- today we spend some effort to understand semiconductors - a highly important topic
- characterized by electrical conductivity that falls between insulators + conductors
- conductivity changes with "doping" concentration, and differently doped materials come together in heterojunctions to form electrical components like transistors
- let's look at the fourth column of the periodic table

C, Si, Ge, Sn

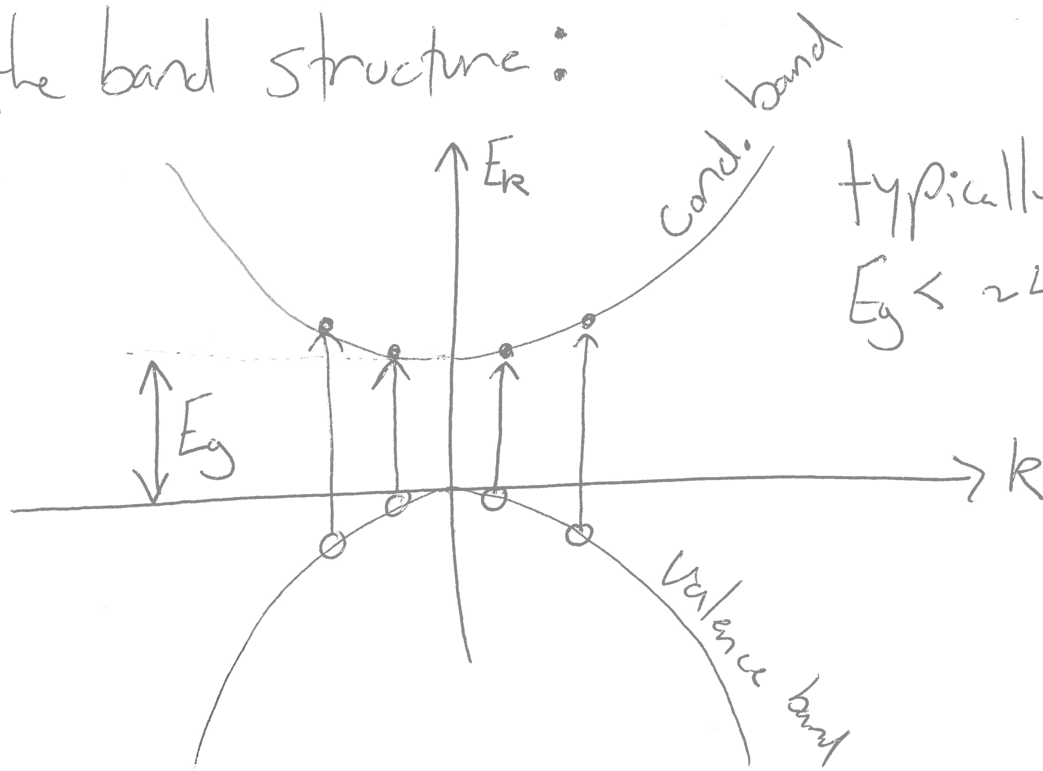
- Si + Ge are currently the most used for electronic applications
- all four elements crystalize in a diamond lattice with each atom surrounded by four atoms in a tetrahedron bound by covalent bonds

- that is, each atom has 4 valence electrons & bond formed is sp^3 hybrid orbital
- covalent bonds give rise to insulators @ 0K (abs. zero), which is interesting because higher T → higher conductivity, the total opposite of conductors
- another major group is the III-V compounds

GaAs, InSb, etc.

which form the zincblende → diamond w/ 2-atom basis

- Recall the band structure:



typically $E_g < \sim 4eV$

- We see why semi-conductors become better at conducting at higher temperatures → more thermal energy leads to more electrons moving from the valence to conduction bands

- basic band structure $E_v = -\frac{\hbar^2 k^2}{2m_h^*}$; v.b.

$$E_c = E_g + \frac{\hbar^2 k^2}{2m_e^*} \text{ ; c.b.}$$

$m_e^* \equiv$ effective mass of electron } will discuss
$m_h^* \equiv$ " " hole } later

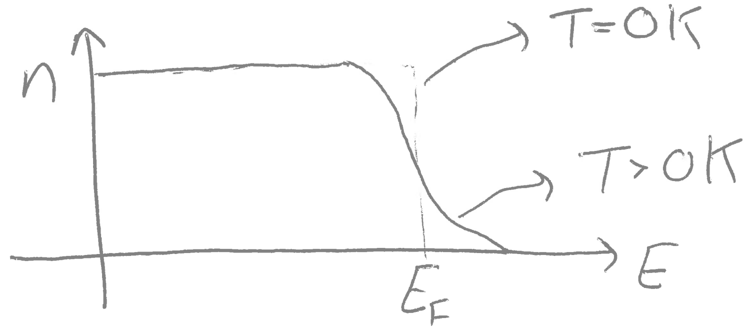
- a semiconductor's primary parameters are these effective masses & the band gap

e.g.

element	E_g (eV)	m_e^*/m_0	m_h^*/m_0
C	5.3	0.97	0.5
Si	1.1	1.6	0.3

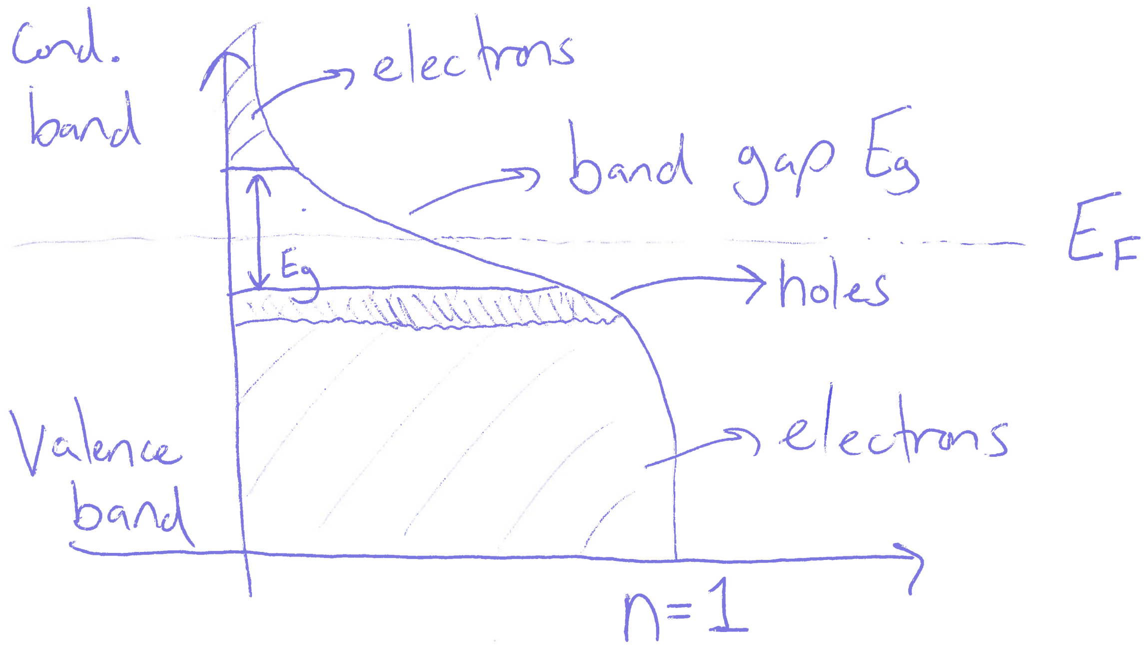
where m_0 is the electron mass

- the valence and conduction bands result from the bonding + anti bonding states in the sp^3 hybrid orbitals, respectively
- note that the mentioned band structure is simplified + in most cases is more complex
- recall once again the density of free electrons in that model



- the probability of finding an electron is temperature-dependent
- let's extend this idea to semiconductors, and note that we are swapping the axes for n + E, as is customary

→



- We see that the Fermi energy lies between the top of the V.b. edge + the bottom of the c.b. edge → indicative of a semiconductor

- let's see if we can approximate the # of electrons in the c.b. (also # of holes in V.b.)

- $$n = \int_{E_{c.b.}\,(\text{bottom})}^{E_{c.b.}\,(\text{top})} n(E)\, g_e(E)\, dE$$

  - integrate over all energies of c.b.

- Without the details, we get

$$n = 2\left(\frac{k_B T}{2\pi\hbar^2}\right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-E_g/2k_B T}$$

$$\propto e^{\left(-1/T\right)\left(E_g/k_B\right)}$$

- we find the probability is dominated by exponential term

- let $T \to 0$, $e^{-1/T} = e^{-1/0} = e^{-\infty} = 0$

- thus no electrons in c.b. (insulator)

- for $T \to \infty$, $e^{-1/T} = e^{-1/\infty} = e^{0} = 1$ which is not physical, but approaches all states in c.b. are full

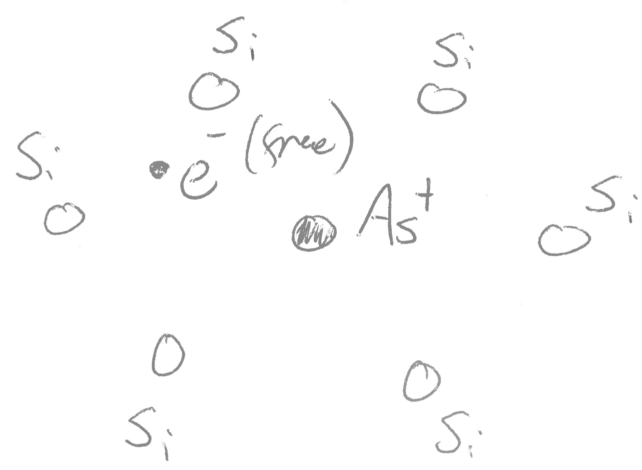
$\longrightarrow$

- "Intrinsic" semiconductors have equal amounts of electrons in c.b. + holes in v.b.
- what if we add impurities?
- take Si "doped" with As

As → penta-valent (5 valence e^-s)

Si → tetra-valent (4 valence e^-s)

- in 2D view



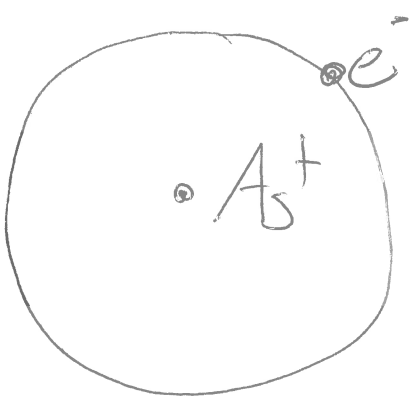
- 4 valence electrons are used in the tetrahedral bonds for each As atom, but one e^- is free to move about → goes into c.b.

- Therefore, higher concentrations of As in Si gives a higher # of electrons in c.b.

- donors that contribute an e^- are called "n-dopants"

- donors that contribut an h^+ (hole) are called "p-dopants"

- for our n-doped sample, the free electron forms bound states with positive As ion



$$V = \frac{e^2}{4\pi\epsilon r}$$

where $\epsilon \neq \epsilon_0$ is the permittivity