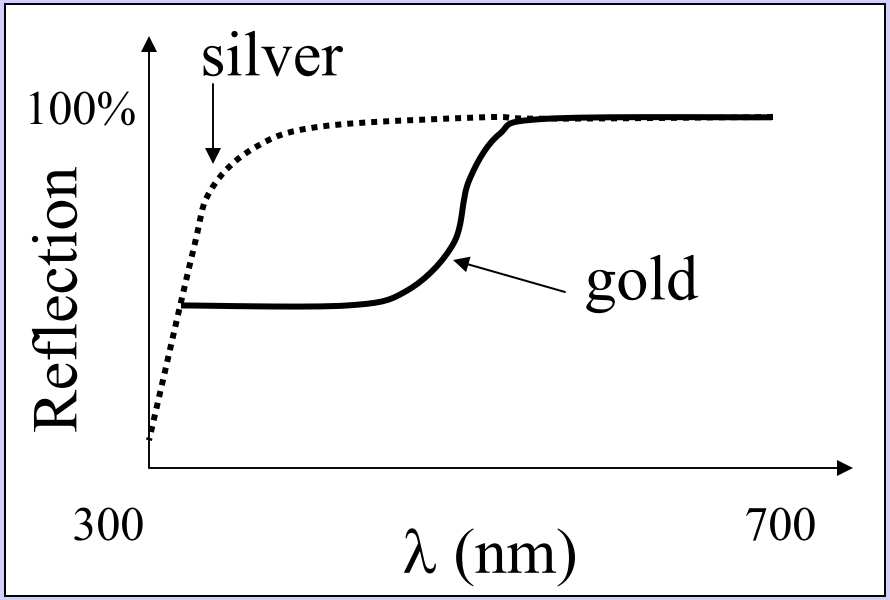
In a slightly different language (but saying the same thing)

- Light is absorbed easily and since metals are good conductors, the absorbed light induces alternating electrical currents on the metal surface. These currents rapidly emit light out of the metal.

- This rapid and effective re-radiation means that the surface of a metal is shiny. The degree of re-radiation (lustre) depends on such matters as surface smoothness.

Difference in colour between metals

- The colours of silver and gold are quite distinct from one another.
- This is due to differences in the number of states above the Fermi edge.
- For silver there are plenty of states available to reflect photons of all wavelengths of visible light with high efficiency.
- Gold does not reflect much high-energy visible light (blue and violet) because of an absence of energy levels in this region. Since gold predominantly reflects at the low-energy (long-wavelength) end of the visible range, it appears yellow.



Colours of pure semiconductors

- For pure semiconductors the colour depends on the energy gap E_g.
  - If $E_{gap} <$ the lowest energy of visible light (λ = 700nm, red, E = 1.7eV) then any wavelength will be absorbed and the colour will be black or metallic (depending on the efficiency of re-radiation):
    - Si (E_{gap}= 1.1eV) ⇒ grey metallic
    - GaAs (E_{gap}= 1.4eV) ⇒ black

  - If $E_{gap} >$ the highest energy of visible light (λ = 400nm, violet, E = 3eV), then no visible light is absorbed and the material is colorless/transparent (e.g. diamond, E_{gap}= 5.4eV).

- If E_{gap} falls in the range of visible light, the colour is the complementary colour to the absorbed wavelengths.
  - HgS (E_{gap}= 2.1eV): $\lambda_{TRANSMITTED}$> 590nm ⇒ red
    HgS is a red pigment "Vermilion".

Colour of doped semiconductors

- Doping (impurity) levels lie within the band-gap of the semiconductor.

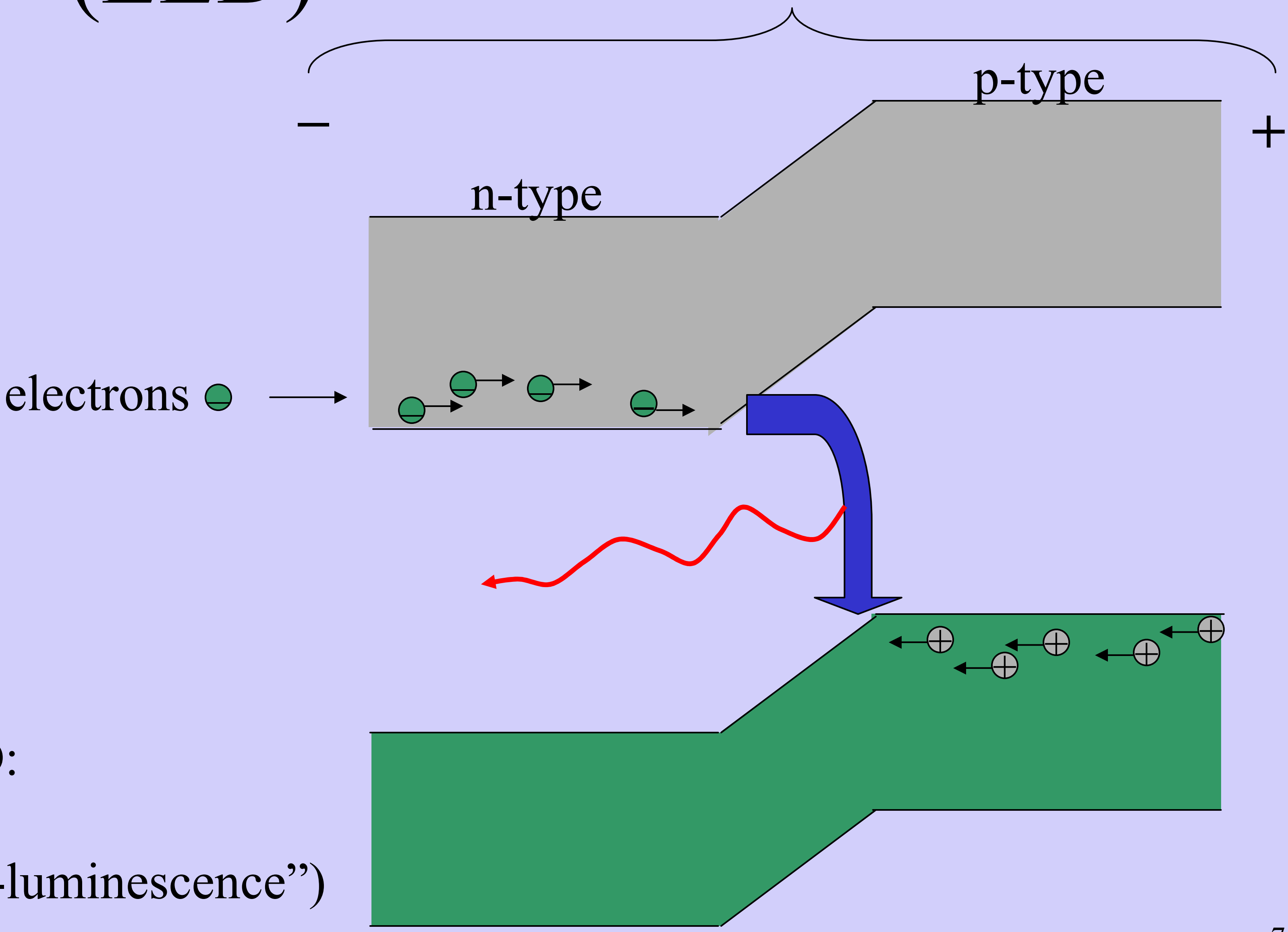
- Because the transition to the impurity level(s) takes less energy than the transition across the entire band-gap, this transition can affect the colour of a wide band-gap semiconductor.

- Example: nitrogen in a diamond. Excitation from these impurity levels absorbs violet light, depleting white light of violet and making nitrogen-doped diamonds appear yellow at nitrogen levels as low as 1 atom in 10^5

Doping with the acceptor atom boron, provides levels nearer the valence band which can be reached by electrons from the valence band under absorption of low energy photons (red light), making the diamond appear blue.

Light emitting diode (LED)

Forward biased pn diode:



Red LED:
GaAs-P
(“electro-luminescence”)