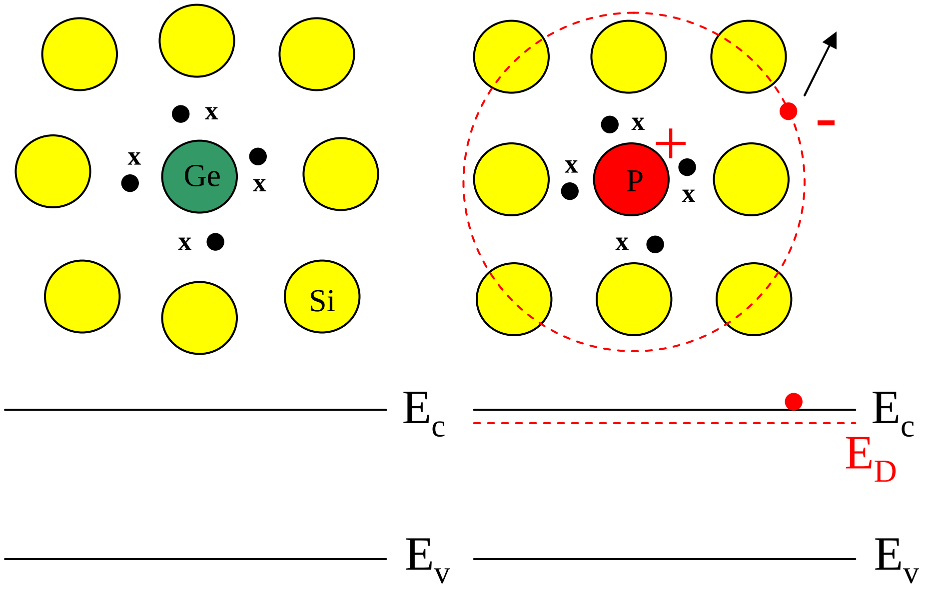
Extrinsic Semiconductors

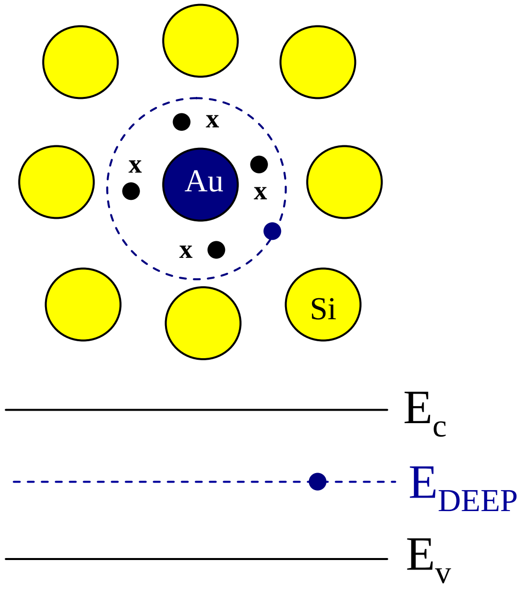
- Adding ‘correct’ impurities can lead to controlled domination of one carrier type
  - n-type is dominated by electrons
  - p-type if dominated by holes
- Adding other impurities can degrade electrical properties

Impurities with close electronic structure to host



isoelectronic *hydrogenic*

Impurities with very different electronic structure to host



deep level

Hydrogenic Model

- For hydrogenic donors or acceptors, we can think of the electron or hole, respectively, as an orbiting electron around a net fixed charge
- We can estimate the energy to free the carrier into the conduction band or valence band by using a modified expression for the energy of an electron in the H atom

$$E_n = \frac{me^4}{8\varepsilon_o^2 h^2 n^2} = -\frac{13.6}{n^2} \quad \text{(in eV)}$$

$$E_n = \frac{me^4}{8\varepsilon_o^2 h^2 n^2} \xrightarrow{\frac{e^2}{\varepsilon_r}=e^2} \frac{m^* e^4}{8\varepsilon_o^2 h^2 n^2}\frac{1}{\varepsilon_r^2} = -\frac{13.6}{n^2}\frac{m^*}{m}\frac{1}{\varepsilon^2}$$

- Thus, for the ground state n=1, we can see already that since ε is on the order of 10, the binding energy of the carrier to the center is <0.1eV
- Expect that many carriers are then thermalize at room T
- Experiment:
  - B acceptor in Si: .046 eV
  - P donor in Si: 0.044 eV
  - As donor in Si: 0.049

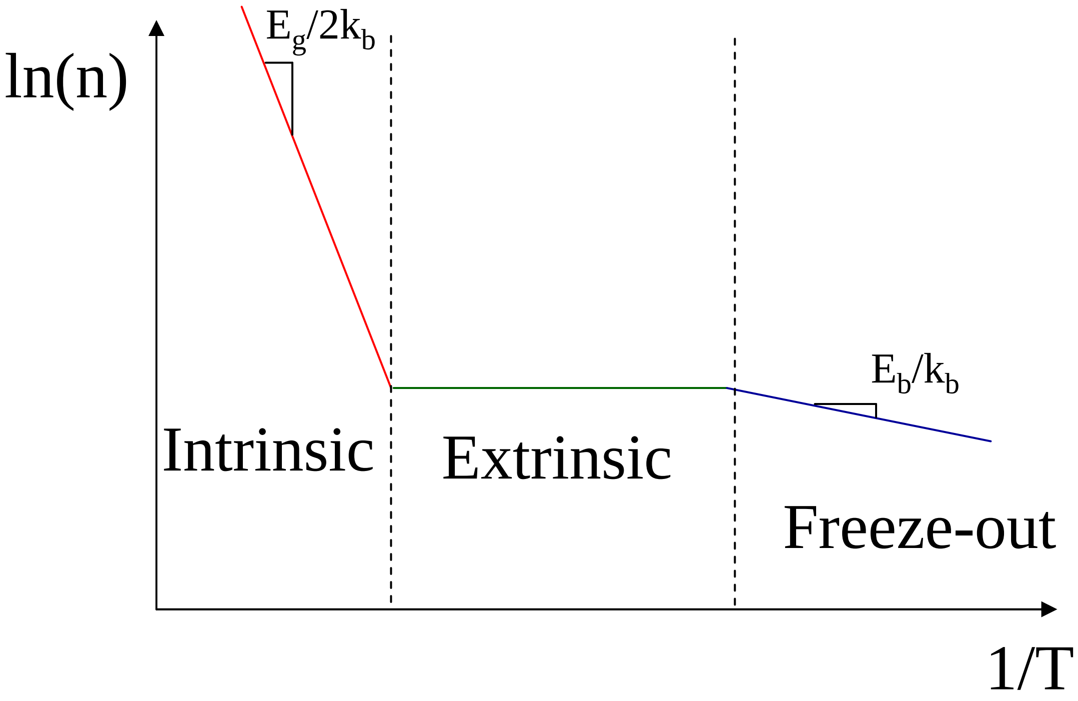
The Power of Doping

- Can make the material n-type or p-type: Hydrogenic impurities are nearly fully ionized at room temperature
  - n_i^2 for Si: $\sim 10^{20}\text{cm}^{-3}$
  - Add 10^{18}cm^{-3} donors to Si: $n \sim N_d$
  - $n \sim 10^{18}\text{cm}^{-3}$, $p \sim 10^2$ (n_i^2/N_d)
- Can change conductivity drastically
  - 1 part in 10^7 impurity in a crystal ($\sim 10^{22}\text{cm}^{-3}$ atom density)
  - $10^{22} * 1/10^7 = 10^{15}$ dopant atoms per cm^{-3}
  - $n \sim 10^{15}$, $p \sim 10^{20}/10^{15} \sim 10^5$
  - □ $\sigma/\sigma_i \sim (p+n)/2n_i \sim n/2n_i \sim 10^5$!

Impurities at the ppm level drastically change the conductivity
(5-6 orders of magnitude)

Expected Temperature Behavior of Doped Material (Example:n-type)

- 3 regimes



Contrasting Semiconductor and Metal Conductivity

$$\boxed{\sigma = \frac{ne^2\tau}{m}}$$

- Semiconductors
  - changes in n(T) can dominate over τ
  - as T increases, conductivity increases
- Metals
  - n fixed
  - as T increases, τ decreases, and conductivity decreases

General Interpretation of τ

- Metals and majority carriers in semiconductors
  - τ is the scattering length
  - Phonons (lattice vibrations), impurities, dislocations, and grain boundaries can decrease τ

$$\frac{1}{\tau}=\frac{1}{\tau_{phonon}}+\frac{1}{\tau_{impur}}+\frac{1}{\tau_{disl}}+\frac{1}{\tau_{gb}}+\ldots$$

$$\tau_i=\frac{l_i}{v_{th}}=\frac{1}{v_{th}\sigma_i N_i}$$

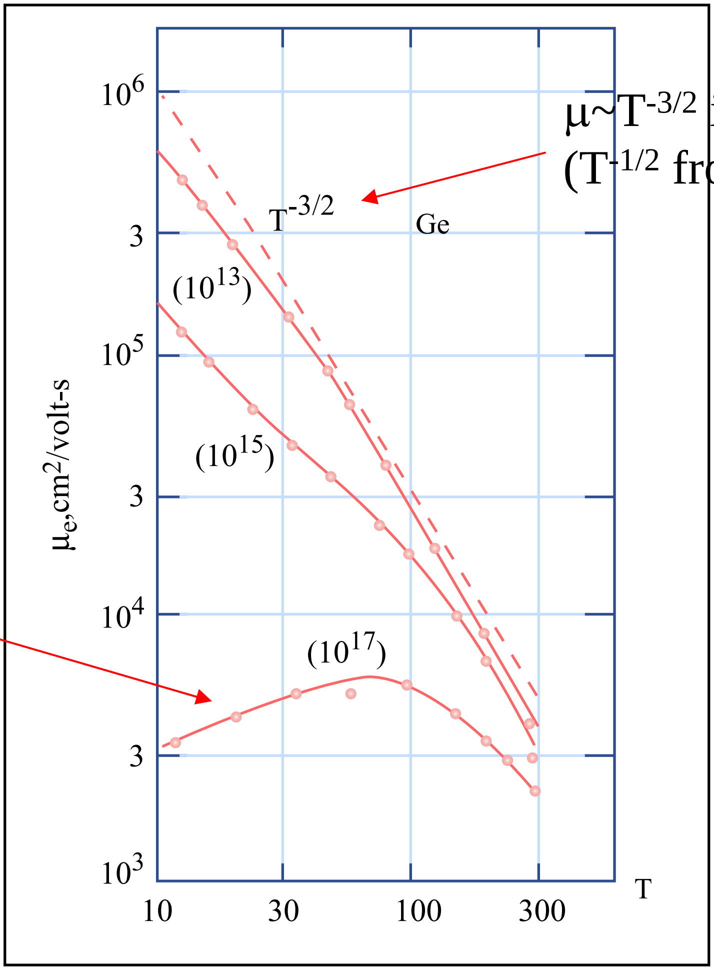
$$l_i\sigma_i N_i=1$$

where σ is the cross-section of the scatterer, N is the number of scatterers per volume, and l is the average distance before collisions

The mechanism that will tend to dominate the scattering will be the mechanism with the shortest l (most numerous), unless there is a large difference in the cross-sections

Example: Si transistor, τ_{phonon} dominates even though τ_{impur} gets worse with scaling

Example: Electron Mobility in Ge



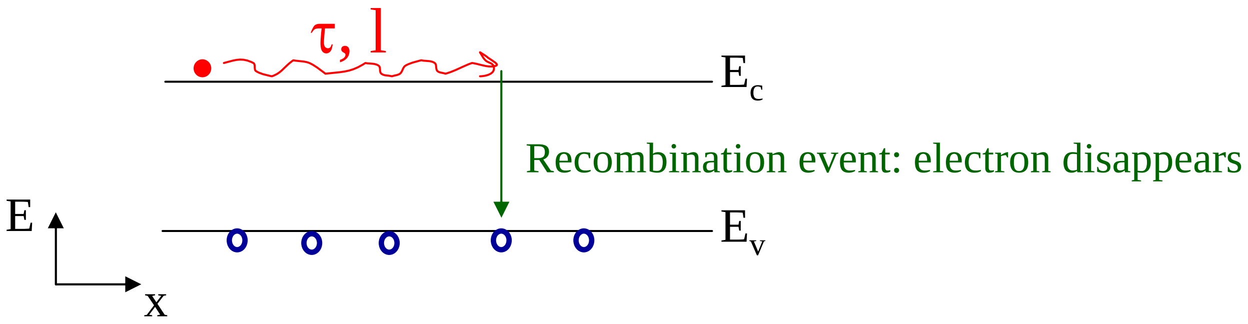
$\mu \sim T^{-3/2}$ if phonon dominated
($T^{-1/2}$ from vth, T^{-1} from x-section σ

At higher doping, the ionized donors are the dominate scattering mechanism

Figure by MIT OpenCourseWare.

Other Interpretation of τ

- Minority carriers in semiconductors
  - can think of τ as the time to recombination: recombination time
  - does not affect Drude model in any way



Imagine p-type material, so there are many more holes than electrons

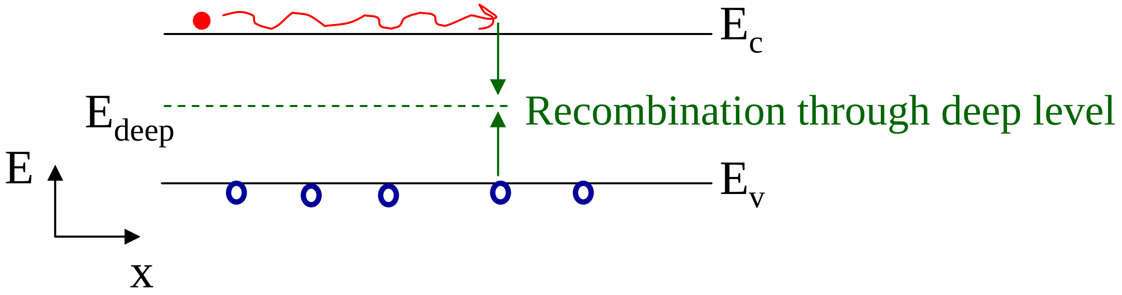
holes=majority carrier

electrons=minority carrier

τ is referred to in this context as the minority carrier lifetime

Other Recombination Pathways

- Deep levels in semiconductors act as carrier traps and/or enhanced recombination sites



- Barrier to capture carrier is $E_g/2$
- Since the probability of the carrier transition is $\sim e^{-\Delta E/kT}$, trapping a carrier with a deep state is very probable
- A trapped carrier can then help attract another carrier, increasing recombination through the deep state

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{intrinsic}}} + \frac{1}{\tau_{deep}}$$

Recombination and Generation (E_c to E_v)

- Generation
  - intrinsic: photon-induced or thermally induced, G=#carriers/vol.-sec
  - extrinsic:deep levels due to traps
  - G_o is the *equilibrium* generation rate
- Recombination
  - intrinsic: across band gap, R=# carriers/vol.-sec
  - extrinsic: deep levels due to traps
  - R_o is the equilibrium recombination rate, which is balanced by G_o

<u>Non-equilibrium intrinsic recombination</u>

n-type material

$$R = \frac{\Delta p}{\tau_h};\ \tau_\mathrm{h} = \frac{p_o}{R_o}$$

Where p_o is the equilibrium minority carrier concentration

p-type material

$$R = \frac{\Delta n}{\tau_e};\ \tau_\mathrm{e} = \frac{n_o}{R_o}$$

Where n_o is the equilibrium minority carrier concentration

<u>Non-equilibrium extrinsic recombination</u>

$$R = \frac{\Delta p}{\tau_h} \qquad \tau_h = \frac{1}{\sigma_h v_{th} N_t}$$

Where σ_h is the capture cross section for holes and N_t is the concentration of recombination centers

$$R = \frac{\Delta n}{\tau_e} \qquad \tau_e = \frac{1}{\sigma_e v_{th} N_t}$$