Physics of Electronics:

5. Semiconductors

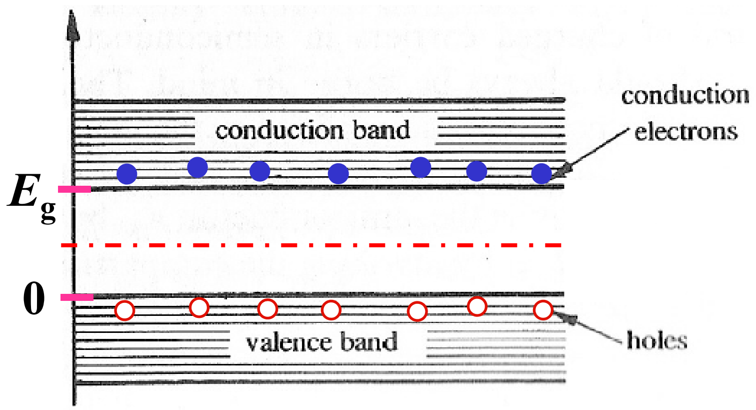
July – December 2009

Contents overview

- Density of carriers in intrinsic semiconductors.
- Density of carriers in extrinsic semiconductors.
- Compensation doping.
- Electrical conduction in semiconductors.
- Continuity equation.
- Semiconductor measurements.

Density of Carriers in Intrinsic sC

- Concentration of conduction electrons:



$$n = \int_{\text{conduction band}} S(E)P(E)\,dE = N_C \exp\left[-\left(E_g - E_F\right)/kT\right]$$

$$p = \int_{\text{valence band}} S_h(E)P_h(E)\,dE = N_V \exp\left[-E_F/kT\right]$$

$$n = p = n_i$$

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

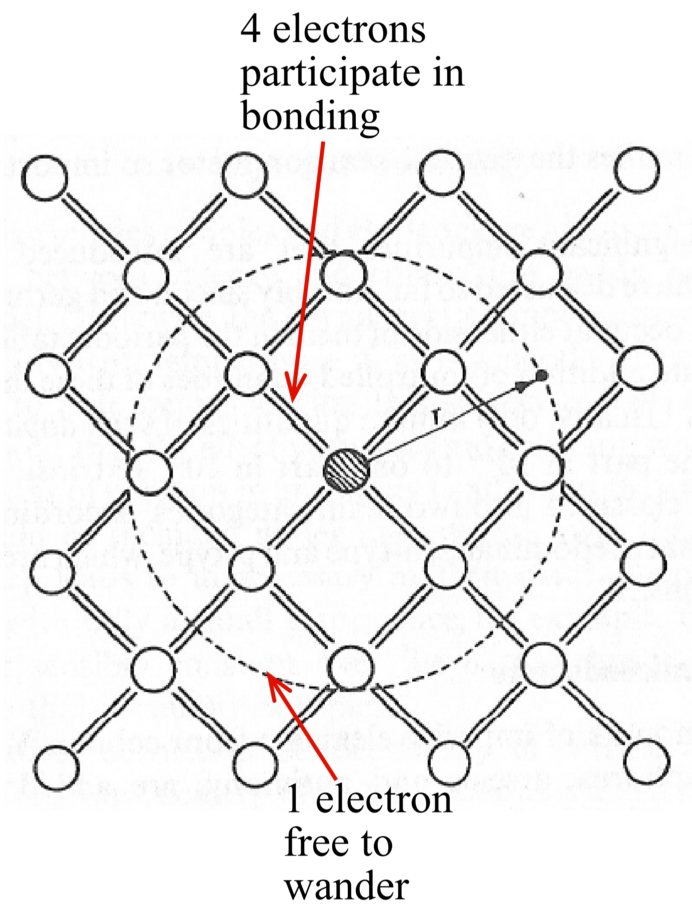
$$E_F = \tfrac{1}{2}E_g - \tfrac{3}{4}kT\log(m_e^*/m_h^*)$$

Extrinsic or Impurity sC

Donors

n-type semiconductors

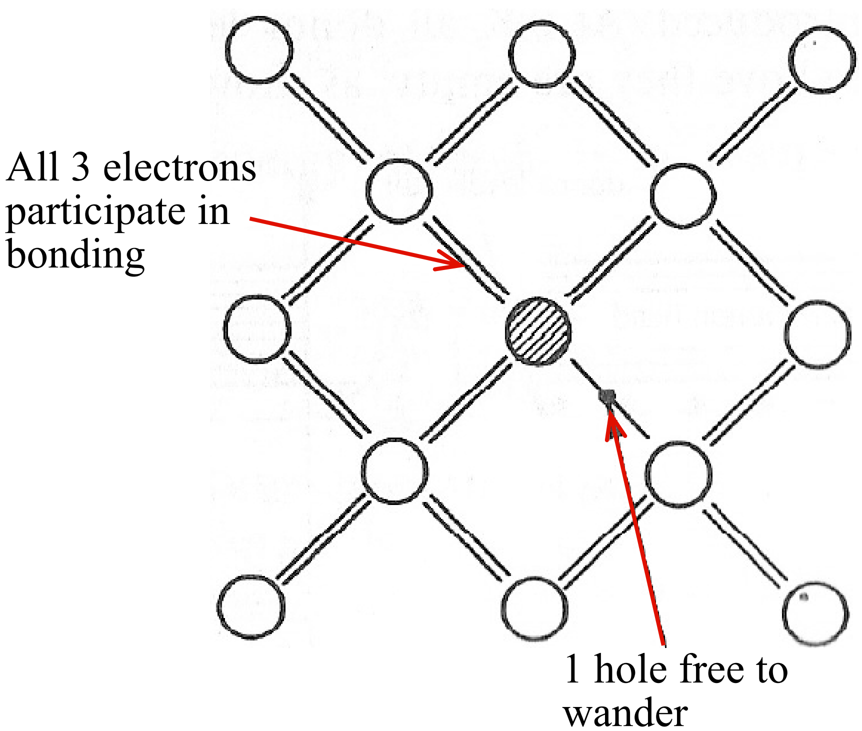
(pentavalent impurities)



Acceptors

p-type semiconductors

(trivalent impurities)

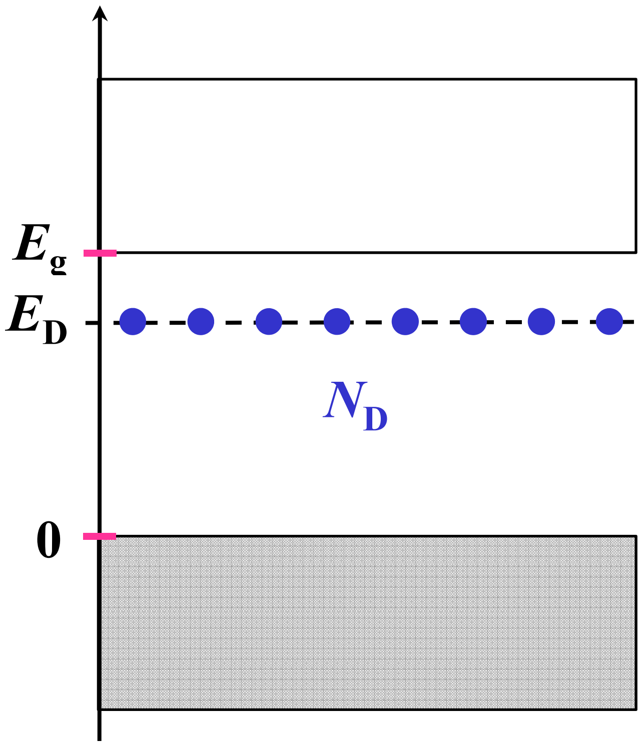


Extrinsic or Impurity sC

Donors

n-type semiconductors

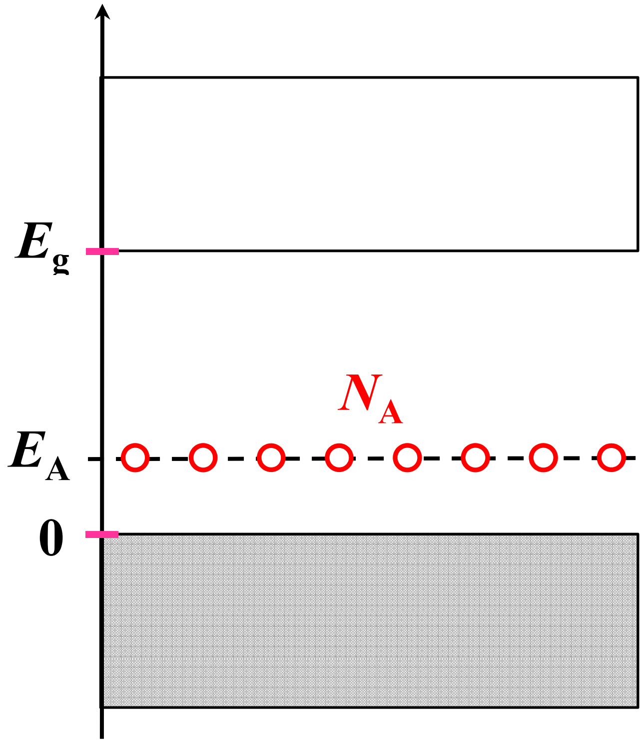
(pentavalent impurities)



Acceptors

p-type semiconductors

(trivalent impurities)



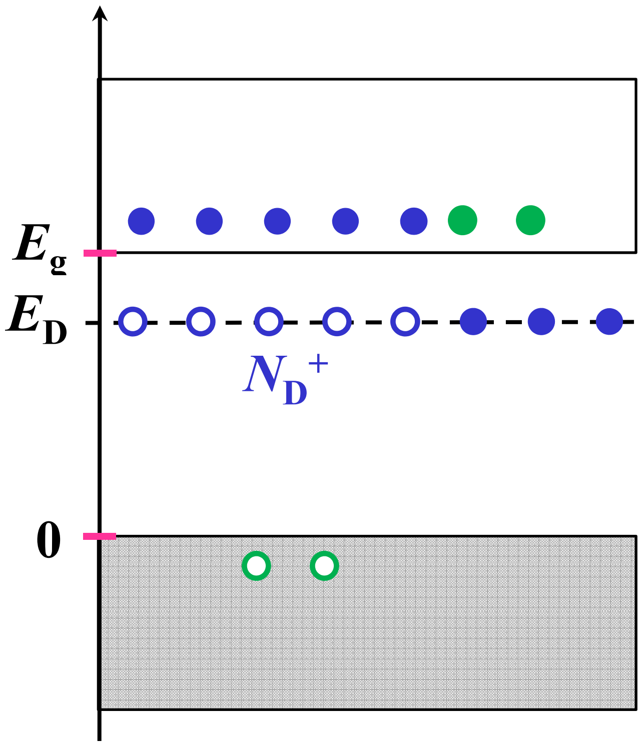
$T = 0$

Extrinsic or Impurity sC

Donors

n-type semiconductors

(pentavalent impurities)

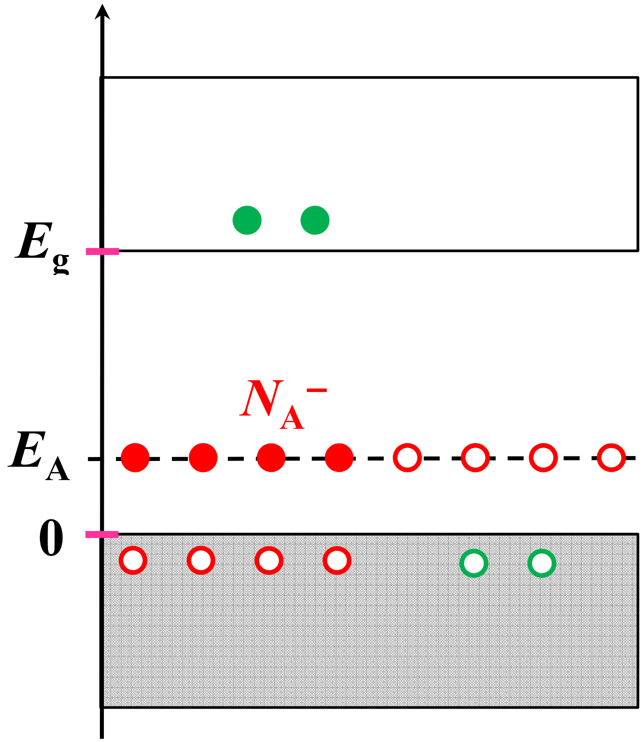


Acceptors

p-type semiconductors

(trivalent impurities)

$T > 0$



Density of carriers in extrinsic sC

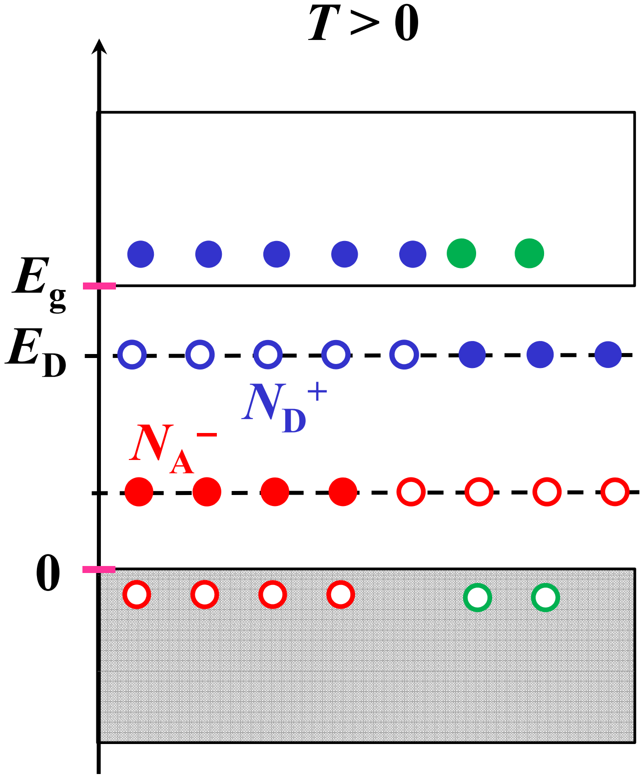
- Consider a sC with donors and acceptors.
- How does EF change?
  - Electrical neutrality

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

$$n = N_C \exp\left[-\left(E_g - E_F\right)/kT\right] \quad p = N_V \exp\left[-E_F/kT\right]$$

$$N_a^- = \frac{N_a}{1+\exp[(E_A - E_F)/kT]}$$

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



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

Density of carriers in extrinsic sC

- Special cases (details left as homework)
  - n-type material ($N_d >> N_a$ & $n >> p$)

$$\overset{0}{\cancel{p}} + N_d^+ = n + \overset{0}{\cancel{N_a^-}} \Rightarrow \exp(E_F/kT) = \frac{-1 + \{1 + (4N_d/N_c)\exp[(E_g - E_D)/kT]\}^{1/2}}{2\exp(-E_D/kT)}$$

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

$$E_F = \tfrac{1}{2}(E_g + E_D) + \tfrac{1}{2}kT\log(N_d/N_c)$$

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

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

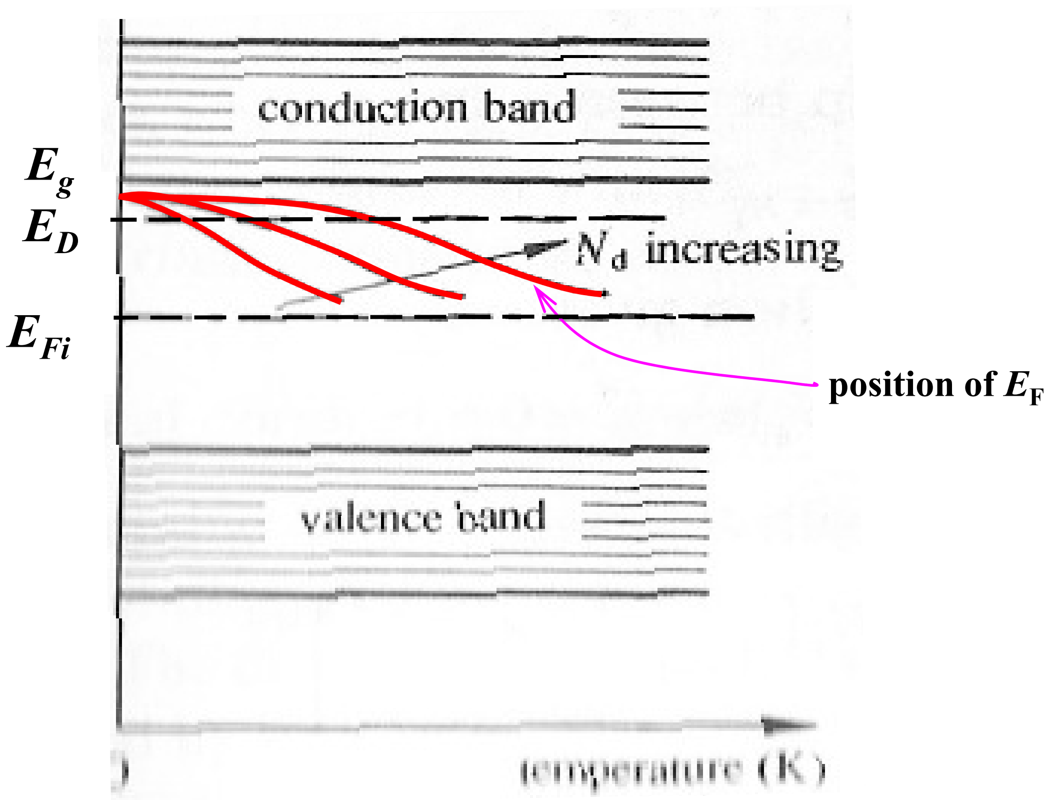
$$E_F = E_g - kT\log(N_c/N_d)$$

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

Density of carriers in extrinsic sC

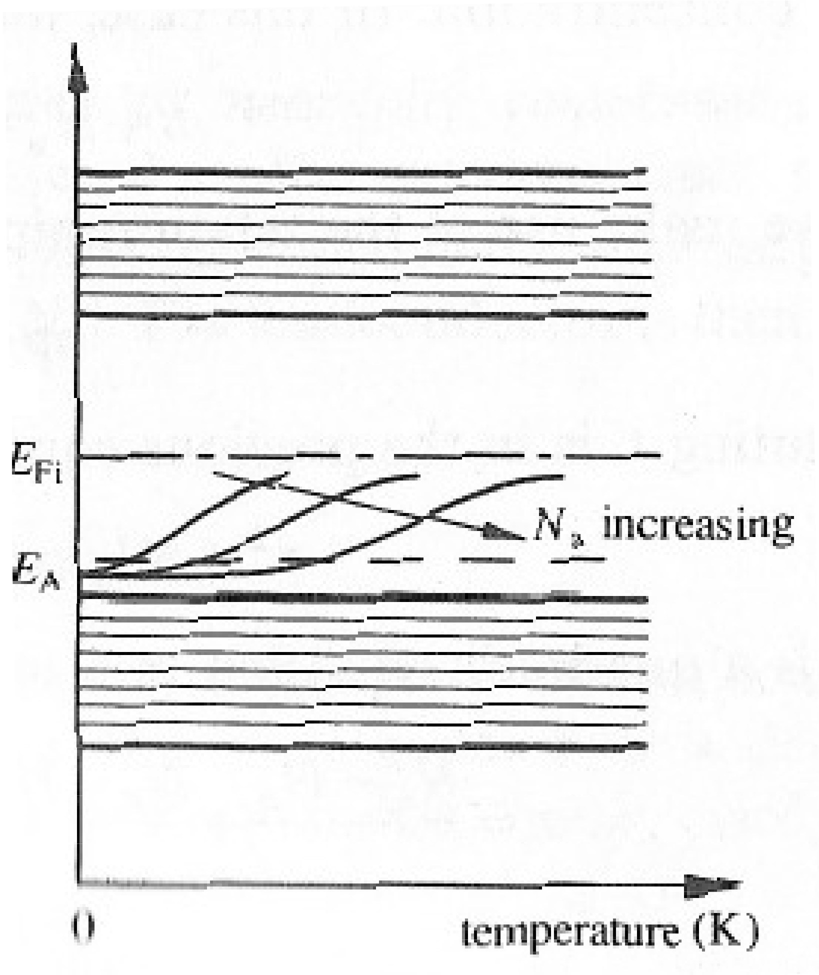
- Special cases (details left as homework)
  - n-type material ($N_d >> N_a$ & $n >> p$)

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



Density of carriers in extrinsic sC

- Special cases (details left as homework)
  - p-type material ($N_a >> N_d$ & $p >> n$)



Compensation doping

- General considerations
  - Consider a sC with both donors and acceptors
  - Suppose all impurities are ionized ($N_a = N_a^+$ & $N_d = N_d^+$)
  - Electrical neutrality:

$$n + N_a = p + N_d \xrightarrow{np = n_i^2} n^2 - (N_d - N_a)n - n_i^2 = 0$$

$$\Rightarrow n = \frac{N_d - N_a}{2} + \frac{N_d - N_a}{2}\left[1 + \left(\frac{2n_i}{N_d - N_a}\right)^2\right]^{1/2}$$

  - Idem:

$$p = -\frac{N_d - N_a}{2} + \frac{N_d - N_a}{2}\left[1 + \left(\frac{2n_i}{N_d - N_a}\right)^2\right]^{1/2}$$

Compensation doping

$$n=\frac{N_d-N_a}{2}+\frac{N_d-N_a}{2}\left[1+\left(\frac{2n_i}{N_d-N_a}\right)^2\right]^{1/2}$$

$$p=-\frac{N_d-N_a}{2}+\frac{N_d-N_a}{2}\left[1+\left(\frac{2n_i}{N_d-N_a}\right)^2\right]^{1/2}$$

- Extrinsic compensated
  - $n_i \ll |N_d-N_a|$:

for $N_d > N_a$:

$$n \simeq N_d - N_a$$

$$p \simeq n_i^2/(N_d-N_a)$$

for $N_a > N_d$:

$$p \simeq N_a - N_d$$

$$n \simeq n_i^2/(N_a-N_d)$$

majority carriers large (T independent)

minority carriers low (strong T dependence)

Compensation doping

$$n = \frac{N_d - N_a}{2} + \frac{N_d - N_a}{2}\left[1 + \left(\frac{2n_i}{N_d - N_a}\right)^2\right]^{1/2}$$

$$p = -\frac{N_d - N_a}{2} + \frac{N_d - N_a}{2}\left[1 + \left(\frac{2n_i}{N_d - N_a}\right)^2\right]^{1/2}$$

- Intrinsic compensated
  - $n_i \gg |N_d - N_a|$:

$$n = n_i + (N_d - N_a)/2$$

$$p = n_i + (N_d - N_a)/2$$

Conclusions

- Extrinsic sC are created by adding impurities:
  - Donors (extra electrons) and acceptors (extra holes).
- Concentration of majority and minority carriers was found