B. Conductivity $\sigma = \frac{ne^2\tau}{m^*}$

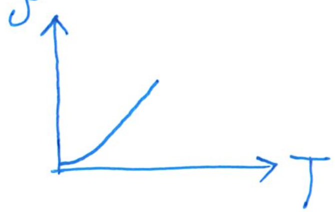
(a) Semiconductors are characterized by their sensitivity of σ to T

- Metals: n = constant (can't change by temperature)

  increasing temperature $\Rightarrow$ more scattering of electrons with phonons

  resistivity increases

  (less conducting)



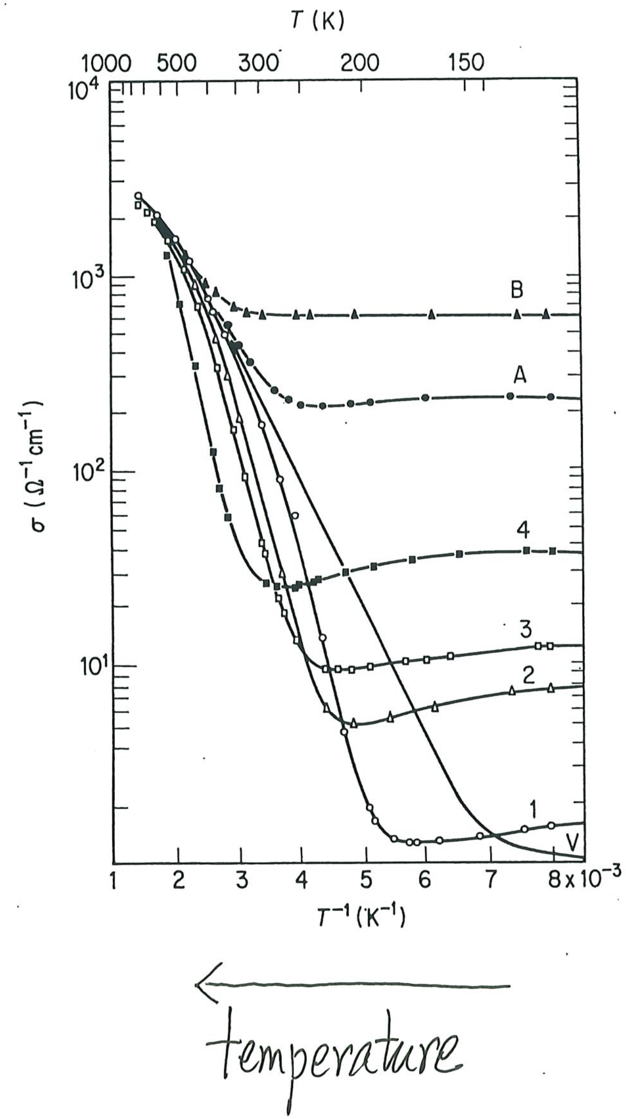
- Semiconductors:

  temperature $\nearrow$: increase charge carriers (ionizing impurities AND exciting electrons across the gap)

  $n(T)$ and $p(T)$ dominate

But electron-phonon & electron-impurity scattering lead to resistance

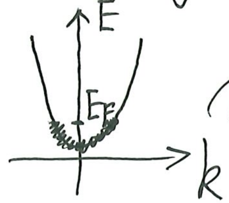
InSb

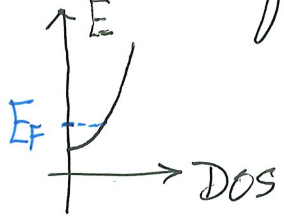


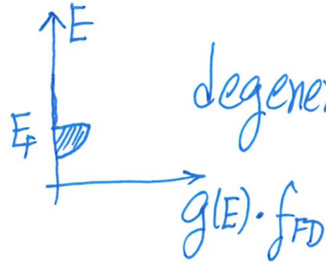
σ ~ grows exponentially with temperature when temperature is high enough (tails of Fermi-Dirac distribution) to increase n and p.
(mostly n(T) and p(T) effect)

σ has a flat region
n (and/or p) determined by donor (ionized) concentration (acceptor concentration)

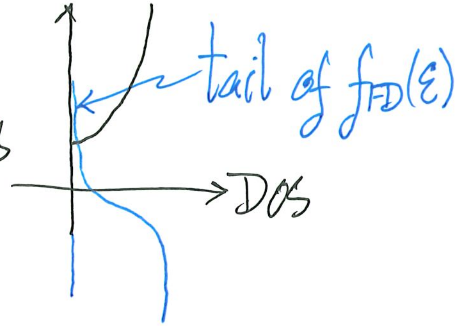
(b) τ due to scattering (collision) restores equilibrium

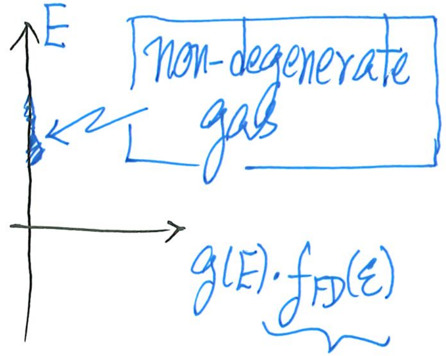
- Equilibrium : 

metals




degenerate Fermi gas

Semiconductors




$\underbrace{g(E) \cdot f_{FD}(\varepsilon)}$ $\approx$ Boltzmann factor

Either way : Equilibrium $\Rightarrow \vec{J} = 0$
no current

- $\vec{\mathcal{E}} \neq 0 \Rightarrow$ Steady Current $\vec{J} \propto \vec{\mathcal{E}} \Rightarrow \vec{J} = \underbrace{\sigma} \vec{\mathcal{E}}$

itself independent of $\vec{\mathcal{E}}$
(linear response, Ohm's Law)

Switch off $\vec{\mathcal{E}} \Rightarrow \vec{J}$ goes back to zero (almost instantly!)

$\therefore$ $\vec{\mathcal{E}} \neq 0$, out of equilibrium $\rightarrow f$ (non-equilibrium distribution)

$$\neq \begin{cases} \dfrac{1}{e^{(E-E_F)/kT}+1} & \text{(metals)} \\ \underbrace{e^{-(E-E_F)/kT}}_{\text{the tail}} & \text{(semiconductors)} \end{cases}$$

and f (non-equilibrium) gives finite $\vec{J}$

Key concept

Q: What is $f_{\text{non-equilibrium}}$?

Switching $\vec{\mathcal{E}}$ off, $\vec{J} \rightarrow 0$! How? Through collisions!

Back to: $\frac{d\vec{p}}{dt} = -e\vec{\mathcal{E}} - \frac{\vec{p}}{\tau}$ (saw $\vec{p} \propto \vec{\mathcal{E}}$)

$\vec{\mathcal{E}} = 0$, $\frac{d\vec{p}}{dt} = -\frac{\vec{p}}{\tau} \Rightarrow \vec{p}(t) = \vec{p}(0) \cdot e^{-t/\tau}$

$\vec{p}(0)$: when $\vec{\mathcal{E}}$ is switched off

$e^{-t/\tau}$: $\boxed{\text{goes to zero exponentially fast with time constant } \tau}$

$\Downarrow$

$\vec{p}$ back to equilibrium value of $\vec{p} = 0$ ($\vec{J} = 0$)

$\therefore$ $\boxed{\text{why } \tau \text{ is called the relaxation time}}$

- achieved equilibrium by electron scattering
- very quickly ($\tau \sim 10^{-13}$ s or $\tau \sim 10^{-14}$ s)
- $\boxed{\text{Argument \underline{doesn't need} specific mechanism to drive the system out of equilibrium!}}$

Work for $\vec{\mathcal{E}}$, $\vec{\nabla}T$, $\underbrace{\vec{\nabla}n(\vec{r}), \vec{\nabla}p(\vec{r})}_{\text{concentration gradients}}$ $(\vec{\nabla}\mu(\vec{r}))$

μ: chemical potential

$\left.\begin{array}{l}\vec{\nabla} n(\vec{r}) \\ \vec{\nabla} p(\vec{r})\end{array}\right\}$ lead to diffusion : Diffusion constants D_e, D_p

"Switch off" mechanism that maintain $\vec{\nabla} n(\vec{r})$ $\Rightarrow$ Diffusion Current $\rightarrow 0$

How? Through collisions!

$\vec{\mathcal{E}}$: $\vec{J} = \sigma \vec{\mathcal{E}}$ $\qquad$ $-\vec{\nabla} n(\vec{r})$: $\vec{J}_{diffusion} = e \overset{\boxed{\text{Diffusion Constant}}}{D_e} \underbrace{\left|\frac{dn}{dx}\right|}_{\text{stimulus}}$ $\qquad$ $\vec{J} = (-e) n (-\vec{\nabla} n)$

$= e n \mu_e \underbrace{\vec{\mathcal{E}}}_{\text{stimulus}}$

response (out of equilibrium) $\qquad$ response (out of equilibrium)

[turn off stimulation : Collisions work to restore equilibrium]

$\therefore$ τ goes into σ (and μ_e) $\qquad$ $\therefore$ τ goes into D_e

Expected : Relation between σ and D! (Einstein Relation)