Last Time:

- carrier concentration
  - product of DOS and probability of occupation
  - DOS 3-D $\propto E^{1/2}$
  - occupation probability

    conservation of Energy + Equilibrium $\Rightarrow$ Boltzmann distribution

    + Pauli Exclusion principle $\Rightarrow$ Fermi-Dirac

This Time:

properties of F-D

carrier concentration, E_F "Fermi Energy"

doping

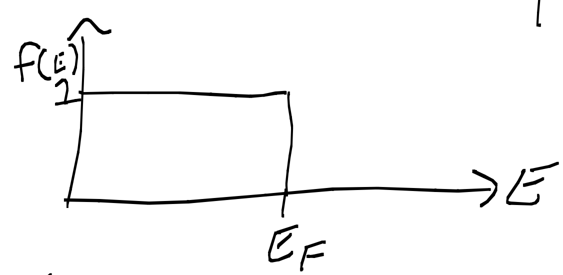
Fermi-Dirac Distribution:

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

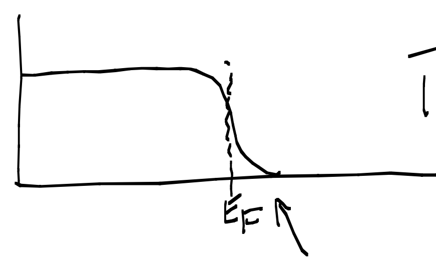
$\underline{T=0}$

$E-E_F>0$ $\quad \frac{1}{1+e^{+/0}} \sim \frac{1}{1+e^{\infty}} \Rightarrow 0$

$E-E_F<0$ $\quad \frac{1}{1+e^{-\infty}} \Rightarrow 1$



$\underline{T\neq 0}$



$$\frac{1}{1+e^{0/kT}} = \frac{1}{1+1} = \frac{1}{2}$$

~ Fermi-Dirac Applet

$\underline{(E-E_F) \gg kT}$

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

Boltzmann Distribution!!

Carrier Concentration for parabolic band in 3-D:

$$n = \int_0^\infty \left[\frac{2^{1/2} m^{3/2}}{\pi^2 \hbar^3} E^{1/2}\right] e^{-(E-E_F)/kT} \, dE = \int N(E) f(E) \, dE$$

$$= \frac{2^{1/2} m^{3/2}}{\pi^2 \hbar^3} e^{E_F/kT} \int_0^\infty E^{1/2} e^{-E/kT} \, dE \qquad x = E/kT, \quad dx = \frac{dE}{kT}$$

$$= \frac{2^{1/2} m^{3/2}}{\pi^2 \hbar^3} e^{E_F/kT} \int_0^\infty (x kT)^{1/2} e^{-x} \, kT \, dx$$

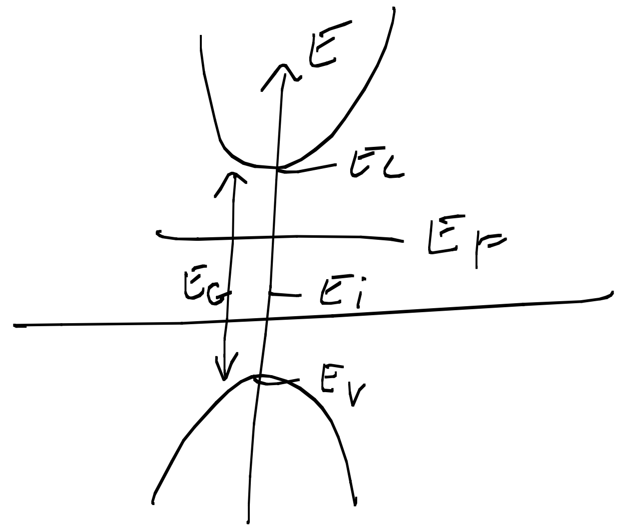
$$= (\qquad)(kT)^{3/2} \underbrace{\int_0^\infty x^{1/2} e^{-x} \, dx}_{\frac{\sqrt{\pi}}{2}}$$

$$= 2\left(\frac{kTm}{2\hbar^2 \pi}\right)^{3/2} e^{E_F/kT}$$

$$= 2\left(\frac{2\pi kTm}{h^2}\right)^{3/2} e^{E_F/kT} = \underbrace{2\left(\frac{2\pi kTm^*}{h^2}\right)^{3/2}}_{} e^{(E_F-E_c)/kT}$$

$$n = \underline{\underline{N_c}} \, e^{(E_F-E_c)/kT}$$

$$P = N_V e^{(E_V - E_F)/kT}$$



Fermi Energy Controls carrier concentration:

- "intrinsic", "extrinsic"

$\downarrow$ (intrinsic): $n_0 = p_0$

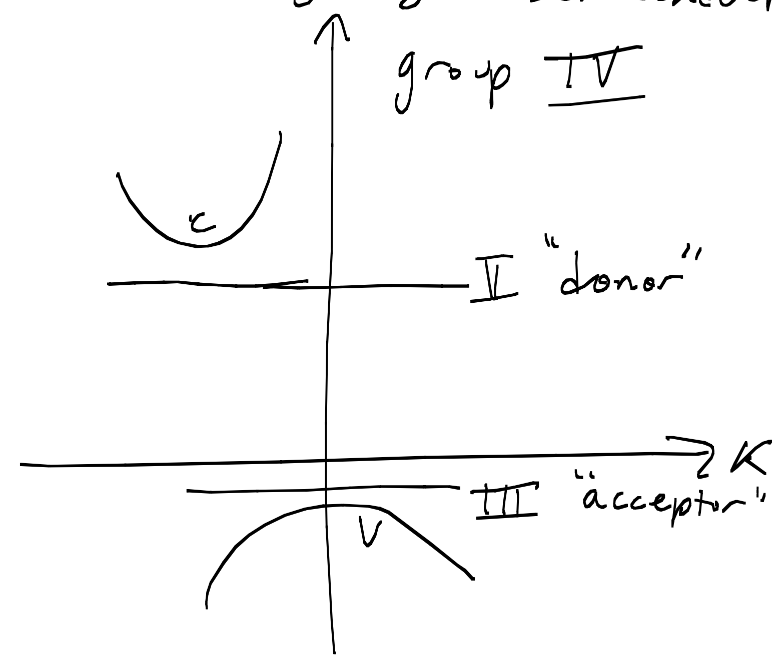
$E_F \sim$ middle of bandgap

$(N_c = N_v)$

$\downarrow$ (extrinsic): $n_0 \neq p_0$

E_F elsewhere

Si Semiconductor group IV



- Carrier Concentration Applet
- doping w/ impurities to control position of E_F $\rightarrow$ "compensation"

"Law of Mass action":

$$n_o = N_c e^{(E_F - E_c)/kT} \qquad p_o = N_v e^{(E_v - E_F)/kT}$$

$$n_o p_o = N_c N_v e^{-(E_c - E_v)/kT} = N_c N_v e^{-E_G/kT} = n_i^2$$

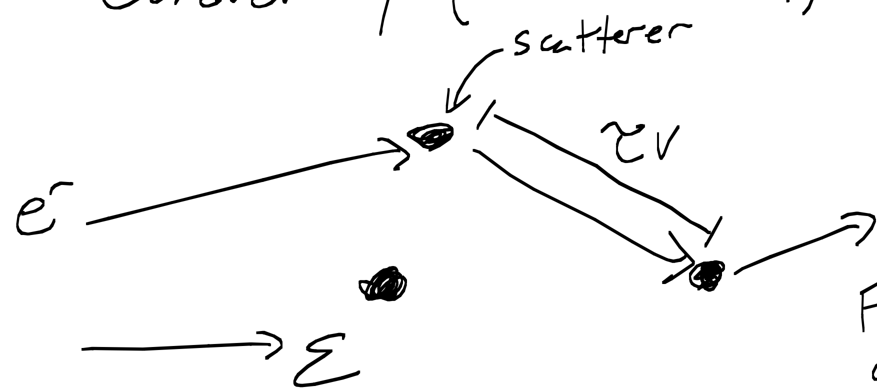
$$\boxed{n_o p_o = n_i^2}$$ "LoMA"

$$n_o = N_c e^{(E_F - E_c)/kT} e^{E_i/kT} e^{-E_i/kT} = N_c e^{(E_F - E_i)/kT} e^{(E_i - E_c)/kT}$$

$$= \underbrace{N_c e^{(E_i - E_c)/kT}} e^{(E_F - E_i)/kT}$$

$$\boxed{n_o = n_i e^{(E_F - E_i)/kT}}$$

"Drude" Conductivity (Section 3.4)



$F = ma$

$a = \frac{F}{m}$

$$J = nqv = nq\underbrace{a}\tau = nqq\frac{\mathcal{E}}{m^*}\tau = \left(\frac{nq^2\tau}{m^*}\right)\mathcal{E} = \sigma\mathcal{E}$$

$J = \sigma \mathcal{E}$ Ohm's Law

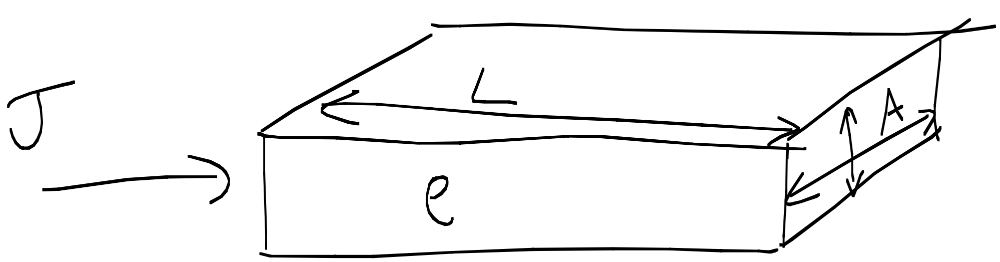
conductivity

Ohm's Law:

$$J = \sigma \mathcal{E} \qquad V = IR$$

$$J = \frac{I}{A} = \sigma \frac{V}{L}$$

$$V = \frac{L}{A\sigma} I = \left(\frac{L\rho}{A}\right) I = IR$$



Mobility

$$\sigma = \frac{nq^2\tau}{m^*} = nq\left(\frac{q\tau}{m^*}\right) = nq\mu$$

mobility

$$\mu = \frac{q\tau}{m^*} = \frac{\frac{q\tau\mathcal{E}}{m^*}}{\mathcal{E}} = \frac{v}{\mathcal{E}} = \frac{cm^2}{s \cdot V}$$

$$J = \sigma\mathcal{E} = nq\mu\mathcal{E}$$