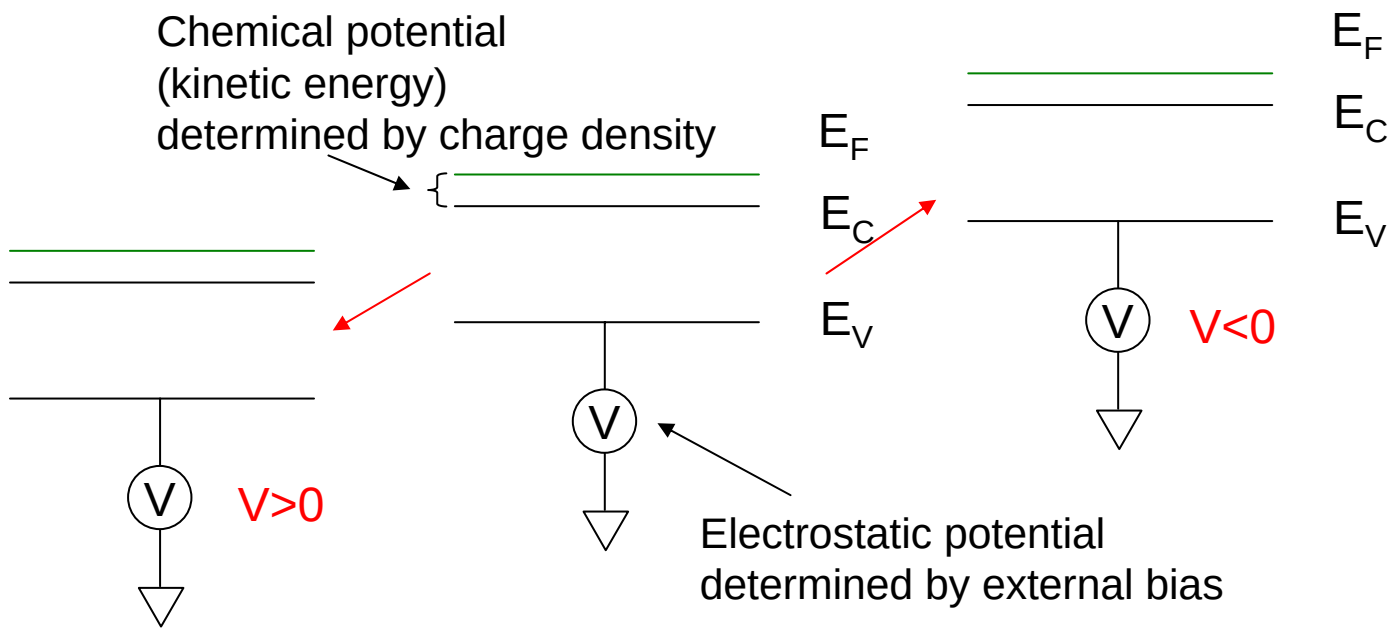
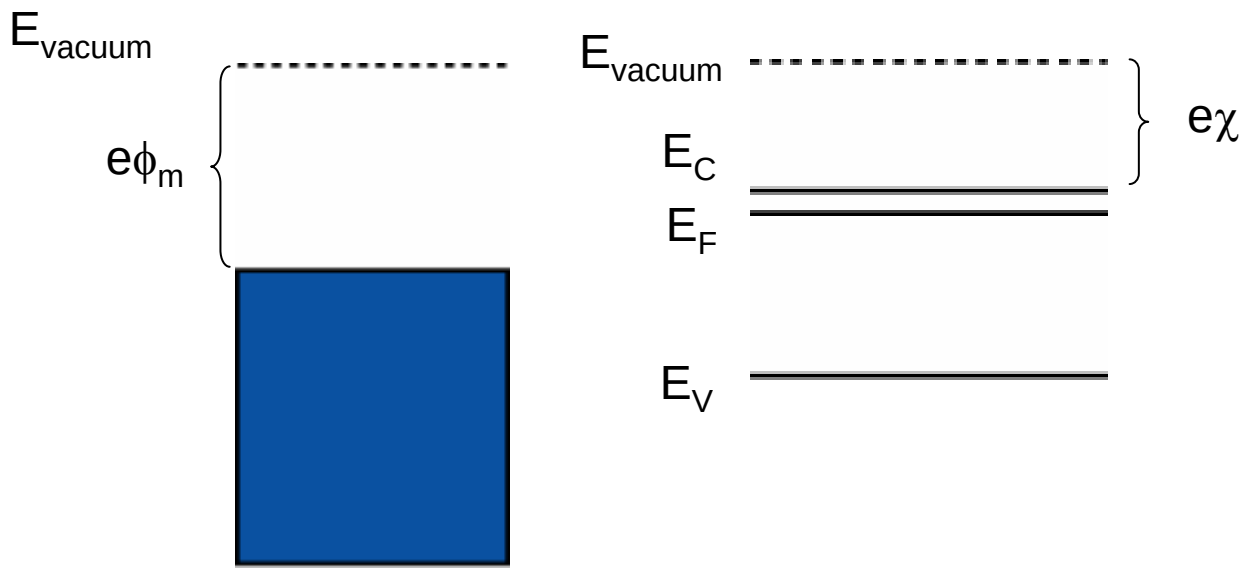
A few words about drawing the energy levels



E_F, electrochemical potential
= chemical potential + electrostatic potential (bias) + constant

Energy levels are referred to electrons! $\Phi=(-e)*V$
positive bias, levels ↓ negative bias, levels ↑

About the constants



Work function $e\phi_m$: the amount of energy required to take an electron from the Fermi level within a material and remove it to infinity. Concept more useful for metals.

Electron affinity $e\phi_m$: the energy difference between the bottom of the conduction band and the vacuum level. Concept more useful for semiconductors since E_F depends on carrier density.

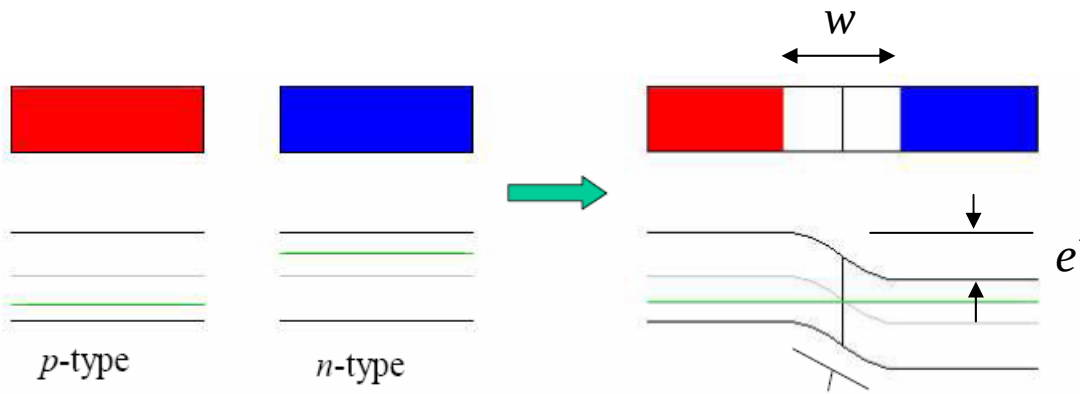
Joining materials with different Fermi levels

- Electrochemical potential needs to line-up
- Can get appreciable charge transfer, causing local changes in band structure!
- Many energy scales to contend with: E_F, E_C, E_V, Φ on both sides of junction, etc.
- Certain common situations arise in technology….

http://home3.netcarrier.com/%7Echan/SOLIDSTATE/BANDS/bands.html

Semiconductor-semiconductor junctions

One of the most commonly used: the *p*-*n* junction

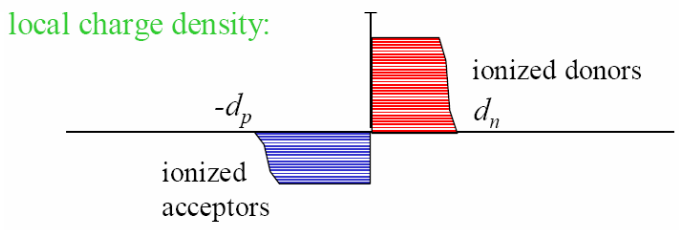


$$w = \sqrt{\frac{2\varepsilon\varepsilon_0}{e}\left(\frac{N_A + N_D}{N_A N_D}\right)V_{bi}}$$

eV_{bi} built-in potential

$$\frac{dE}{dx} = \frac{\rho}{\varepsilon\varepsilon_0} = \frac{eN_A}{\varepsilon\varepsilon_0}$$

$$-\frac{d^2V}{dx^2} = \frac{eN_A}{\varepsilon\varepsilon_0}$$



Many possibilities exist. Play with the java program below.

http://home3.netcarrier.com/%7Echan/SOLIDSTATE/BANDS/bands.html

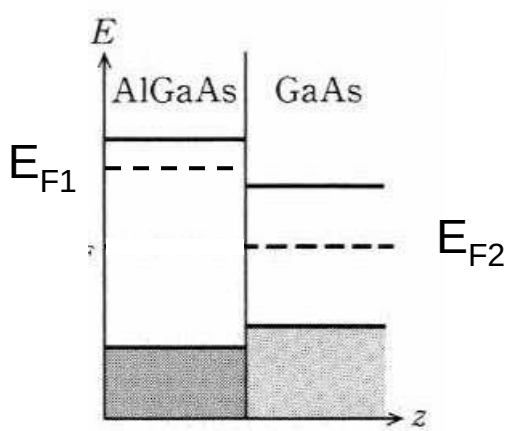
Semiconductor-semiconductor junctions

GaAs/AlGaAs heterostructure interface

$$\frac{d^2E}{dx^2} = \frac{eQ}{\varepsilon\varepsilon_0}$$

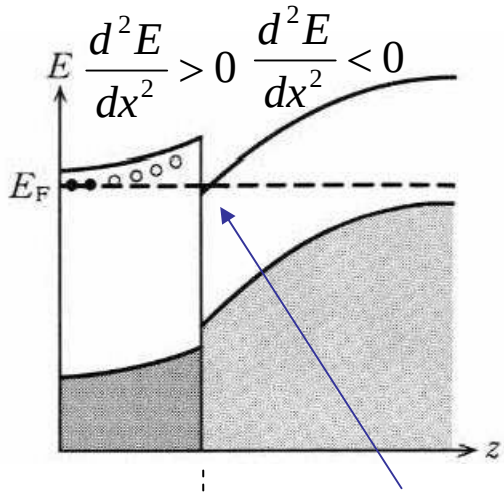
E, electron energy
Q, net charge

before contact



n-doped AlGaAs

after contact



$$\frac{d^2E}{dx^2} < 0 (> 0)$$

for net negative (positive) charge determines band shape

two-dimensional electron gas (2DEG)

confined in Z direction

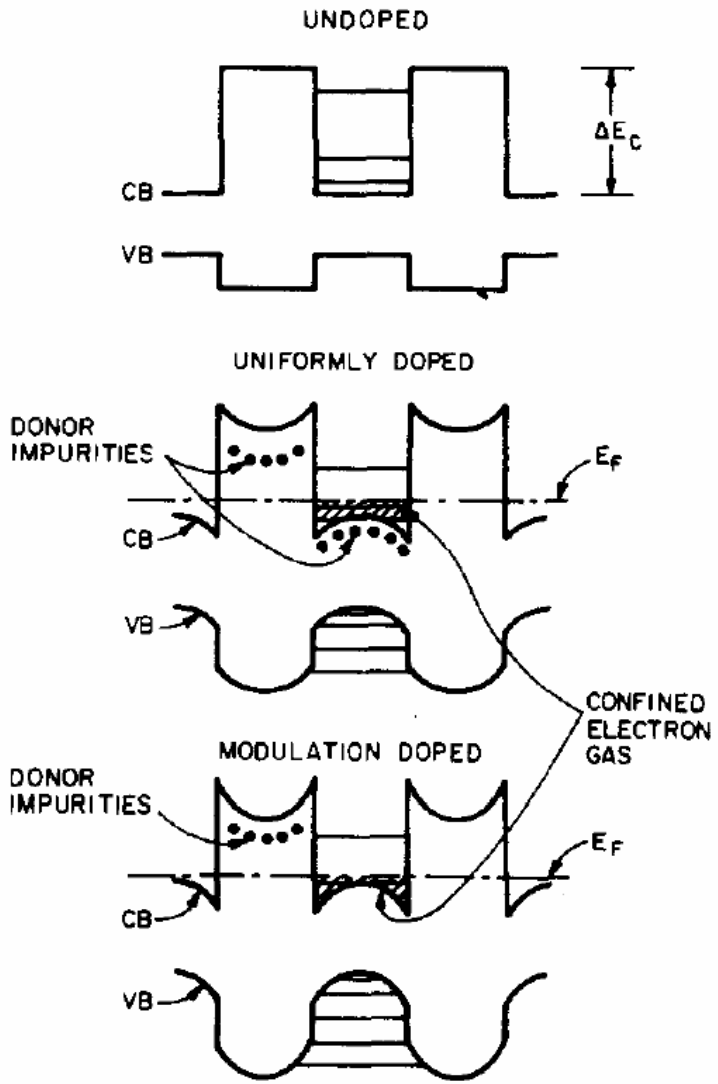
free in X,Y direction

Modulation doping

Undoped $Al_xGa_{1-x}As$ layer as spacer layer to further minimize dopant scattering. (δ doping)

World record μ=1.4x10^7 cm^2/Vs, mean free path 120 μm.
Umansky, APL, 71, 683 (1997)

Si: $\mu \sim 1500$ cm^2/Vs

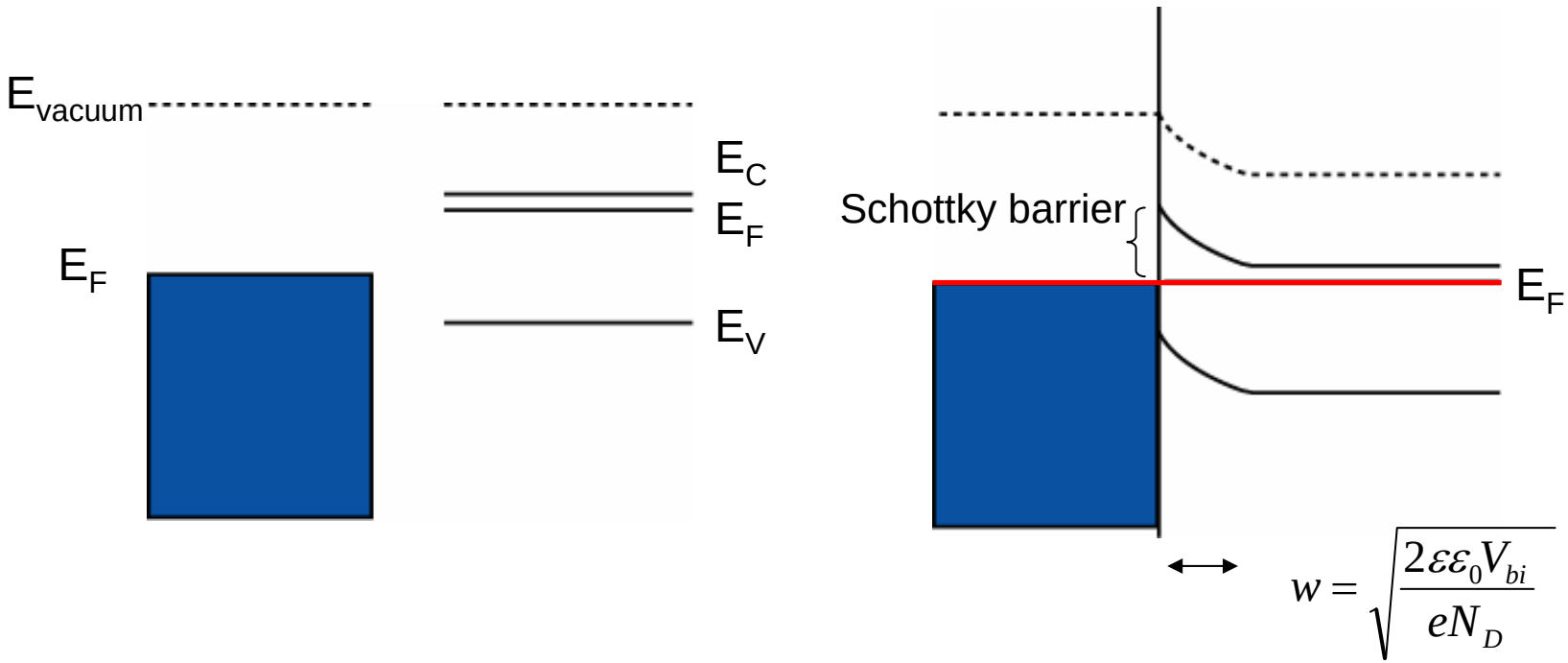


Dingle, APL, 33, 665 (1978)

Metal-semiconductor junctions

before contact

after contact



Schottky barrier height = $e\phi_m$-$e\chi$

Surface and interface states summary

- Surface states and interface states exist when symmetry of infinite periodic lattice is broken.
- Normally located inside the band gap, and close to mid gap

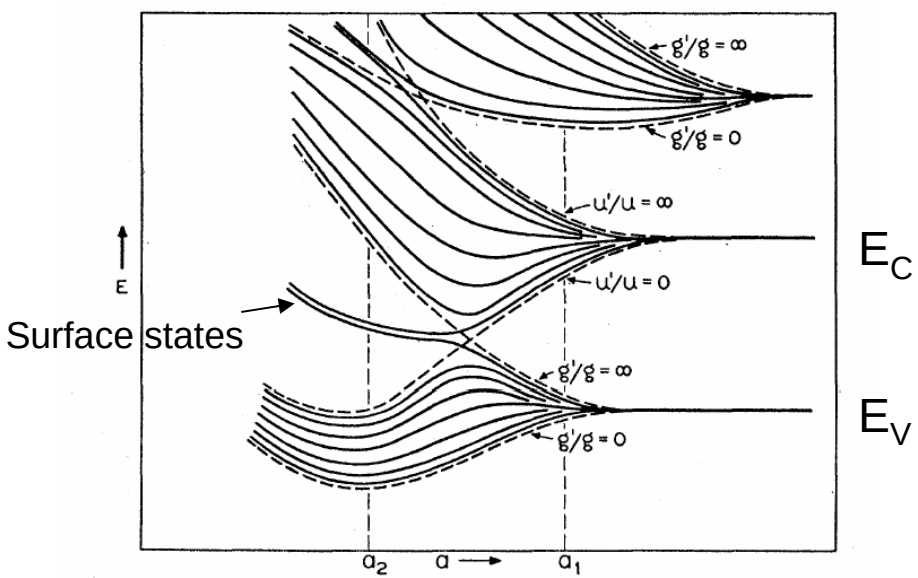
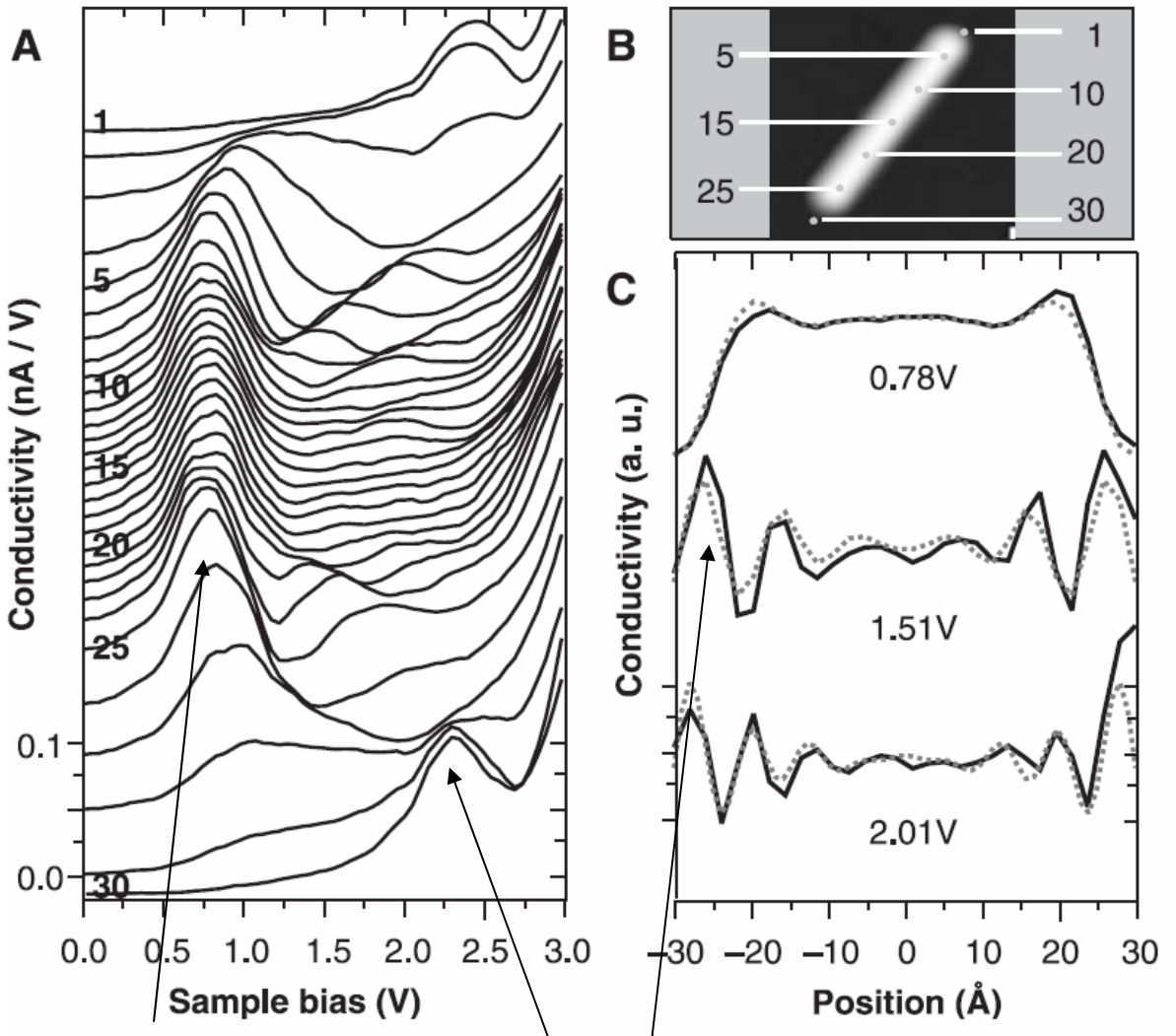


FIG. 2. Energy spectrum for a one-dimensional lattice with eight atoms.

W. Shockley, Phys Rev. **56**, 317, (1939)

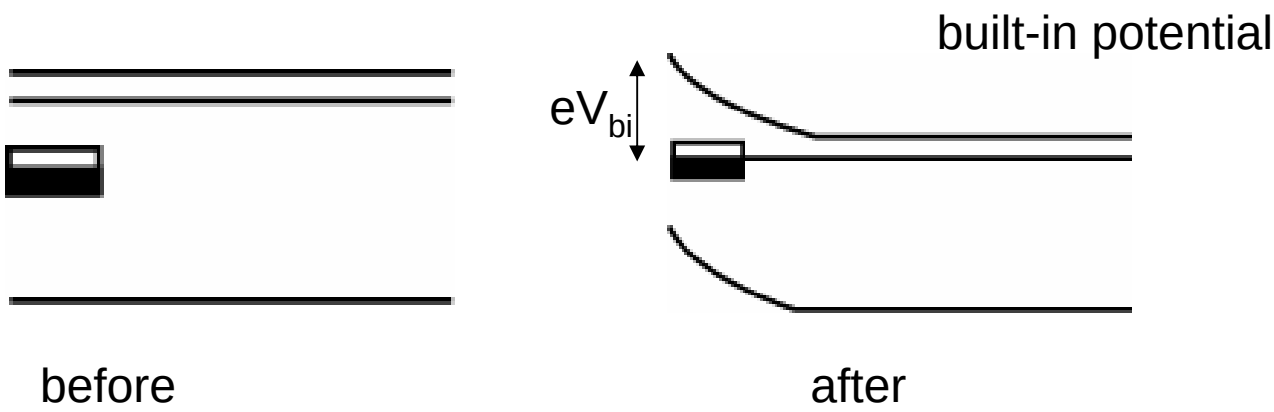


E_V

defect states (like surface states)

Surface and interface states summary

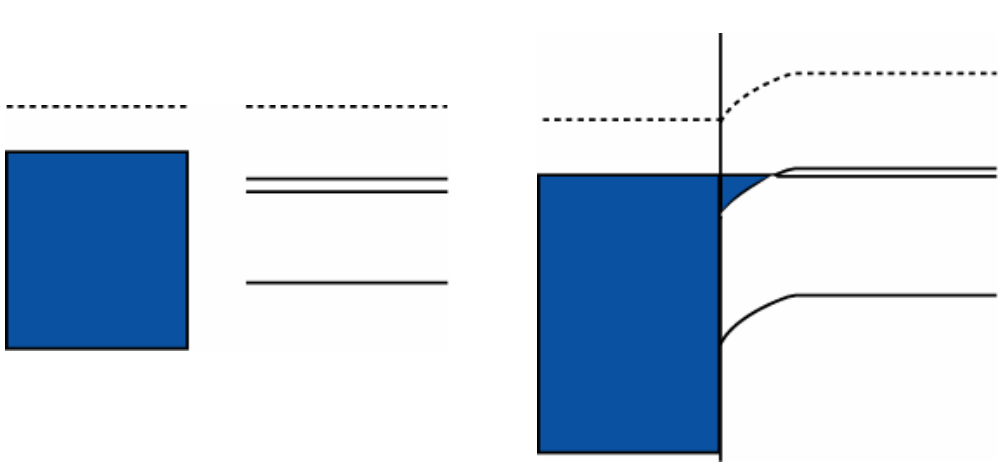
- Density of surface states can be very high: number of surface states can be comparable to number of atoms on surface!
- Surface states normally partially filled. Charges need to flow from balk in to empty surface states until Fermi level line-up (Fermi level pinning)

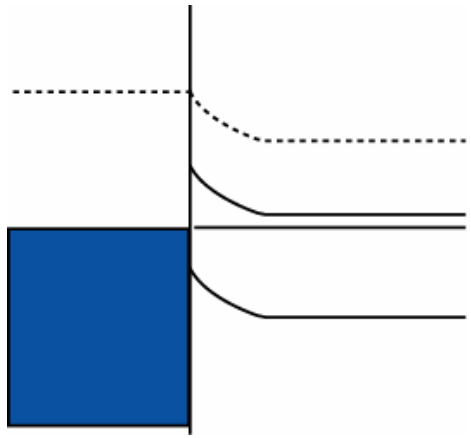


Ohmic contacts

before

after





True Ohmic contacts, hard to obtain due to interface states (which always pins the Fermi level close to mid gap).

Effective Ohmic contacts, electrons can directly tunnel through the depletion region

$$w = \sqrt{\frac{2\varepsilon\varepsilon_0 V_{bi}}{eN_D}}$$