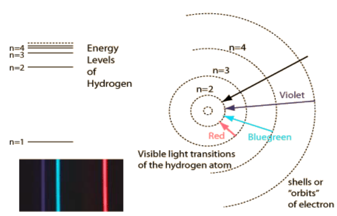
Physics of solid state devices

Short introduction to the principles of operation

Solid state physics terminology

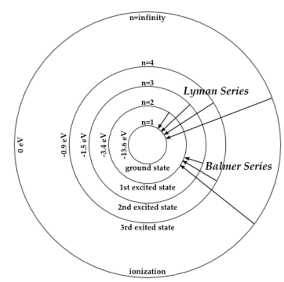
- Energy bands instead of atomic energy levels (bands are broadened levels)
- Conduction and valence bands, forbidden band (band gap)-> insulators, semiconductors, and metals
- Fermi level determining the type of charge carriers in semiconductors: electrons (n-type) or holes (p-type)
- Contacts of two semiconductors (p-n junctions) or metal and a semiconductor; built in electric fields
- Defects, trapping, recombination, charge carrier collection, devices

Quantized energy states



- The electrons in free atoms can be found in only certain discrete energy states
- These states are associated with the orbits or shells of electrons in an atom, e.g., a hydrogen atom

Quantized energy states



http://astro.unl.edu/naap/hydrogen/transitions.html

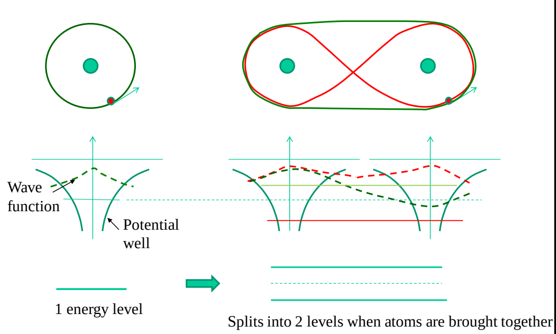
Hydrogen:
Rydberg formula for transition energies

$$E_{photon} = E_0\left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right)$$

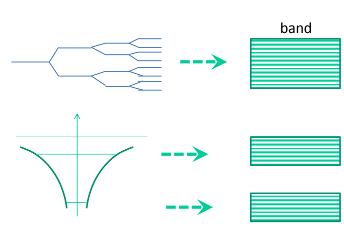
$$E_0 = 13.6\ \text{eV}$$

This formula works for all hydrogen-like atoms with small corrections: n-> n-δ, where δ is a quantum defect, measured value

Energy level splitting in molecules



Atomic levels become bands

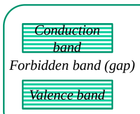


In solids, atomic energy levels broaden to form energy bands

Different atomic levels form different bands

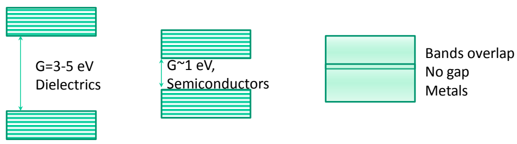
- Brining multiple atoms together results in further level splitting
- When levels start overlap they form energy bands

Terminology and classification of solids

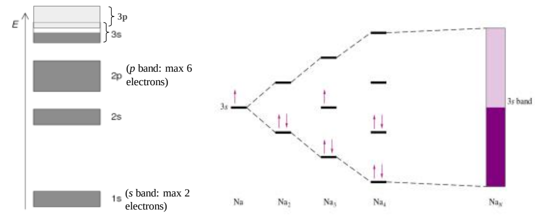


Conduction band is the lowest fully empty, no electrons at T=0

Valence band is the highest band filled with electrons, no empty states at T=0



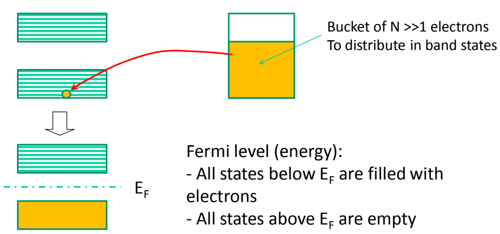
Example: Sodium band structure



- Sodium has 11 electrons, its **outer** shell is half full (1 electron in s band)
- It is easy for electrons in the valence band to be excited into empty higher energy states of conduction band
- Sodium conducts electricity well since there is no band gap

Pauli principle and Fermi energy

Pauli exclusion principle: not more than 2 electrons (with opposite spins) per state

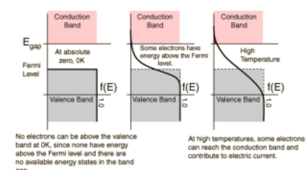


Fermi level (energy):
- All states below E_F are filled with electrons
- All states above E_F are empty (at zero T)

Fermi-Dirac statistics

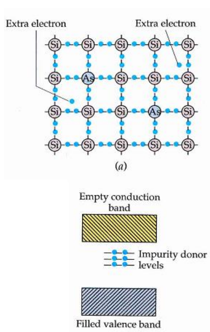
The probability that a given available electron energy state will be occupied at a given temperature *T*

$$f(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$



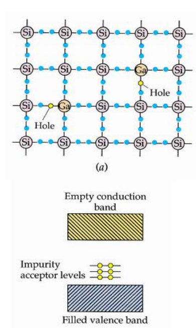
- Electrons have half-integer spin are fermions (as opposed to bosons, having integer spin)
- Energy distributions are described by Fermi-Dirac statistics, Fermi function *f*(E)

Doping of semiconductors: n-type



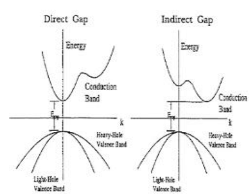
- A very small number of atoms of a group V element, e.g., arsenic As, are added to the silicon Si (group IV element) as substitutional atoms
- Additional valence electrons are introduced into the material because each As atom has 1 extra valence electron; donor levels are added just below the conduction band
- These additional electrons are bound only weakly to their parent impurity atoms
  - even at very low temperature they can be promoted into the conduction band of the semiconductor

Doping of semiconductors: p-type

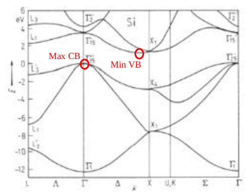


- A very small number of atoms of a group III element, e.g., gallium Ga, are added to the silicon Si (group IV element) as substitutional atoms
- There will be a deficit in the number of valence electrons in the material
- This introduces electron-accepting levels just above the top of the valence band
  - even at very low temperature they can be promoted into the conduction band of the semiconductor

Bands in semiconductors



In indirect band gap semiconductors conservation of momentum requires emission (absorption) of a phonon for each transition (radiative recombination or absorption) involving photons

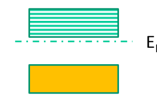


Band structure of silicon (indirect gap)

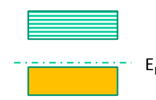
M. Grundmann, *The Physics of Semiconductors*, 2nd ed., Graduate Texts in Physics, Springer-Verlag Berlin Heidelberg 2010

Fermi level in semiconductors

Intrinsic



n type



p type

- Position of the Fermi level is related to the type of semiconductor: close to CB for *n* type, close to VB for *p* type
- When two materials are brought in contact, the Fermi levels are connected (under thermal equilibrium)

Brining two materials in contact: metals

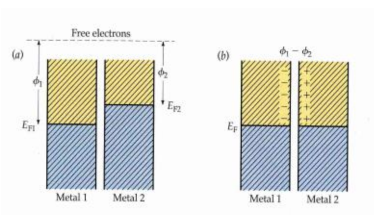


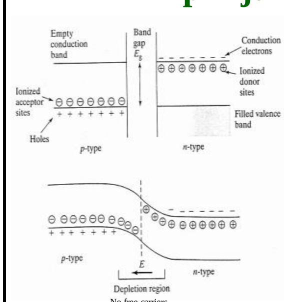
Table 39-2 Work Functions for Some Metals

Metal	ϕ, eV
Ag silver	4.7
Au gold	4.8
Ca calcium	3.2
Cu copper	4.1
K potassium	2.1
Mn manganese	3.8
Na sodium	2.3
Ni nickel	5.2

$$V_{contact} = \frac{\Phi_1 - \Phi_2}{e}$$

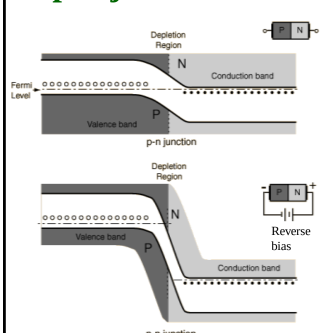
- Electrons move to the material where their energy is lower, leaving unbalanced positive charge behind
- Similar to flat-plate capacitor: built-in electric field

Brining two materials in contact: p-n junctions



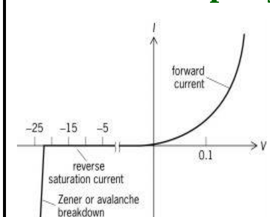
- In p-type semiconductor holes are created by negatively charged acceptor impurities
- In n-type, conduction electrons are donated by positively charged donors
- At a pn junction holes diffuse from the *p* side, and electrons from the *n* side, creating charges of opposite sign on both sides and thus creating a built-in electric field (bands are tilted)

p-n junction under reverse bias



- To reverse-bias the p-n junction, the p side is made more negative
- This increases the built-in electric field, improving separation and collection of charges produced by radiation
- The depletion width (sensitive region) is also increased
- Most often used in radiation detection as it improves signal to noise ratio

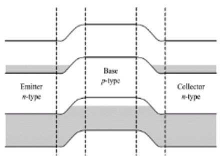
Current-voltage characteristics of p-n junction



$$I = I_s\left(e^{\frac{qV}{\eta kT}} - 1\right)$$

- Diodes have exponential *I-V* curve
- Useful part typically from –3 to 3V
- Breakdown voltage is not readily predicted (10-30 V in different diodes)

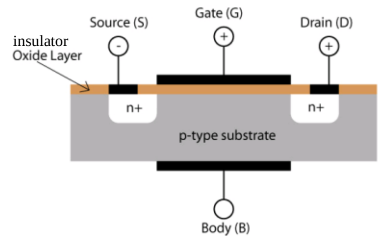
Example: Bipolar transistor



1956 Nobel prize in physics for invention of a transistor by Bardeen, Brattain, and Shockley

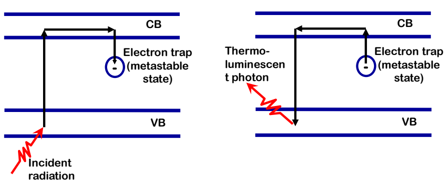
- Device structure: two *p-n* junctions connected back-to-back
- Voltage applied to the base determines the current between emitter and collector; exponential amplification due to change in barrier height
- It is called bipolar because both electrons and holes carry current in the device
- Can occur in either *n–p–n* or *p–n–p* configurations

Example: MOSFET



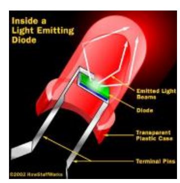
- Metal oxide-semiconductor field effect transistor
- Same principle of operation (gate ~ base)
- Simplified fabrication

Example: TLD



- Radiation excites electron into CB; to lower its energy it moves into a 'trap' (metastable defect state)
- After heating electron acquires energy to get back to CB
- Recombination with a hole from VB results in energy release emitted as optical photon

Example: LED



- Light-emitting diodes: applied forward bias excites electron into CB
- Upon recombination with a hole a photon is emitted (in some semiconductors)
- Color depends on the band gap of the semiconductor forming p-n junction
  - Red – higher wavelength, lower band gap (AlGaAs, GaAsP)
  - Blue – lower wavelength, wider band gap (ZnSe, InGaN)
- Laser diodes – same principle, higher forward bias (electrically pumped lasers)