Lecture 15

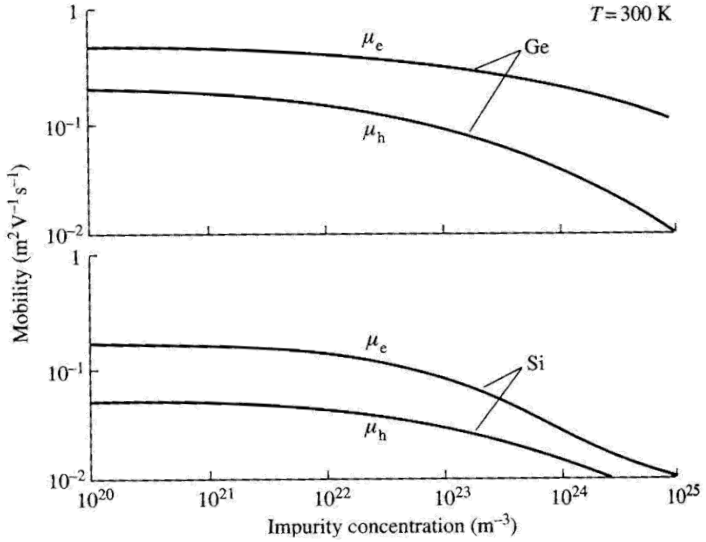
Reading Material

Reading:

Chapter 8 Solymar and Walsh

Dependence of carrier mobility on impurity density

- Recall that at room temperature, when the material acts extrinsic, the combined scattering effect of holes and electrons can be empirically used to calculate the conductivity $$\sigma = \frac{q^2}{m_e^*}\tau_e N_e + \frac{q^2}{m_h^*}\tau_h N_h$$
- We see from measurements of carrier mobility that the mobility decreases with increasing impurity concentration (note that electron mobility is greater than hole mobility due to relative effective mass)



Carrier Mobility as a Function of Impurity Density

- We discussed that the product of electron and hole densities in an intrinsic semiconductor is constant at any given temperature
- For an extrinsic semiconductor this is still true with

$$N_e N_h = 4\left(\frac{2\pi\kappa_B T}{h^2}\right)^3 \left(m_e^* m_h^*\right)^{3/2} e^{-E_g/\kappa_B T}$$

Intrinsic Semicondutor $\begin{cases} r_{\text{int } rinsic} = aN_i^2, \text{ rate of recombination is proportional to intrinsic hole and electron desity} \\ g_{\text{int } rinsic} = aN_i^2, \text{ rate of generation is proportional to intrinsic hole and electron desity} \end{cases}$

Extrinsic Semicondutor $\begin{cases} r_{extrinsic} = aN_e N_h, \text{ rate of recombination is proportional to intrinsic hole and electron desity} \\ g_{extrinsic} = aN_i^2, \text{ rate of generation is proportional to intrinsic hole and electron desity} \end{cases}$

$r_{extrinsic} = aN_e N_h = g_{extrinsic} = aN_i^2$, in thermal equilibrium, therefore

$N_e N_h = N_i^2$

Compounds

- In addition to using single element crystals that exhibit semiconductor behavior (insulators at low temperatures, conductance increases with increasing temperature)
  - We can form compounds that exhibit same behavior that allow us to modify the bandgap and some other properties
  - One common class is III-V (e.g. GaAs, AlSb)
  - We can make GaAs extrinsic by changing the proportion of Ga to As, excess Ga for p-type and excess As for n-type
  - Another class is the II-IV (e.g. InP)

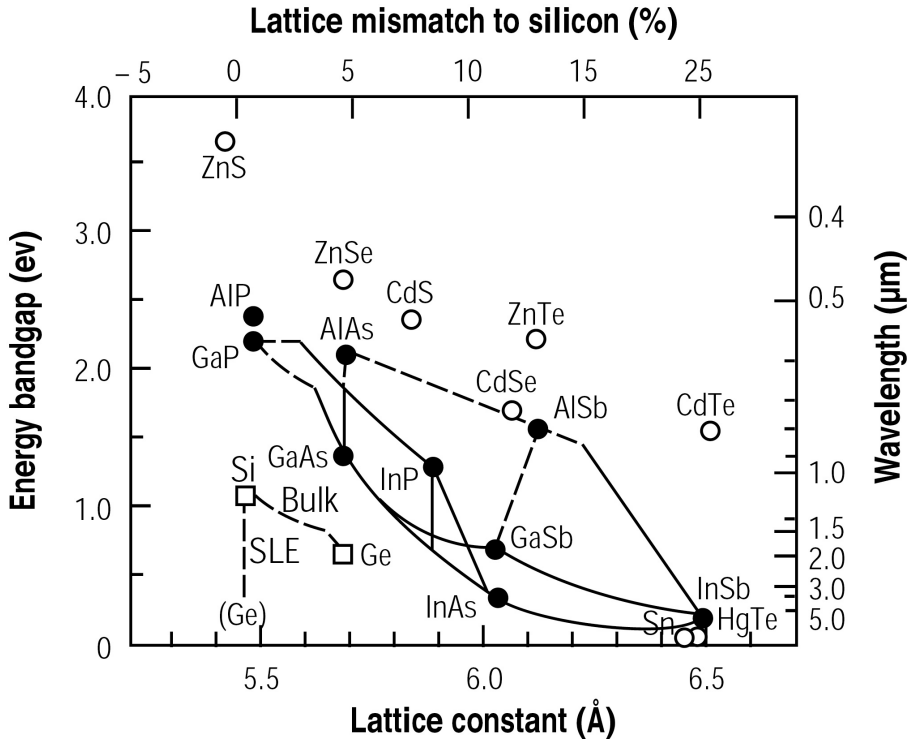


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Table 8.3 *Semiconductor properties I. Energy gap and structure*

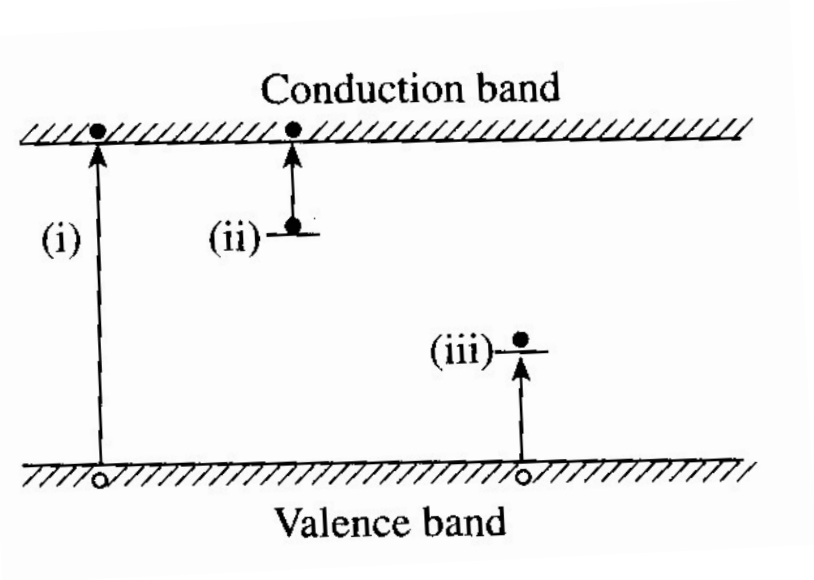
Semiconductor	Energy gap eV	Melting point K	Ionic % of bond	Lattice spacing Å
Group IV				
C	5.4	382	0	3.56
Si	1.11	1680	0	5.43
Ge	0.67	1210	0	5.66
SiC	2.9		18	3.08, 5.05
Group III–V				
Al N	6.02	3070		3.11, 4.98
Al P	3.34	1770		5.45
Al As	2.2	1870		5.66
Al Sb	1.6	1330		6.15
Ga N	3.34	2770		3.19, 5.18
Ga P	2.24	1730		5.45
Ga As	1.42	1520	31	5.65
Ga Sb	0.67	980	26	6.10
In N	2.0	2475		3.54, 5.70
In P	1.27	1330	42	5.80
In As	0.36	1215	36	6.06
In Sb	0.17	798	32	6.48
Group II–VI				
Zn O	3.20	2248	62	4.63
Zn S	3.54	1925	62	5.41
Zn Se	2.58	1790	63	5.67
Zn Te	2.26	1658	61	6.10
Cd O	2.5	2020	79	
Cd S	2.42	1750	69	5.58
Cd Se	1.74	1512	70	6.05
Cd Te	1.44	1368	67	6.48

Non-Equilibrium

- We can change the state of the semiconductor from thermal equilibrium to non-equilibrium by imparting energy to the semiconductor in a manner where it is not in balance with its external environment. Some processes include:
  - Optical injection
  - Current injection
  - Voltage
  - Thermal
  - Stress
- A semiconductor that is placed in non-equilibrium by an external source, will then return to equilibrium when that source is removed (if it is the only source) with a time constant characteristic called the carrier lifetime (sometimes referred to as τ)

Non-Equilibrium

- Three ways to generate conducting carriers via creation of electron-hole pairs – now we can create more of one or both than was available in TE.
  - For a material that is un-doped, donor doped, acceptor doped or both donor and acceptor doped
    - (i) Energy absorbed to break bonds in the valance band to create a electron-hole pair across the valance-conduction band gap
    - (ii) Energy absorbed to break bonds in the valance band to create a electron-hole pair across the valance-acceptor band gap, ionizing the acceptor impurities. This process creates a conducting hole and leave behind a fixed ion.
    - (iii) Break bonds in the valance band to create a electron-hole pair across the donor-conduction band gap, ionizing the donor impurities. This process creates a conduction electron and leaves behind a fixed ion.

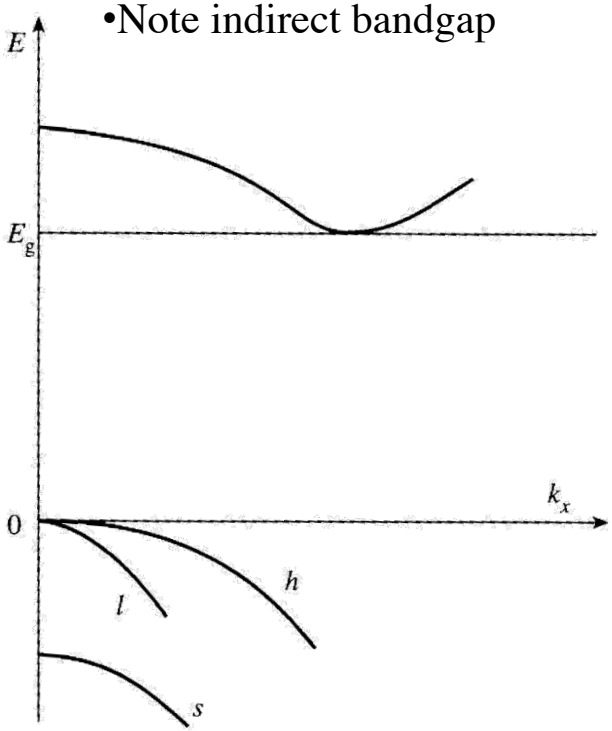


Real Semiconductors

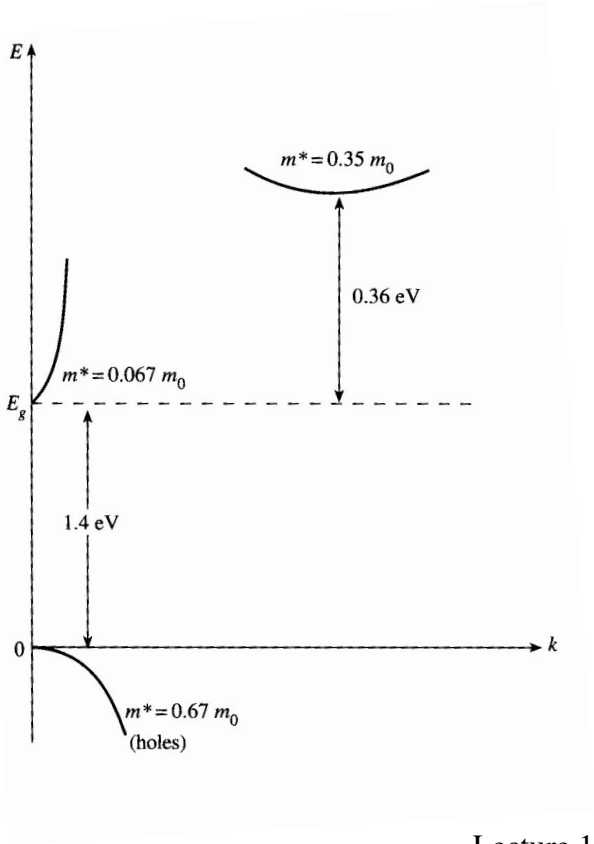
- So far we have made many assumptions about the band structure, like one valance band, parabolic shapes of E vs. k, etc.
- The cubic lattice assumption for the band structure does not yield many real important properties
- For example, the constant energy in k are not spheres
- In the valance band we find that there multiple types of holes

Real Semiconductors

- E vs. k for Si in a particular direction
  - Three types of holes
    - Heavy
    - Light
    - Split-off
  - Note indirect bandgap

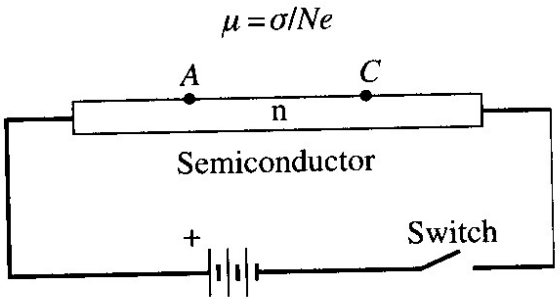


- E vs. k for GaAs in a particular direction
  - Second valley in conduction band

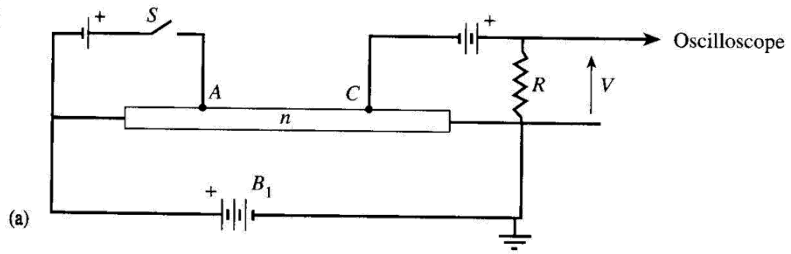


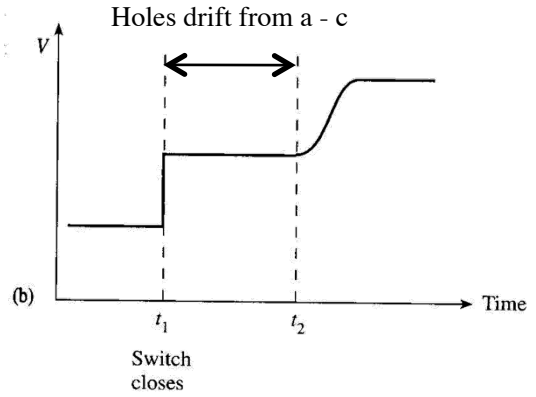
Measurement of Mobility

- Drift Velocity in DC field



- Haynes-Shockley Experiment

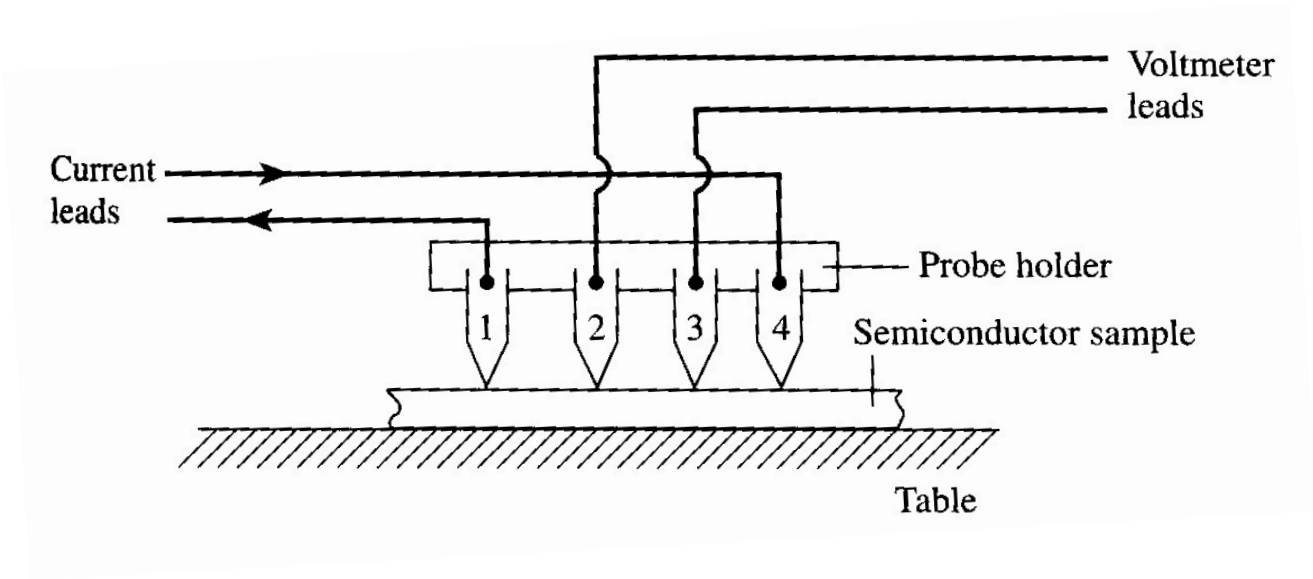




Four-Point Probe

- Current passed from 1 to 4 and voltage measured from 2 to 3
- For equal probe spacing d (and wafer thickness much greater than d)

$$\sigma = \frac{I_{1,4}}{2\pi V_{2,3} d}$$



Effective Mass using Cyclotron Resonance

- Effective mass measured from absorption peaks as a function of microwave frequency.
- Can be measured in different directions to get picture of bandgap.

$$m^* = \frac{qB}{\omega_c}$$