Physics of Electronics:

6. Semiconductors

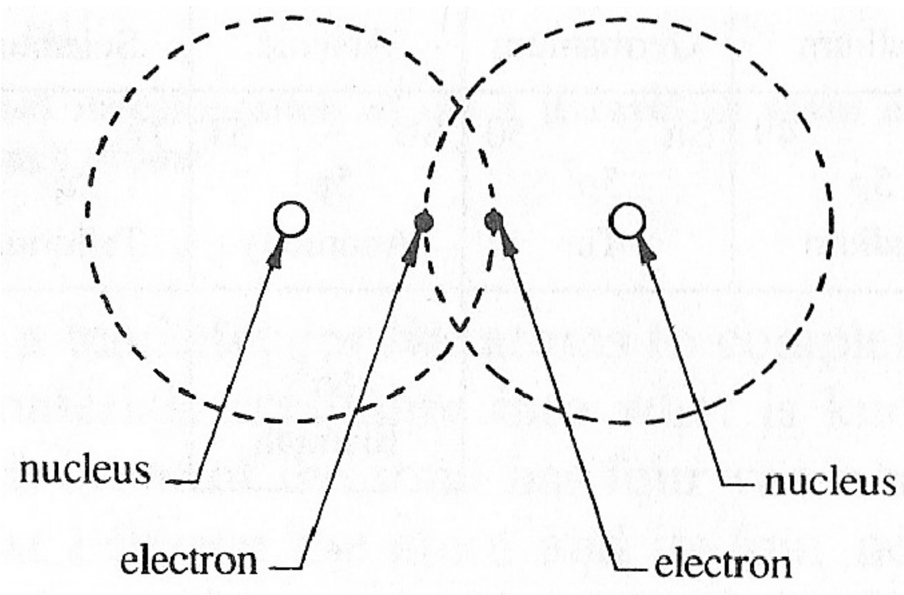
July – December 2009

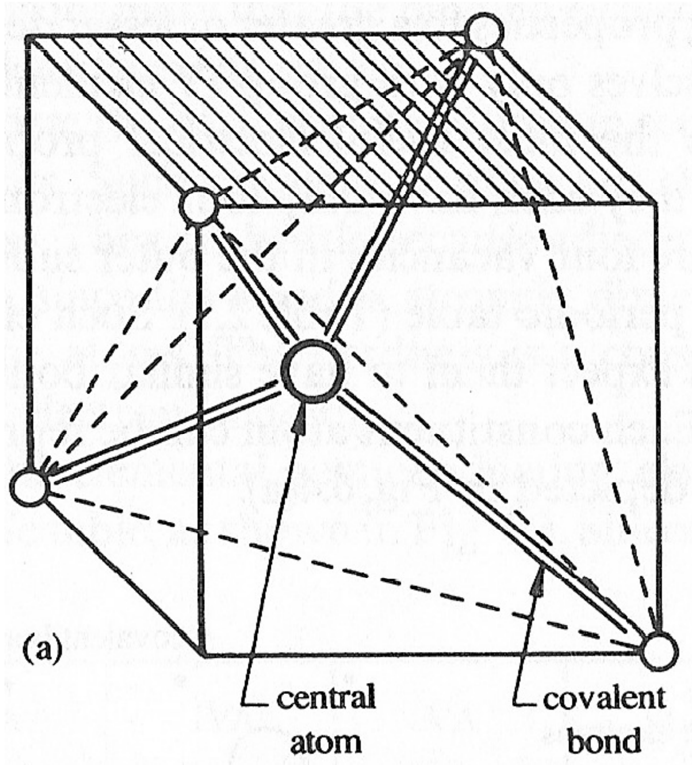
Contents overview

- Crystal structure of semiconductors.
- Conduction processes in semiconductors.
- Density of carriers in intrinsic semiconductors.
- Extrinsic semiconductors.
- Electron processes in real semiconductors.

Covalent Bond

- Valence electrons are shared
  - Among atoms that have unfilled shells
  - Example: hydrogen molecule

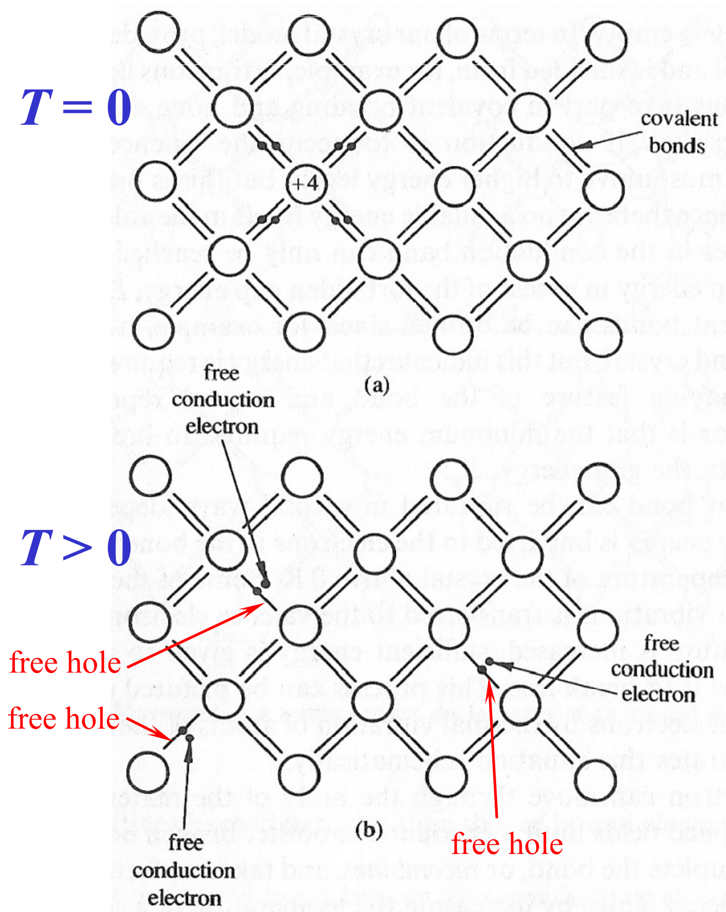




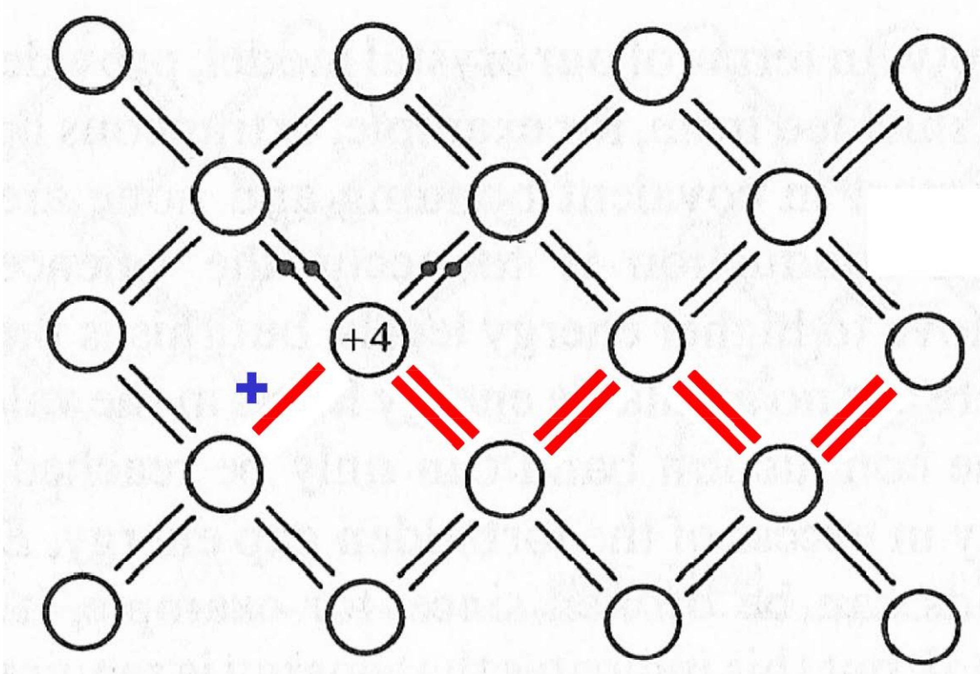
Conduction Processes

- Vacancies:

Electrons and holes are created at $T > 0$:

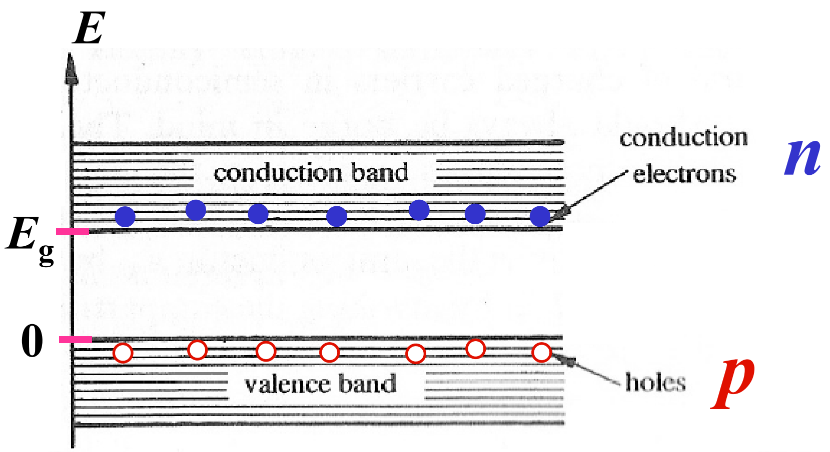


Electrons (m_e^*) and holes (m_h^*) move independently in an external field. Pictorially for holes we have:



Density of Carriers in Intrinsic sC

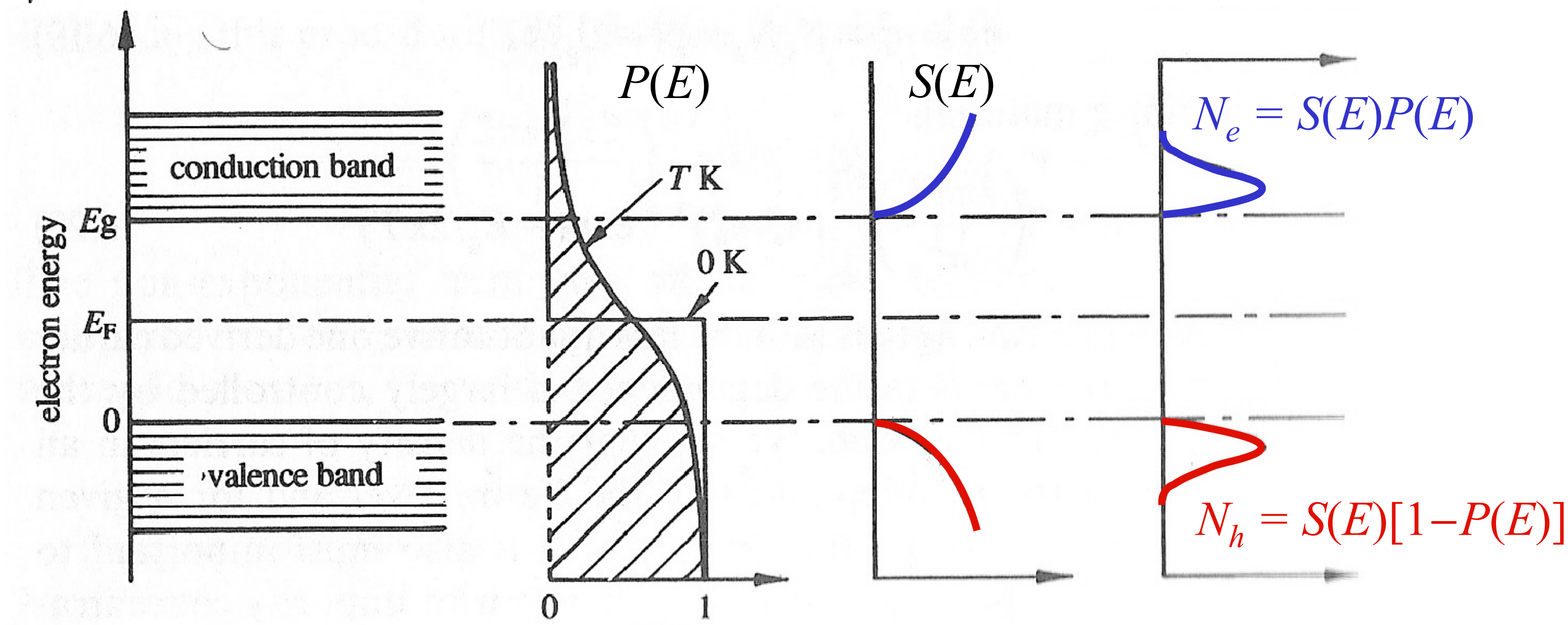
- Concentration of conduction electrons:



$$n = \int_{\text{conduction band}} S(E)P(E)\,dE$$

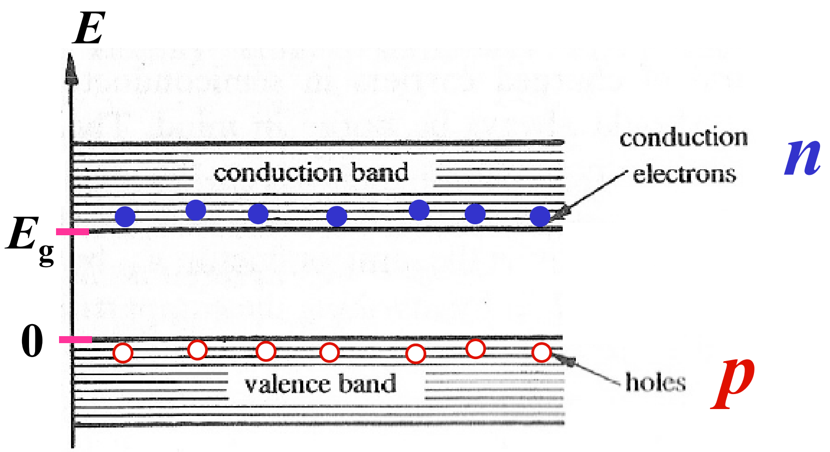
density of states

probability of occupation



Density of Carriers in Intrinsic sC

- Concentration of conduction electrons:



$$n = \int_{\text{conduction band}} S(E)P(E)\,\mathrm{d}E$$

density of states

probability of occupation

Density of states for free electrons: $S(E) = \dfrac{\left(8\sqrt{2}\right)\pi m^{3/2}}{h^3} E^{1/2}$

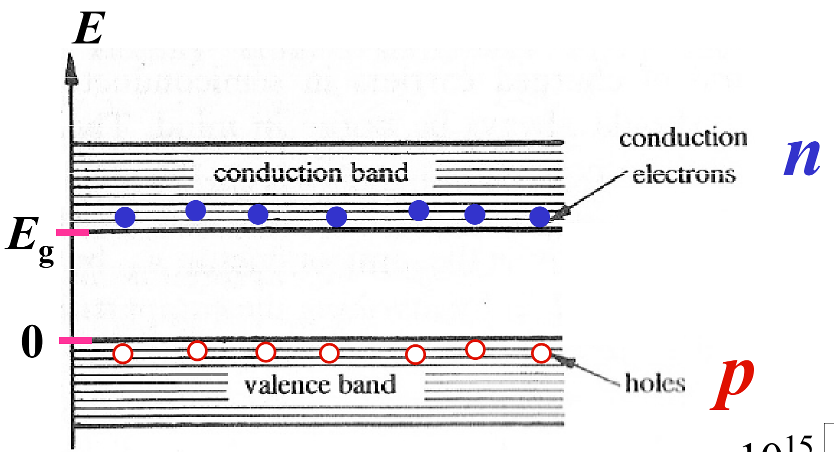
For conduction electrons in a crystal: $S(E) = \dfrac{\left(8\sqrt{2}\right)\pi m^{*3/2}}{h^3} \left(E - E_g\right)^{1/2} = C\left(E - E_g\right)^{1/2}$

$$\Rightarrow\quad n = C\int_{E_g}^{\infty} \frac{(E-E_g)^{1/2}\,\mathrm{d}E}{1+\exp[(E-E_F)/kT]} \quad \xrightarrow{E-E_F>>kT} \quad n \simeq C\int_{E_g}^{\infty} (E-E_g)^{1/2}\exp[-(E-E_F)/kT]\,\mathrm{d}E$$

$$\Rightarrow\quad n = 2\underbrace{\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}}_{N_c} \exp[-(E_g - E_F)/kT]$$

Density of Carriers in Intrinsic sC

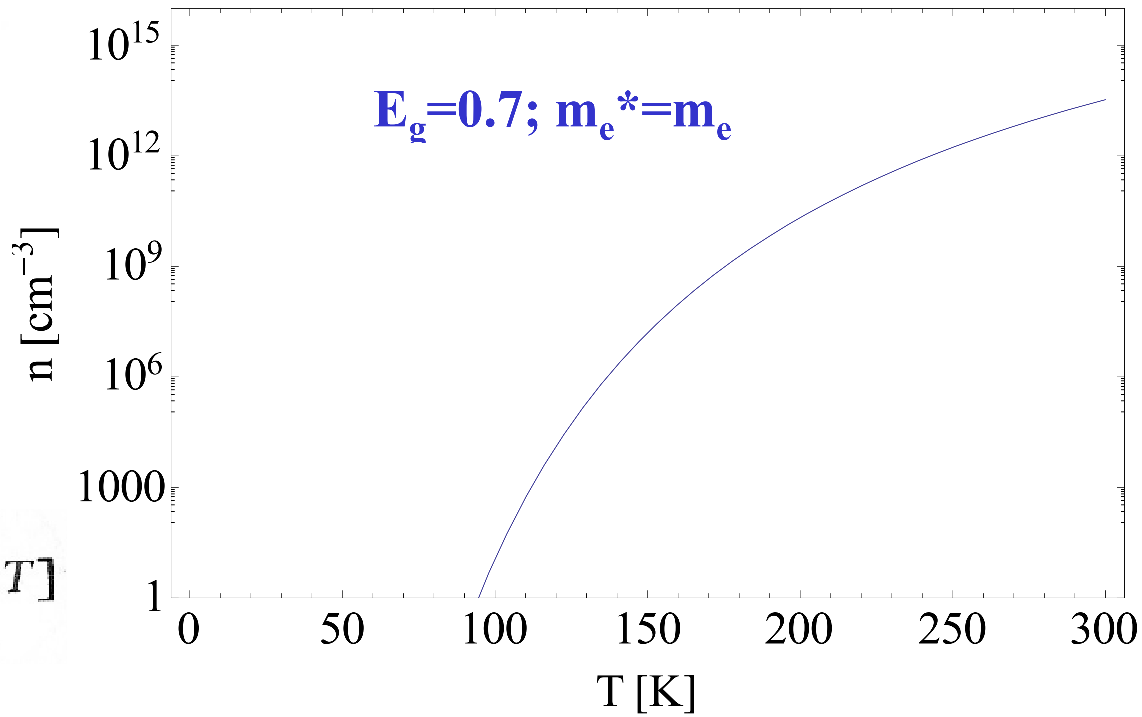
- Concentration of conduction electrons:



$$n = \int_{\text{conduction band}} S(E) P(E) \, dE$$

density of states

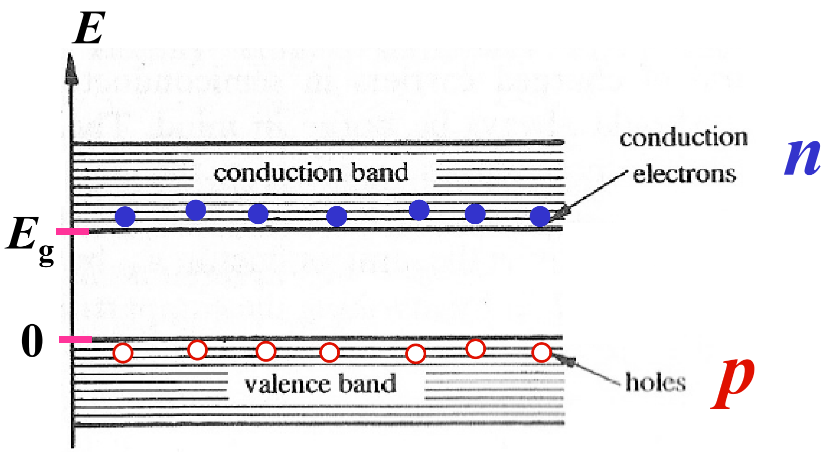
probability of occupation



$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \exp[-(E_g - E_F)/kT]$$

Density of Carriers in Intrinsic sC

- Concentration of holes:



$$p = \int_{\text{valence band}} S_h(E) P_h(E)\,\mathrm{d}E$$

$$P_h(E) = 1 - P(E) = 1 - \frac{1}{1+\exp[(E-E_F)/kT]} = \frac{\exp[-(E_F-E)/kT]}{1+\exp[-(E_F-E)/kT]}$$

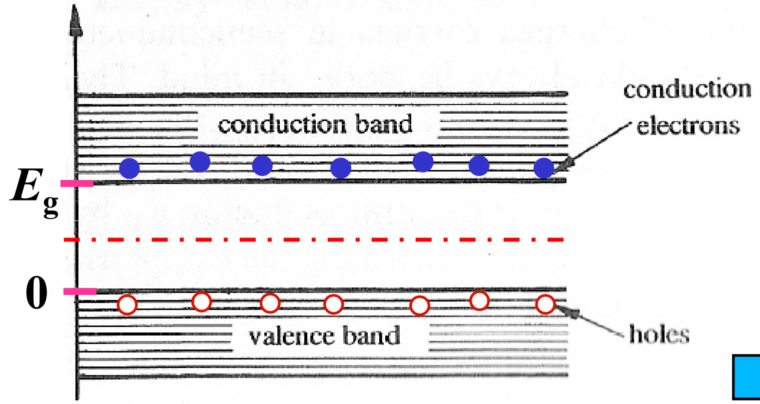
$$S(E) = \frac{(8\sqrt{2})\pi (m_h^*)^{3/2}}{h^3}(-E)^{1/2}$$

$E\text{-}E_F >> kT$

$$p = 2\underbrace{\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}}_{N_v} \exp(-E_F/kT)$$

Density of Carriers in Intrinsic sC

- Intrinsic density:



$$n = p = n_i$$

From previous results:

$$np = n_i^2 = N_c N_v \exp(-E_g/kT)$$

$$\boxed{n_i = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/4} \exp(-E_g/2kT)}$$

This is also valid for impurity sc's

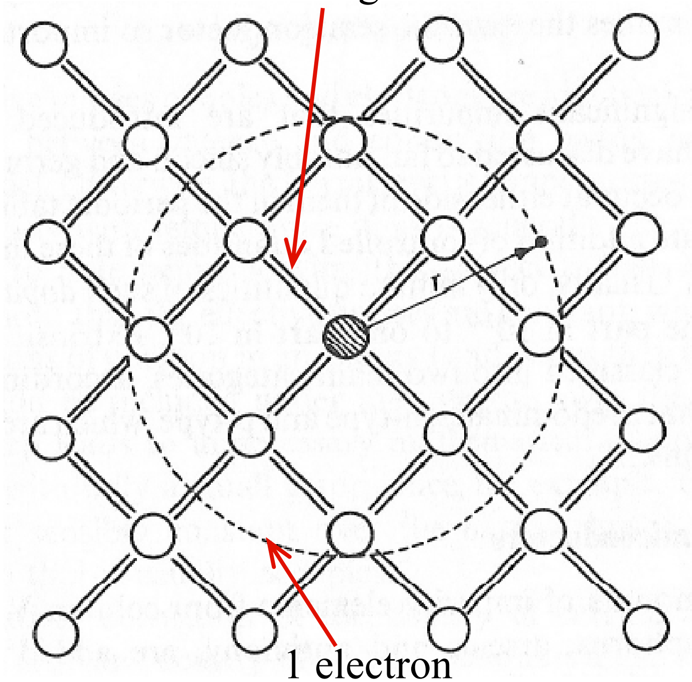
- Fermi level:

$$n = p \;\Rightarrow\; (m_e^*)^{3/2} \exp[-(E_g - E_F)/kT] = (m_h^*)^{3/2} \exp(-E_F/kT)$$

$$\Rightarrow\; \boxed{E_F = \tfrac{1}{2}E_g - \tfrac{3}{4}kT\log(m_e^*/m_h^*)} \;\xrightarrow{m_e^* = m_h^*}\; E_F = E_g/2$$

Extrinsic or Impurity sC

- They are obtained by adding tri/pentavalent impurities (1 part in 10^{10} to 1 part in 10^3).
- n-type semiconductors (pentavalent impurities)



We have a hydrogen type atom:

$$r_H = \frac{h^2 \varepsilon_0}{\pi e^2 m_e} = 0.05\,\text{nm} \qquad E_H = -\frac{m_e e^4}{8\varepsilon_0^2 h^2} = -13.6\,\text{eV}$$

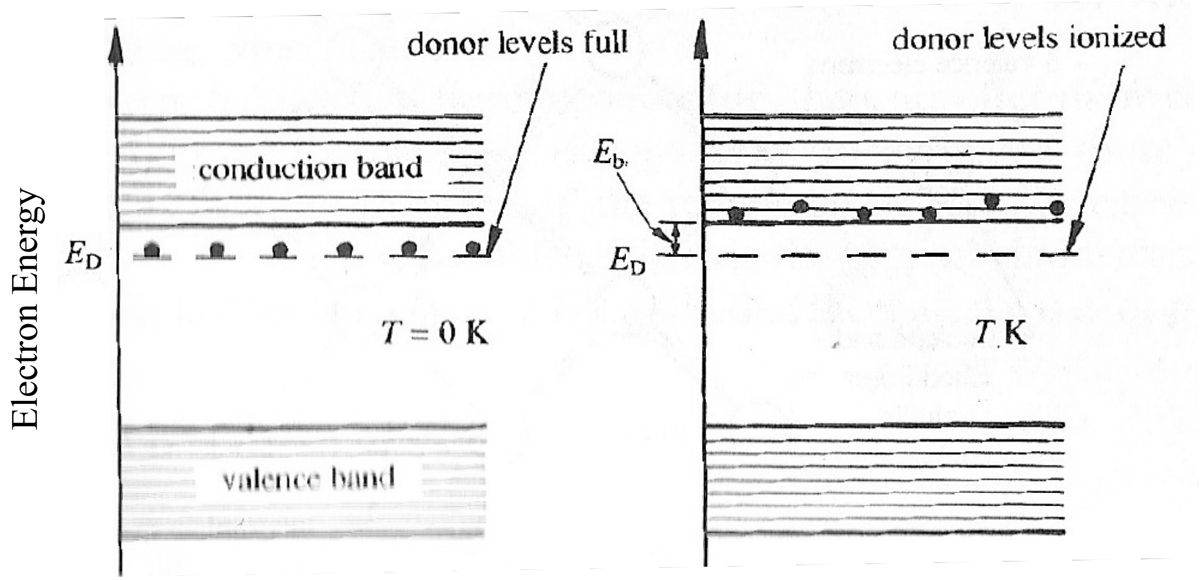
$$r_b = \frac{h^2 \varepsilon_r \varepsilon_0}{\pi e^2 m_e^*} = \varepsilon_r \left(\frac{m_e}{m_e^*}\right) r_H \qquad E_b = -\frac{m_e^* e^4}{8\varepsilon_r^2 \varepsilon_0^2 h^2} = -\frac{E_H}{\varepsilon_r^2}\left(\frac{m_e^*}{m_e}\right)$$

For germanium: $m_e^* = 0.6 m_e \quad \epsilon_r = 16$

$r_b = 1.4\,\text{nm} \qquad E_b = -0.03\,\text{eV}$

Extrinsic or Impurity sC

- n-type semiconductors (pentavalent impurities)
  - Band structure

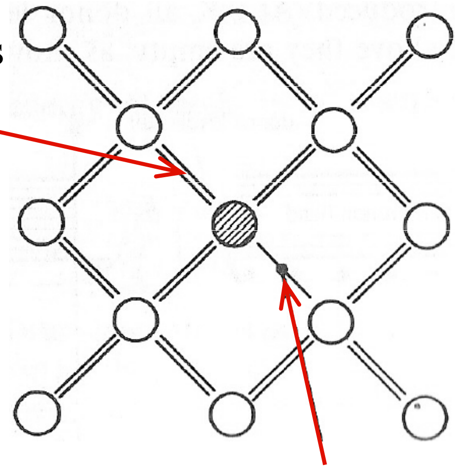


  - Density of conduction electrons. Example: germanium
    - Intrinsic $E_g = 0.75\,\text{eV}$, $T = 300$ K $\Rightarrow$ $n_i = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2}(m_e^* m_h^*)^{3/4}\exp(-E_g/2kT) = 10^{19}\,\text{m}^{-3}$ minority carriers
    - Extrinsic density = 10^{28} atom/m3, doping = 1 ppm $\Rightarrow$ $n_e = 10^{22}$ m^{-3} majority carriers

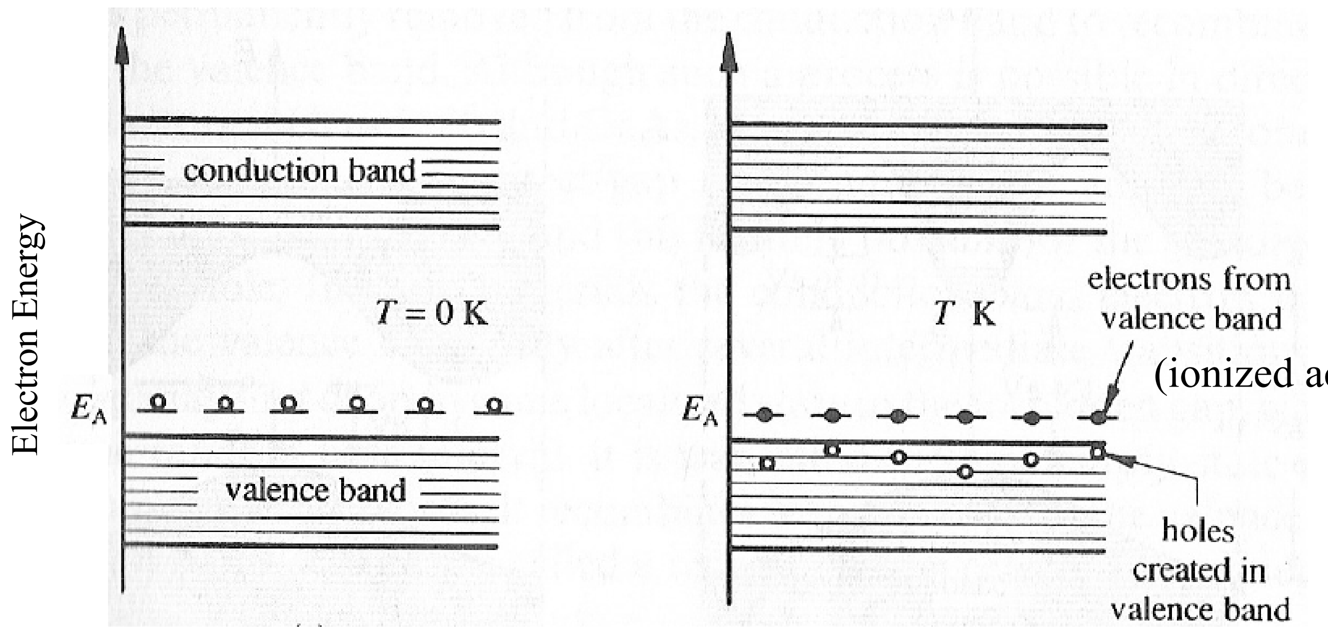
Extrinsic or Impurity sC

- p-type semiconductors (trivalent impurities)

All 3 electrons participate in bonding



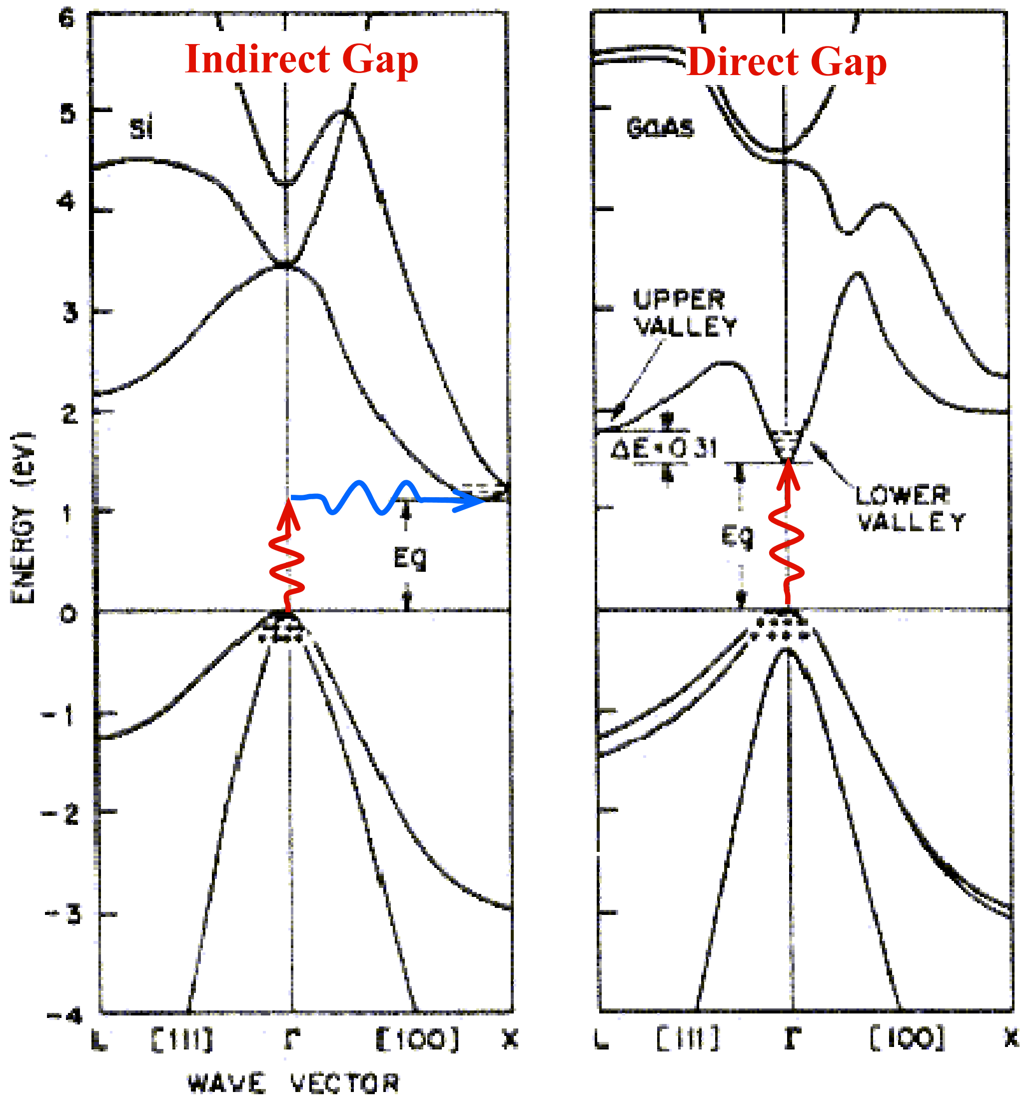
The incomplete bond can, at $T > 0$, be filled creating a hole in the valence band.



Electron Processes in Real sC

- Direct and indirect gap sC

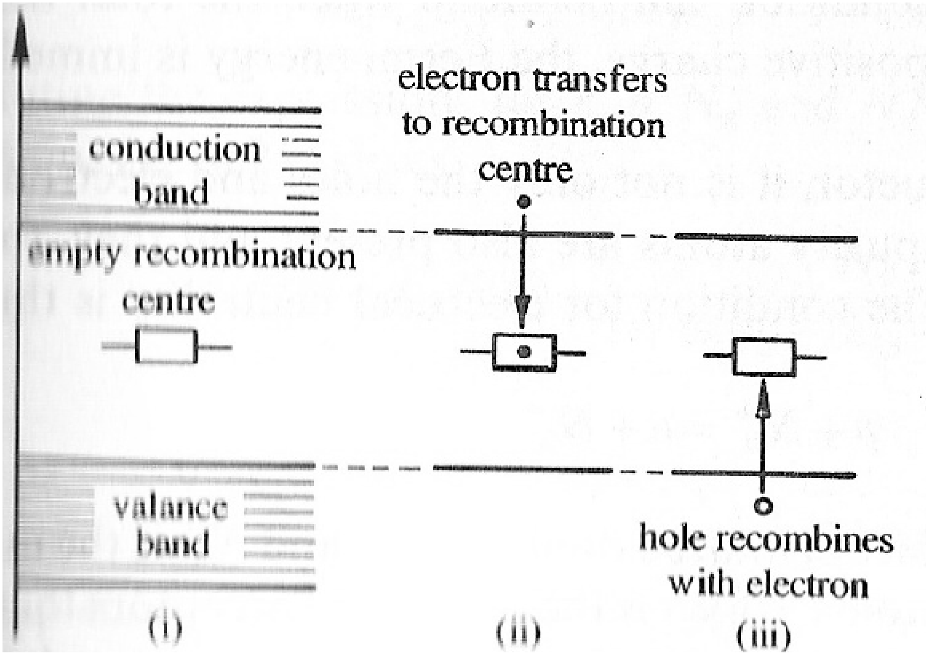
The minimum separation cannot be reached optically.



The minimum separation can be reached optically (by means of a photon).

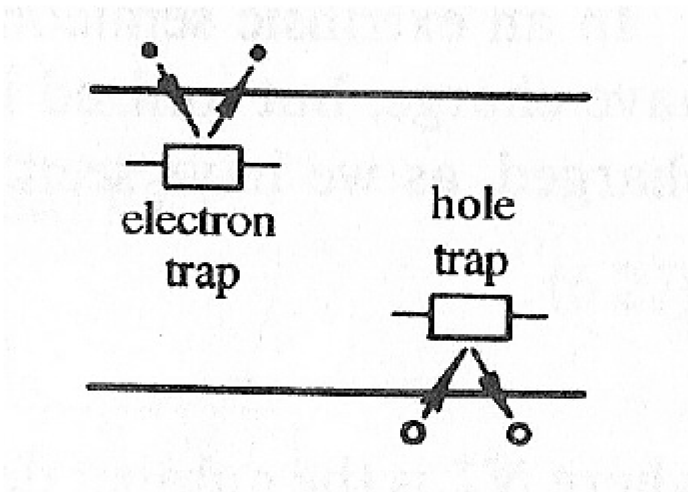
Electron Processes in Real sC

- Recombination
  - Permanent loss of a carrier.
  - Due to conservation of momentum
    - Possible in direct-gap sC's.
    - Marginally probable in indirect-gap sC's. Intermediate steps are required.



Electron Processes in Real sC

- Trapping
  - Temporary removal of a carrier on localized states



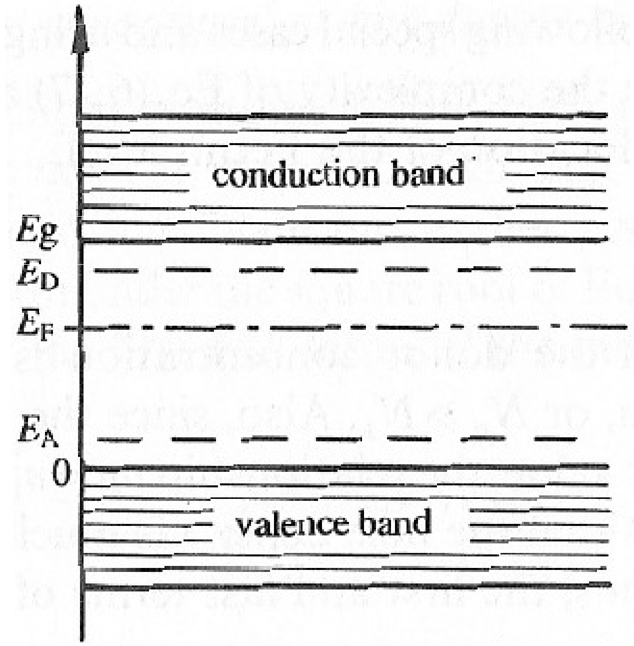
- Localized states
  - Lattice defects (dislocations, vacancies).
  - Impurities.

Density of carriers in extrinsic sC

- Consider a sC with donors and acceptors.
- How does EF change?
  - Electrical neutrality

$$p + N_d^+ = n + N_a^-$$

  - Concentration holes and electrons:



$$p = N_v \exp(-E_F/kT) \qquad n = N_c \exp[-(E_g - E_F)/kT]$$

  - Concentration of ionized impurities:

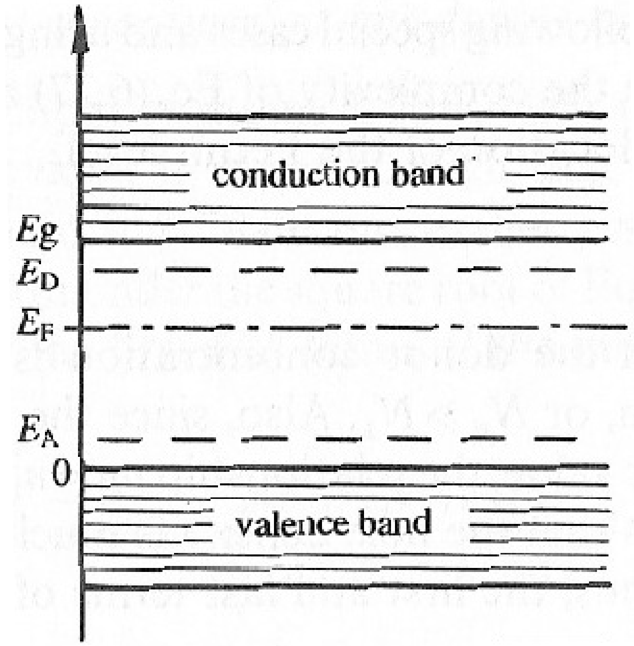
ionized impurities = impurity concentration × prob. finding e/h at the imp. level

$$N_a^- = \frac{N_a}{1+\exp[(E_A - E_F)/kT]} \qquad \& \qquad N_d^+ = N_d\left(1 - \frac{1}{1+\exp[(E_D - E_F)/kT]}\right)$$

Density of carriers in extrinsic sC

- Consider a sC with donors and acceptors.
- How does EF change?
  - Electrical neutrality

$$p + N_d^+ = n + N_a^-$$

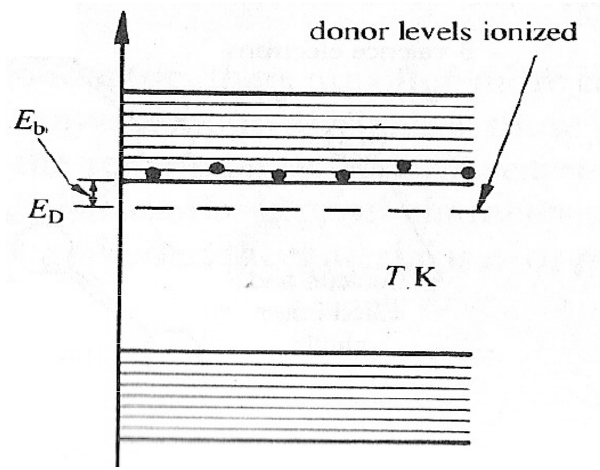


$$N_v \exp(-E_F/kT) + \frac{N_d}{1+\exp[-(E_D - E_F)/kT]} = N_c \exp[-(E_g - E_F)/kT] + \frac{N_a}{1+\exp[(E_A - E_F)/kT]}$$

From where E_F can be obtained

Density of carriers in extrinsic sC

- n-type material:
  - $N_d >> N_a$ & $n >> p$



$$\Rightarrow \quad \cancel{p}^{\,0} + N_d^+ = n + \cancel{N_a^-}^{\,0}$$

$$\Rightarrow \quad \exp[-(E_D+E_g)/kT]\exp(2E_F/kT)+\exp(-E_g/kT)\exp(E_F/kT)-N_d/N_c=0$$

$$\Rightarrow \quad \exp(E_F/kT)=\frac{-1+\{1+(4N_d/N_c)\exp[(E_g-E_D)/kT]\}^{1/2}}{2\exp(-E_D/kT)}$$

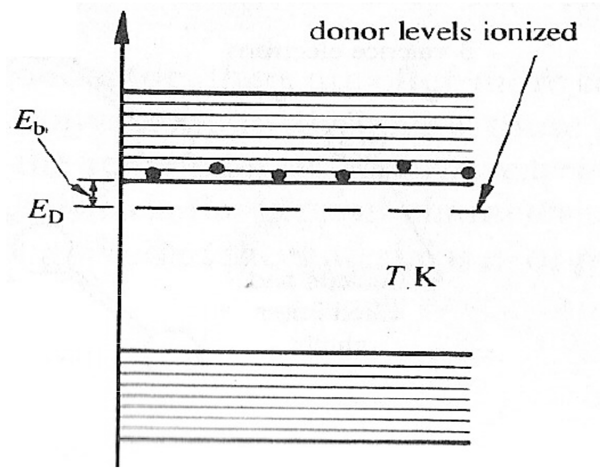
  - T low ($\exp[(E_D-E_g)/kT] >> 1$) OR N_d large ($N_d/N_c >> 1$)

$$\Rightarrow \quad \exp(E_F/kT)\simeq\frac{2(N_d/N_c)^{1/2}\exp[(E_g-E_D)/2kT]}{2\exp(-E_D/kT)} \quad \Rightarrow \quad \boxed{E_F=\tfrac{1}{2}(E_g+E_D)+\tfrac{1}{2}kT\log(N_d/N_c)}$$

$$\Rightarrow \quad \boxed{n=(N_dN_c)^{1/2}\exp[(E_D-E_g)/2kT]\propto N_d^{1/2}}$$

Density of carriers in extrinsic sC

- n-type material:
  - $N_d >> N_a$ & $n >> p$



$$\Rightarrow \quad \cancel{p}^{\,0} + N_d^+ = n + \cancel{N_a^-}^{\,0}$$

$$\Rightarrow \quad \exp[-(E_D+E_g)/kT]\exp(2E_F/kT) + \exp(-E_g/kT)\exp(E_F/kT) - N_d/N_c = 0$$

$$\Rightarrow \quad \exp(E_F/kT) = \frac{-1+\{1+(4N_d/N_c)\exp[(E_g-E_D)/kT]\}^{1/2}}{2\exp(-E_D/kT)}$$

  - T high ($\exp[(E_D-E_g)/kT] << 1$) OR N_d low ($N_d/N_c << 1$)

$$\Rightarrow \exp(E_F/kT) = \frac{-1+1+(4N_d/2N_c)\exp[(E_g-E_D)/kT]}{2\exp(-E_D/kT)} \Rightarrow \boxed{E_F = E_g - kT\log(N_c/N_d)}$$

$$\Rightarrow \quad \boxed{n = N_c\exp(-E_g/kT)(N_d/N_c)\exp(E_g/kT) = N_d}$$

Conclusions

- An crystal model for sC was introduced:
  - Electron form the covalent bonds.
  - Once broken, those electron are free to conduct.
  - Behind the electron, a hole is formed.
  - The energy necessary to break the bond is E_g.
- The density of electrons and holes was calculated.
- Extrinsic sC are created by adding impurities:
  - Donors (extra electrons) and acceptors (extra holes).
- Electron processes in sC were qualitatively studied.