EE 116 Lecture 6

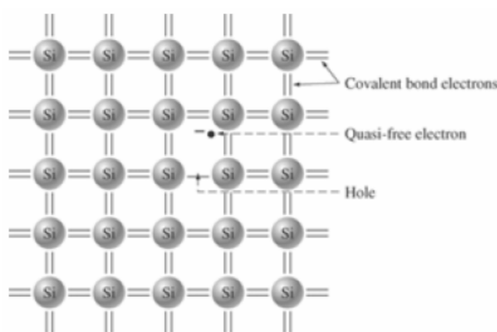
Intrinsic Material, Doping, Carrier Concentrations

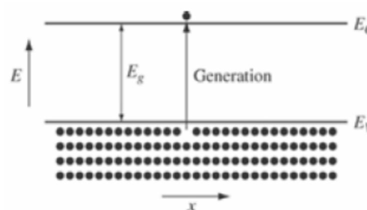
- https://truenano.com/PSD20/contents/toc2.htm

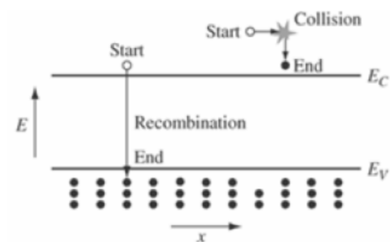
- Begin skimming Ch. 2.6
- Read: 2.6.4 to 2.6.4.2

Also see CCH Ch. 1

- Intrinsic semiconductor = pure, without external additives

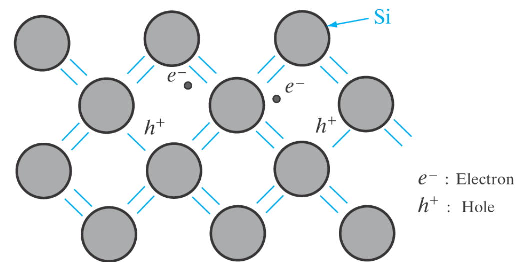






- No free charge carriers at T = 0 K
- What about at T = 300 K?
- How much energy to break a bond?

- How many electron-hole pairs (EHPs) are created when bonds are broken by thermal agitation?



- In thermal equilibrium
  - generation = recombination

- Simple probability:
  - Recombination driven by # of electrons (*n*) and holes (*p*) available
  - Generation intrinsically driven only by temperature (# bonds broken by thermal agitation) ~ $\exp(-E_G/k_B T)$

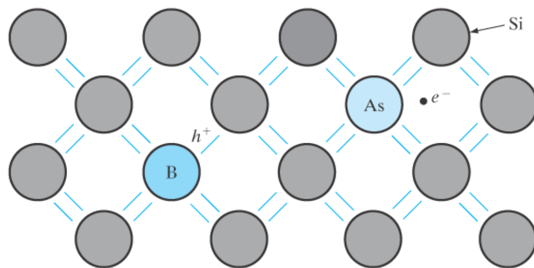
- Hence at thermal equilibrium: $np = n_i^2$

- At room temperature (T ~ 300 K) intrinsic concentrations:
  - n_i ~ 2 x 10^6 electrons and holes per cm^3 in GaAs
  - ~ 1 x 10^{10} cm^{-3} in Si
  - ~ 2 x 10^{13} cm^{-3} in Ge

- What about the band gaps of these materials?
- To get a sense of scale, how do these numbers:
  - compare with N_A → 6.02 x 10^{23} atoms/mol (~few cm^3)
  - compare with number of Si atoms per cm^3 (x4 valence electrons per atom) → 5 x 10^{22} cm^{-3}

- What if temperature is increased?

- How to manipulate carrier concentrations
- Doping = purposely introducing impurities into the crystal
- *Intrinsic* material = pure, undoped. *Extrinsic* = doped.



IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te

- Donors and acceptors… of what?

- Ex: compare # of valence electrons (e.g. 5 for As) with number of electrons of the atom it replaces (e.g. 4 for Si)

- Arsenic (As) dopant in Si: 4 electrons used up for bonding with neighbors. But, how loosely bound is that 5th electron that As brought into the Si lattice?
- Approximate binding energy using Niels Bohr's model:

$$E_B \approx \frac{m^* q^4}{2K^2 \hbar^2}$$

be careful with choice of m^* and $K = 4\pi\epsilon_r\epsilon_0$

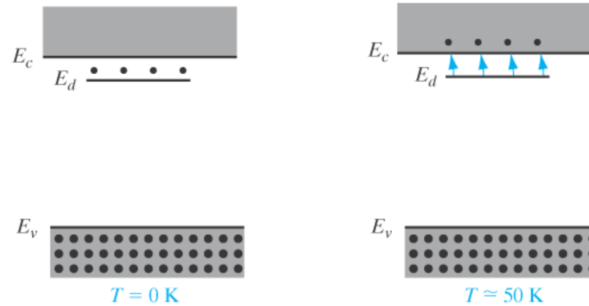
- The real numbers of donors and acceptors in Si:

Donor in Si	P	As	Sb
Binding energy (eV)	0.045	0.054	0.039

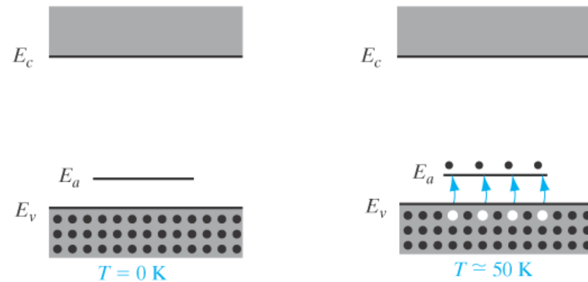
Acceptor in Si	B	Al	Ga	In
Binding energy (eV)	0.045	0.067	0.072	0.16

- (note: binding energy = ionization energy)

- Where are the donor and acceptor levels on the band diagram model?



- Recall: thermal agitation energy ~ 3/2 k_BT



- Extrinsic (doped) material:
  - n-type semiconductor if…
  - p-type semiconductor if…

- Ex: what are the electron & hole concentrations in a Si wafer doped with 10^{15} cm^{-3} As atoms (at room T). Is this n- or p-type Si?

- How much has the resistivity changed from intrinsic Si?

Summary:

- Band gap energy (E_G) is energy required to free an electron from a covalent bond
  - E_G = 1.1 eV for Si at 300 K
  - Insulators have “large” E_G, semiconductors have “small” E_G

- Dopants in Si:
  - Substitute pre-existing Si atoms on lattice sites
  - Group-V elements are *donors*, contribute conduction electrons
  - Group-III elements are *acceptors*, contribute holes
  - Low ionization energy (~50 meV) → all ionized at room T
  - Useful dopant concentrations in Si range from 10^{15} to 10^{20} cm^{-3}

(<1% Si atoms replaced in even highest doped samples)

EE 116 Lectures 7-8

Doping, Fermi Level, Density of States

- Read → Online Ch. 2.5.1-2.5.2
- Ch. 2.6.1-3 and 2.6.4.3-4

Also see CCH Ch. 1

- How to calculate electron (and hole) densities for:
  - Any temperature
  - Any doping concentration
  - Any energy level

- Recall that in thermal equilibrium: $np = n_i^2$
- What if I turn the light on? (qualitatively)

- We are (typically) dealing with large concentrations, not individual electrons → we need a statistical treatment of these electron (or hole) populations

- Two key concepts needed to “count” populations:
  1) The probability of finding electrons (or holes) in a state
  2) The number (i.e. density) of states available

- Recall that electrons (and holes) obey the Pauli exclusion principle, i.e. electrons are fermions
  - So are neutrons, protons (all spin = 1/2)

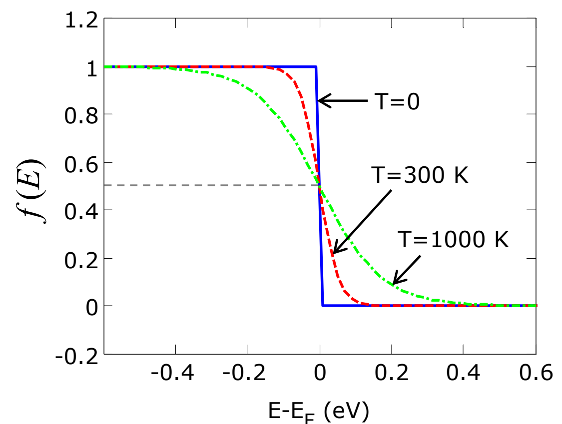
- But photons and phonons (vibrations) are bosons

1) Fermi-Dirac probability function for electrons & holes

≈ the probability of finding a spectator in a seat as you go up from the bottom row of a stadium

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

- What this looks like →



- When $E >> E_F$ we recover the Maxwell-Boltzmann (MB) function:

- What is the meaning of the Fermi level, E_F?

2) Density of states in Si conduction & valence band

- Counting states (i.e. "stadium seats per row")**:

$$g(E) = \frac{8\pi\sqrt{2}}{h^3} m_n^{*3/2} \sqrt{E - E_C}$$

- Most important feature is ~$E^{1/2}$ (more states at higher E)
- E with respect E_C (no states in the band gap)
- What is m^* here?
- Bonus: what about in 1D or 2D nanostructures?**

**details are in BVZ Ch. 2.4 (not required in 116)

- So how do we calculate electron & hole concentrations knowing the density of states and probability of occupation?

$$n_0 = \int_{E_C}^{\infty} f(E) g_C(E) dE$$

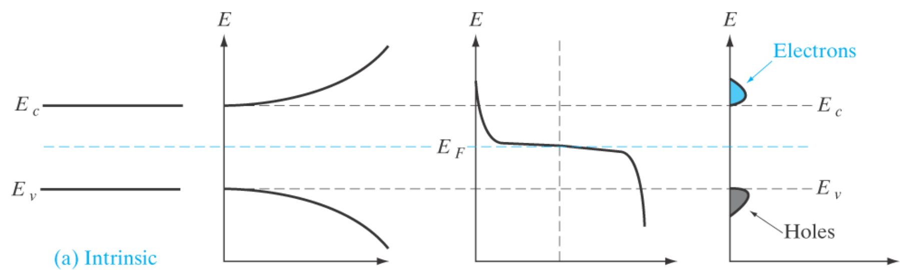
- This is the density of electrons in the C-band. What about holes in the V-band?

$$p_0 = \int_{-\infty}^{E_V} [1 - f(E)] g_V(E) dE$$

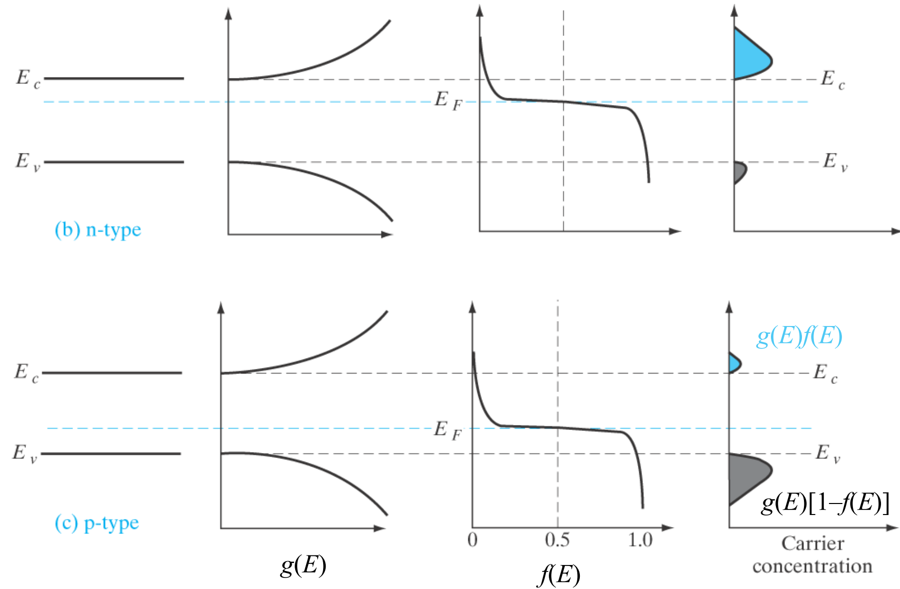
- These are tough integrals, we can approximate them if E_F is inside the band gap (non-degenerate case, MB statistics)

$$n_0 \approx N_C e^{-(E_C - E_F)/kT} \quad \text{where} \quad N_C = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

- Where is E_F in intrinsic material?



- What happens with E_F when we start doping the material?



- We can write similarly for holes: $p_0 \approx N_V e^{-(E_F - E_V)/kT}$

- And so the product: $n_0 p_0 = N_C N_V e^{-E_G/kT} =$

- Is there an easier way to write these?
- Recall if the material is intrinsic, $E_F = E_i =$ where?
  → $E_C - E_i = E_G/2$

- Write n_i with N_C and N_V as above
- But we know $n_i \sim 10^{10}$ cm^{-3} in Si so it's easier to rewrite:

$n_0 = n_i e^{(E_F - E_i)/kT}$ $\quad p_0 = n_i e^{(E_i - E_F)/kT}$ (is the product as it should be?)

- Sample problem: Si doped with 10^{16} Boron atoms per cm^3. What are the electron & hole concentrations at room T? (assume lights off.) Is this n- or p-type material? Where is the Fermi level E_F?