Physics 489 S 04 Lecture 22
Semiconductors I: Properties of homogeneous materials, A & M Ch. 28, Kittel Ch. 8.

1. Semiconductors are materials whose conductivity can be modified greatly in controllable ways by temperature, adding foreign atoms, and electric fields
   Usually they are insulators at T=0 with narrow gaps ($\approx 0\ to\ \approx 2\ eV$) in their perfect crystalline form

2. Key properties: Magnitude of gap, effective masses of bands at top of filled bands and bottom of empty bands

   Examples: (Most values are from Kittel, Chapt. 8)

	Gap		m*e	m*h
	0K	300K		
Si	1.17 eV	1.12 eV	1.0 , 0.2me	0.52, 0.16
Ge	0.75	0.67	1.6, 0.082	0.34, 0.043
GaAs	1.5	1.4	0.066	0.5, 0.082
InSb	0.23	0.16	0.015	0.39, 0.021

3. Electrons and Holes
   Occupation of band-like states given by Fermi function
   For $E_c - \mu >> k_BT$, and $\mu - E_v >> k_BT$,
   Probability for state in conduction band to be full =
   $f(E) \approx exp(-(E-\mu)/k_BT)$, for $E > E_c$
   Probability for state in valence band to be empty =
   $1 - f(E) \approx exp(-(\mu - E)/k_BT)$, for $E < E_v$
   Integrating in effective mass approx. gives the density of electrons and holes:
   $n = Nexp(-(E_c - \mu)/k_BT)$,
   $p = Pexp(-(\mu - E_v)/k_BT)$,
   where $N = 2(m_e^* k_BT/2\pi\hbar^2)^{3/2}$, etc., which varies slowly with T.

4. Law of mass action: $np = NPexp(-E_g/k_BT)$ independent of Fermi Energy μ.

5. Intrinsic semiconductors (perfect crystals) at $T > 0$,
   Charge neutrality: $n = p = n_i(T) = (NP)^{1/2}exp(-E_g/k_BT)$
   μ is at center of gap at T=0, $\mu(T) = \mu(0) + 0.5k_BTln(N/P)$

6. Extrinsic semiconductors: doped crystals
   Charge of carriers: $n - p = N_{donors} - N_{acceptors}$, $np = n_i(T)^2$
   If $N_{donors} > N_{acceptors}$, μ is increased nearer conduction band, n increased, p decreased
   If $N_{donors} < N_{acceptors}$, μ is decreased nearer val. band, p increased, n decreased

7. Conduction properties
   Mobilities: $\mu_e = ne^2\tau_e/m_e^*, \mu_h = ne^2\tau_h/m_h^*$
   Conductivity: $\sigma = n_e\mu_e + n_h\mu_h$ - electron and hole always add!
   Hall Effect: $R_H = (1/ec)(p - n(\mu_e/\mu_h)2)(p + n((\mu_e/\mu_h))^2$
   Thermoelectric Effect: Π = heat / charge per carrier - can determine sign of carriers

8. Doping – Donors and Acceptors: Examples: As or Ga in Si

9. Bound States of electrons or holes - Hydrogenic Binding:
   Binding $= E_d$ *or* $E_a = Ryd(m * /\epsilon^2) \approx 13.6eV(0.1/10^2) \approx 0.01\ eV$
   Radius $= R \approx bohr\ radius(\epsilon/m^*) \approx 0.52A(10/0.1) \approx 50A$
   Because of interactions among electrons, there is an energy cost to put two electrons (or two holes) on on impurity site. This favors having one electron (or hole) which has a spin that can be detected by magnetic resonance. Example of effects discussed in Lecture 1 and given in problem(s).

10. Thermal excitation of free carriers from donor or acceptor sites
    In n type crystal, $N_{donors} > N_{acceptors}$, at low T the density of free carriers is:
    $n/N_d = 2Nexp(-(E_d/2)/k_BT)$, where E_d plays the role of a gap
    Similarly for p type crystals
    At high T, n and p approach the intrinsic regime $n \approx p \approx n_i(T)$

11. Degenerate metal formed at T=0 by overlap of donor or acceptor sites
    If the impurity states overlap strongly, the exclusion principle forces the electrons to tend to pair with opposite spins - for large overlap they form a metal:
    Mott Transition - insulator to metal as density increases
    Very roughly this happen when the hydrogenic states overlap strongly, i.e. , for densities where N_{donors} *or* $N_{acceptors} > (1/4\pi R^3/3)$
    Heavily doped semiconductors are metallic with finite conductivity σ at T= 0