Lecture 12

Reading Material

Reading:

Chapter 8 Solymar and Walsh

Hole and Electron Energy Probabilities

- Recall that the probability that a state at energy (E) is occupied by an electron is given by

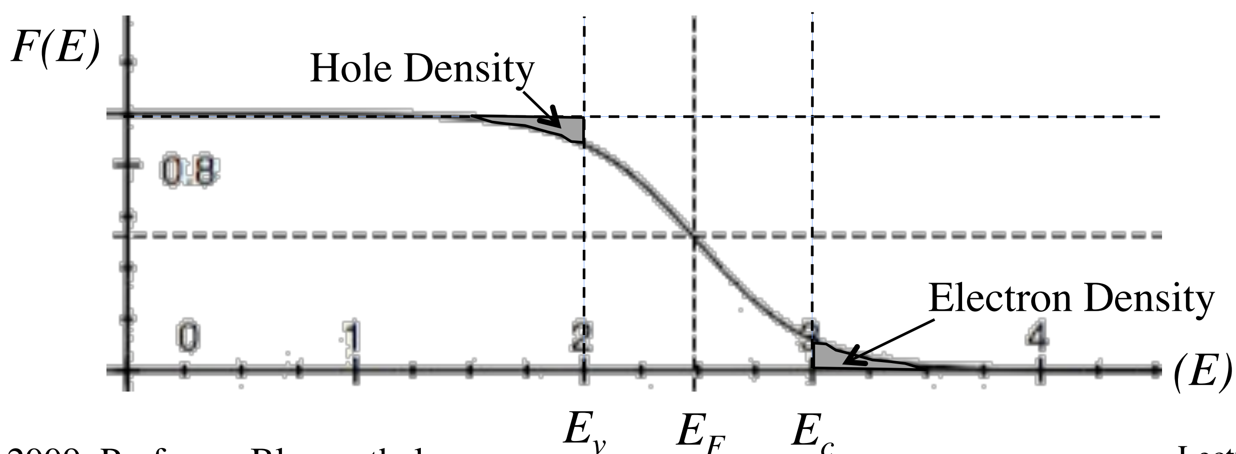
$$f(E) = \frac{1}{e^{(E-E_F)/\kappa_B T} + 1}$$

- And the probability that a state at energy (E) is occupied by a hole is given by

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

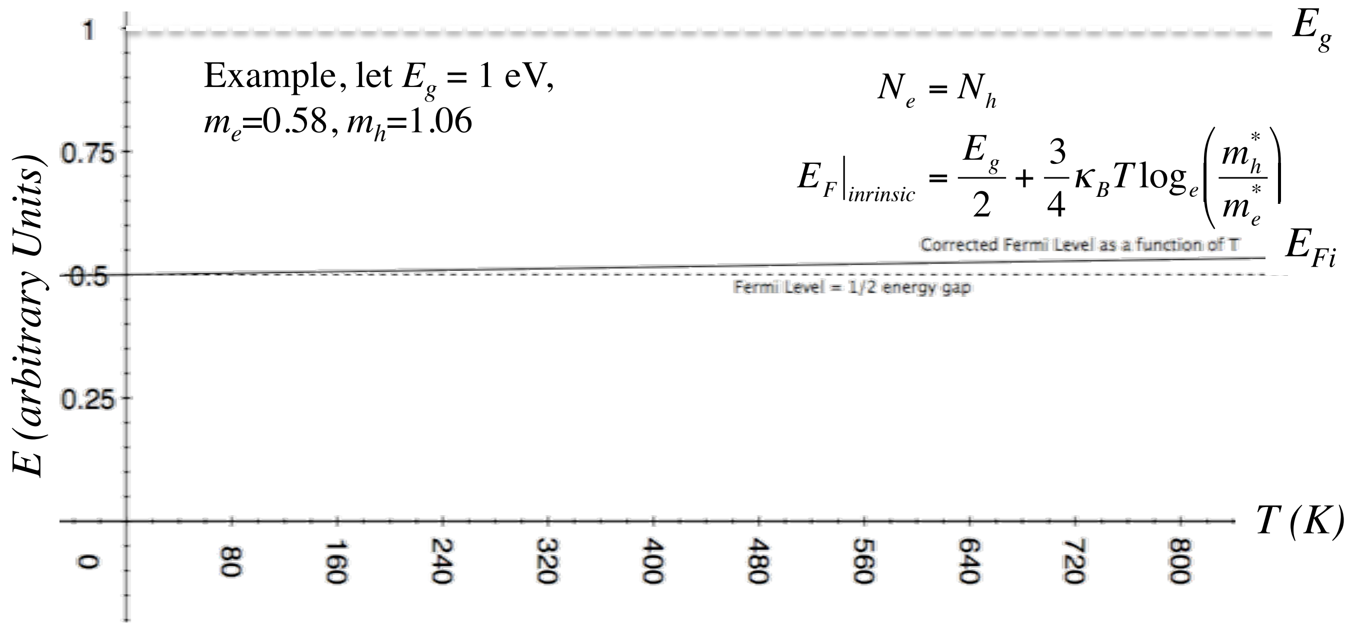
•As an example, consider arbitrary conduction and valance energy levels and relative position of the Fermi level at midpoint. The shaded areas below are indicative of the density of carriers (holes and electrons).

•In an Intrinsic semiconductor in thermal equilibrium and condition of charge neutrality, the number of electrons in the conduction band equals the number of holes in the valence band N_e=N_h.



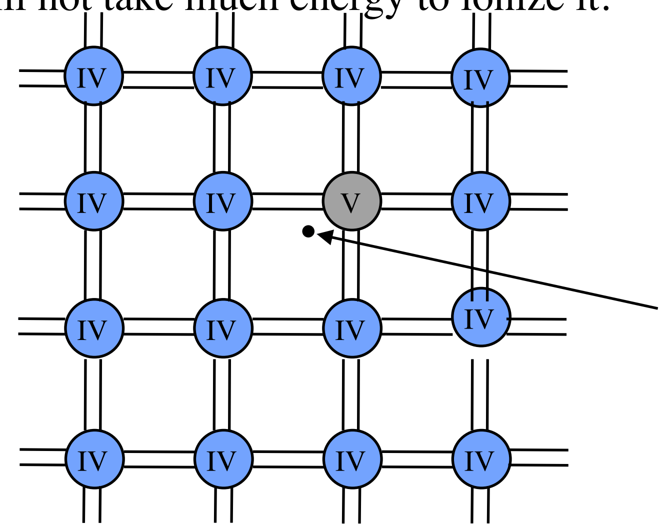
Intrinsic Semiconductors - Fermi Level vs. T

- We saw that the Fermi-Level was offset from the bandgap midpoint by an amount that varies as the natural logarithm of the ratio of the effective hole to effective electron mass and linear with temperature
- We can see how this makes sense, since the effective masses will change the curvature of the conduction and valence bands and the temperature will change the slope of the Fermi transition around the half probability point -> it is the product of the Fermi Function and the density of states two that determines the carrier density in the valance and conduction bands.



Extrinsic Semiconductors

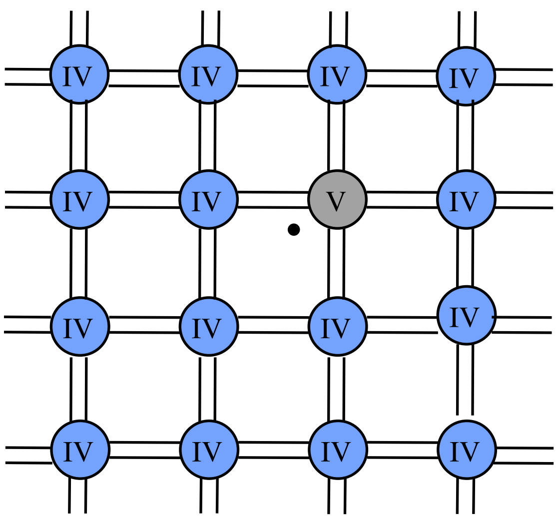
- Now lets consider the example where we take a pure (intrinsic) group IV semiconductor (column IV of the periodic table) and add to it a controlled number per volume of impurities.
- For silicon the impurities would be from the group V (column V of the periodic table)
- As shown below, if we use silicon as the intrinsic semiconductor and either Sb, As or P for the group V impurity, then each group 5 atom will replace one silicon atom and use up 4 valence electrons for covalent bonding.
- Note that the 4 neighboring silicon atoms with 4 valance electrons covalent bonded to the group V atom leaves one electron loosely bonded. Since the group V atom without the loosely bonded electron would be a positive Ion, it will prefer to stay charge neutral, but the electron is very weakly bonded to this atom and it will not take much energy to ionize it.

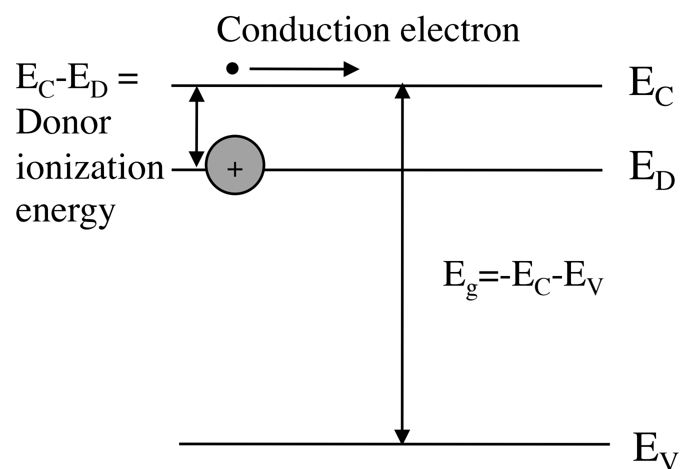


Electron loosely bound to group V impurity

Extrinsic Semiconductors

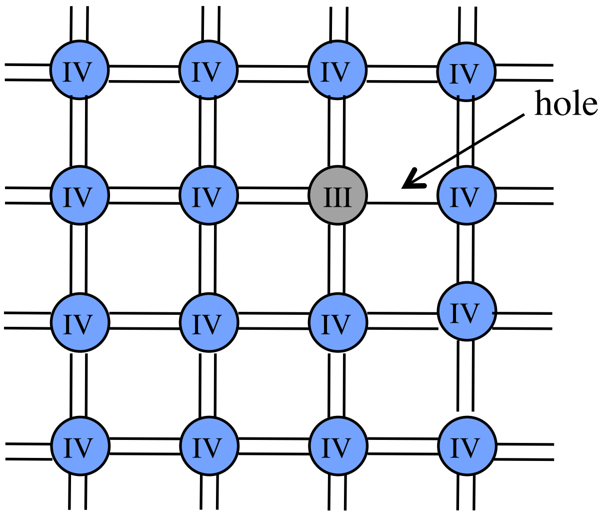
- The energy required to remove this loosely bonded electron from the group V atom is the ionization energy associated with the impurity and is much weaker than the ionization energy of the covalent bonds.
- We represent this reduction in ionization energy by indicating the dopant atoms as having a smaller ionization energy using an energy level closer to the conduction band as shown below.
- The energy required to ionize this impurity atom can be on the order of thermal energy at room temperature, hence with high probability the group V atom will be ionized, donating an electron to the conduction band and becoming a positively charged ion.
- We call this type of impurity a "***Donor***" atom and E_D is the "***Donor Level"***

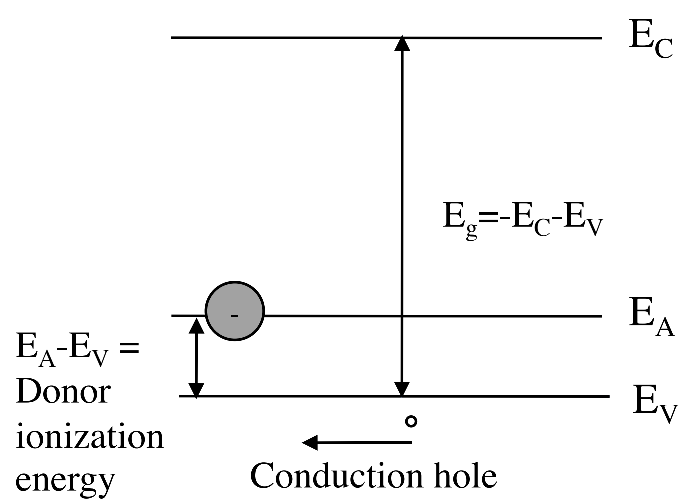




Extrinsic Semiconductors

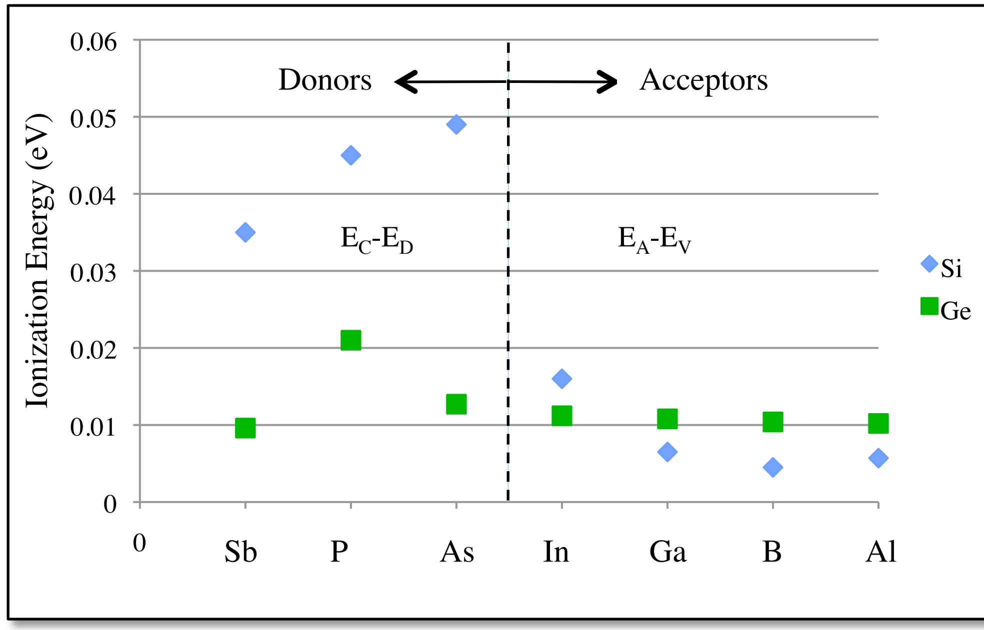
- The same argument can be given when we insert a group III atom, in a group IV intrinsic semiconductor crystal resulting in an electron missing from on of the covalent bonds
- We refer to the missing bond as a "***hole***"
- The energy required to ionize an electron from the valance band to the group III impurity energy can also be on the order of thermal energy at room temperature hence the impurity can at room temperature attract an electron and become a negatively charged ion leaving behind a hole in the valance band.
- We call this type of impurity an "***Acceptor***" atom and E_A is the "***Acceptor Level***"





Example Impurity Ionization Energies in Semiconductors

	Impurity	Ge	Si
Donors	Sb	E_C-E_D=0.0096 eV	E_C-E_D=0.035 eV
	P	E_C-E_D=0.0210 eV	E_C-E_D=0.045 eV
	As	E_C-E_D=0.0127 eV	E_C-E_D=0.049 eV
Acceptors	In	E_A-E_V=0.0112 eV	E_A-E_V=0.0160 eV
	Ga	E_A-E_V=0.0108 eV	E_A-E_V=0.0065eV
	B	E_A-E_V=0.0104 eV	E_A-E_V=0.0045 eV
	Al	E_A-E_V=0.0102 eV	E_A-E_V=0.0057 eV



Fermi Level in Extrinsic Semiconductors

- We are still considering materials that are in thermal equilibrium (e.g. equal energy exchange with outside environment). For example there is not a battery hooked up to the semiconductor.
- In Thermal equilibrium, even the extrinsic semiconductor is going to tend to be charge neutral.
- Accounting for all the charges contributions

$$N_e + N_A^- \underset{\text{Dynamic Equilibrium}}{\longleftrightarrow} N_h + N_D^+$$

- The number of ionized Donor impurities is given by the total number of Donors times the probability (at a temperature T) that the electron associated with the Donor is not at energy E_D, which can be written using the Fermi Dirac probability for holes

$$N_D^+ = N_D\left[1 - F\left(E_D\right)\right]$$

- The number of ionized Acceptor impurities can be figure out in an similar manner where we now are concerned with the probability that an electron occupies the Acceptor energy

$$N_A^- = N_A F\left(E_A\right)$$

N and P-Type Semiconductors

- Now lets consider the case where an intrinsic semiconductor is predominantly doped with either a Donor or an Acceptor impurity such that there are excess electrons or holes respectively.
- Define

$$\boxed{\begin{array}{l} \text{N - Type Semiconductor} \begin{cases} N_D^+ >> N_A^- \\ N_e >> N_h \end{cases} \\ \text{P - Type Semiconductor} \begin{cases} N_A^- >> N_D^+ \\ N_h >> N_e \end{cases} \end{array}}$$

- In this extreme, we assume that in an N-type all free electrons come from the Donor atoms and none from the covalent (valance band) bonds and the in a P-type all free holes are due only to ionization to the Acceptor atoms and not from the covalent bonds.
- This approximation leads to

$$\boxed{\begin{array}{l} \text{N - Type Semiconductor } \Rightarrow N_e \approx N_D^+ \\ \text{P - Type Semiconductor } \Rightarrow N_h \approx N_A^- \end{array}}$$

N and P-Type Semiconductors

- Using the equations we developed previously for carrier density assuming Maxwell-Boltzman distribution for the tails of the Fermi-Dirac statistics and referencing the valance band energy to 0eV and the conduction band energy to E_g we can write

$$\text{N - Type}\left\{ N_e \approx N_c \exp\left(-\frac{E_g - E_F}{\kappa_B T}\right) \approx N_D^+ \approx N_D\left[1 - \exp\left(1 + \frac{E_F - E_D}{\kappa_B T}\right)^{-1}\right]\right.$$

$$\text{P - Type}\left\{ N_h \approx N_c\left[1 - \exp\left(-\frac{E_g - E_F}{\kappa_B T}\right)\right] \approx N_A^- \approx N_A \exp\left(1 + \frac{E_A - E_F}{\kappa_B T}\right)^{-1}\right.$$

- Lest first assume that $\frac{E_F - E_D}{\kappa_B T} \Rightarrow -\infty$

$$N_e \approx N_c \exp\left(-\frac{E_g - E_F}{\kappa_B T}\right) \approx N_D^+ \approx N_D$$

$$N_c e^{-\frac{E_g}{\kappa_B T}} e^{\frac{E_F}{\kappa_B T}} = N_D$$

$$C e^{\frac{E_F}{\kappa_B T}} = N_D, \text{ where } C = N_c e^{-\frac{E_g}{\kappa_B T}}$$

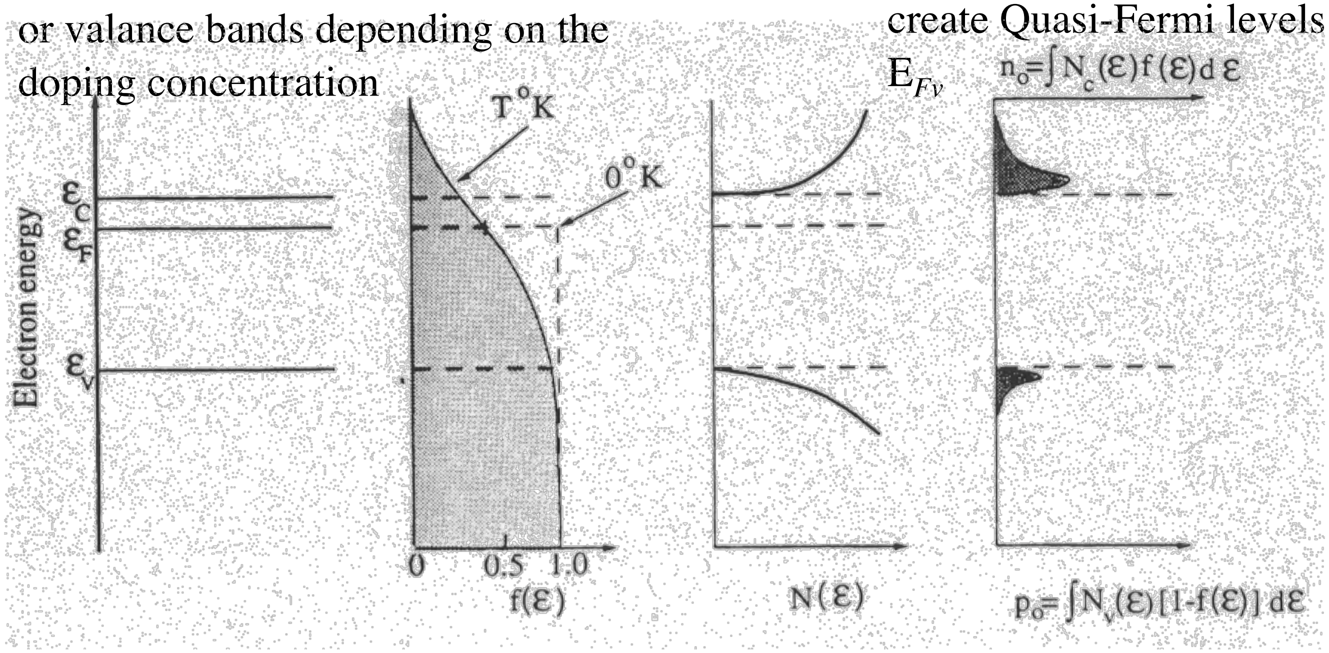
Note linear dependence on T and Ln dependence on N_D. N_D has small effect in this regime.

$$\left\{ E_F = \kappa_B T \ln\left(\frac{N_D}{C}\right) \right.$$

Extrinsic Semiconductors

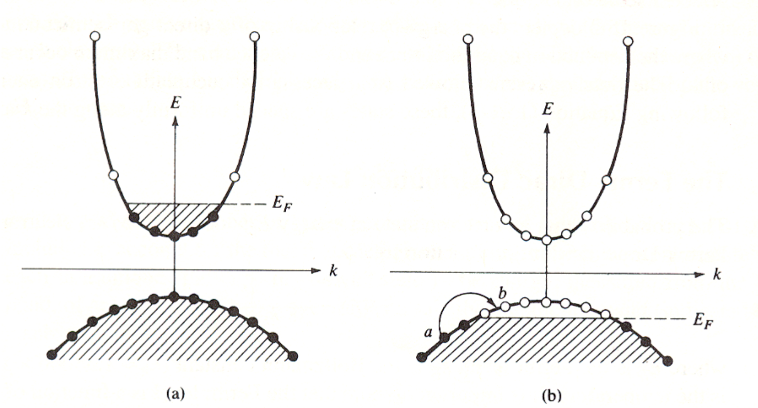
- Doping the semiconductor can move the Fermi level into the conduction or valance bands depending on the doping concentration

- Disturbing the SC from TE, for example with current injection, will create Quasi-Fermi levels E_{Fc} and E_{Fv}



Doping Influence on Fermi Level

- Doping the semiconductor can move the Fermi level into the conduction or valance bands depending on the doping concentration



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