Physics of Electronics:

6. Semiconductors

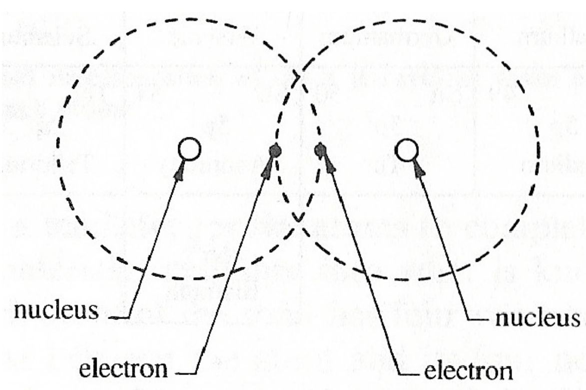
July – December 2008

Contents overview

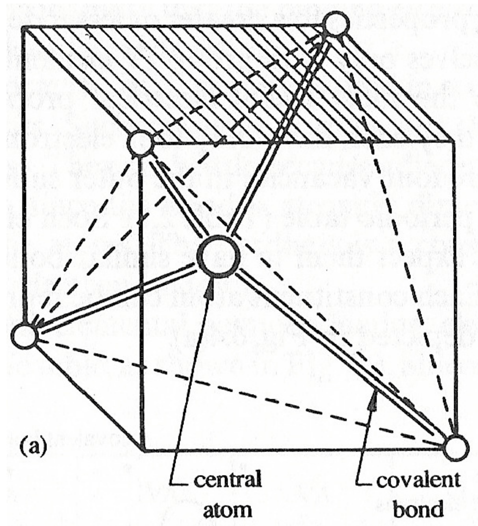
- Crystal structure of semiconductors.
- Conduction processes in semiconductors.
- Density of carriers in intrinsic semiconductors.
- Extrinsic semiconductors.
- Electron processes in real semiconductors.
- Density of carriers in extrinsic semiconductors.
- Compensation doping.
- Electrical conduction in semiconductors.

Covalent Bond

- Valence electrons are shared.

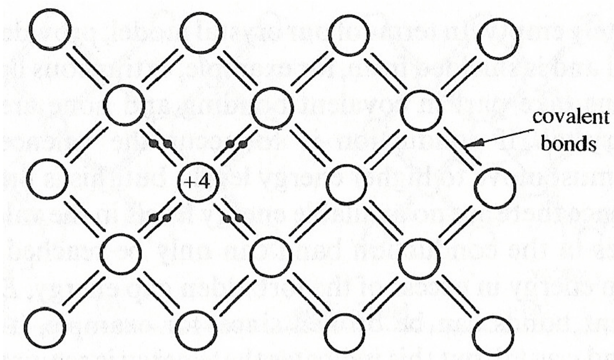


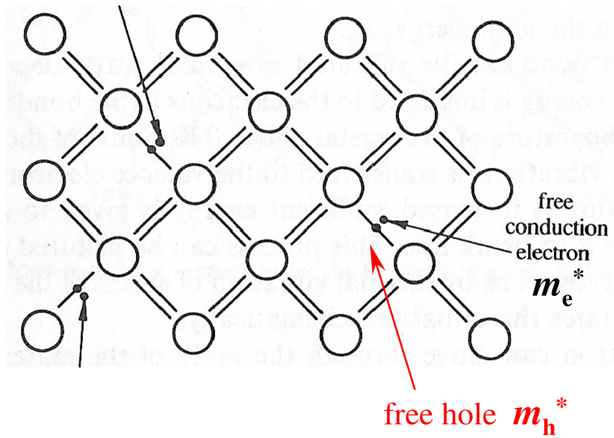
Valency group	IIIA	IVA	VA	VIA	VIIA
	B 5 $2p$ Boron	C 6 $2p^2$ Carbon			
	Al 13 $3p$ Aluminium	Si 14 $3p^2$ Silicon	P 15 $3p^3$ Phosphorus	S 16 $3p^4$ Sulphur	
	Ga 31 $4p$ Gallium	Ge 32 $4p^2$ Germanium	As 33 $4p^3$ Arsenic	Se 34 $4p^4$ Selenium	
	In 49 $5p$ Indium	Sn 50 $5p^2$ Tin	Sb 51 $5p^3$ Antimony	Te 52 $5p^4$ Tellurium	I 53 $5p^5$ Iodine
			Bi 83 $6p^3$ Bismuth		



  - Holes and electrons

$T = 0$

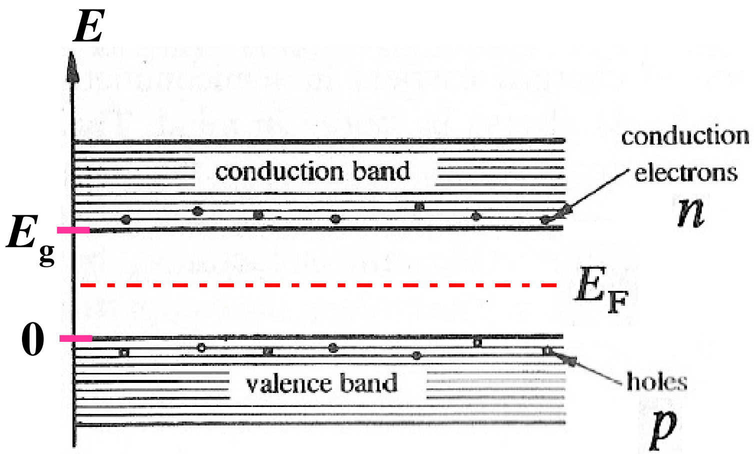




$T > 0$

Density of Carriers in Intrinsic sC

- Concentration of conduction electrons:



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

$$p = \int_{\text{valence band}} S_h(E)[1 - P(E)]dE$$

For electrons: $S(E) = \frac{(8\sqrt{2})\pi(m_e^*)^{3/2}}{h^3}(E-E_g)^{1/2}$

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

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

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

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

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

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

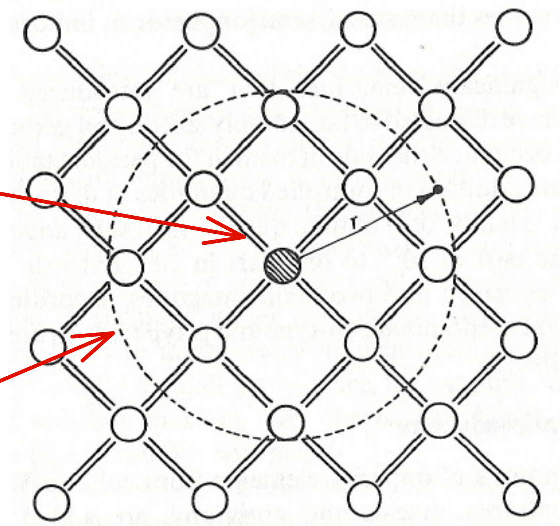
valid also for extrinsic sC!!

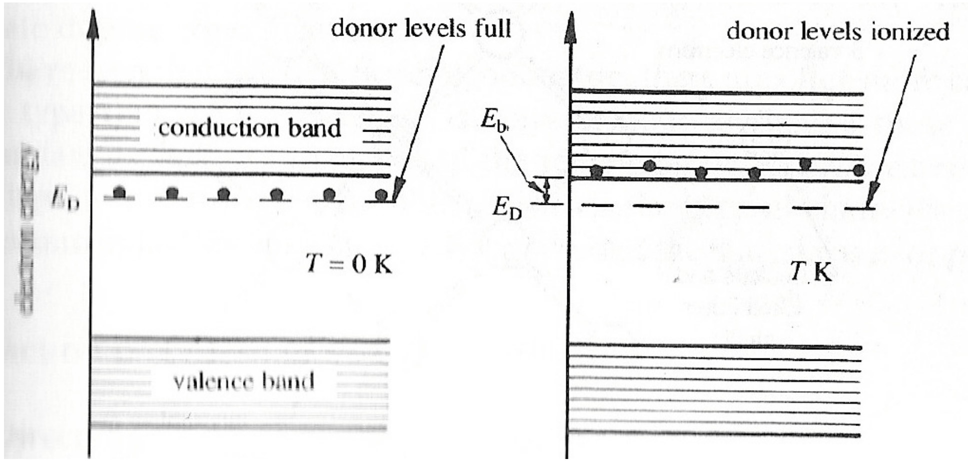
Extrinsic or Impurity sC

- n-type semiconductors (pentavalent impurities)

4 electrons participate in bonding

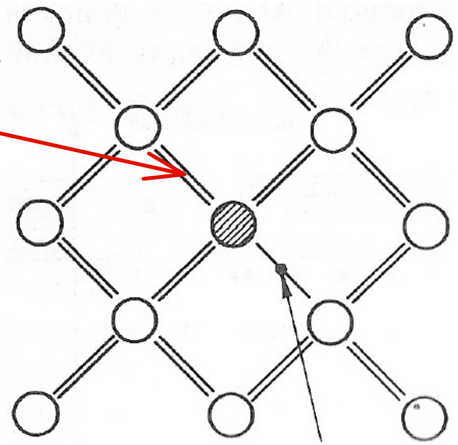
1 electron free to wander

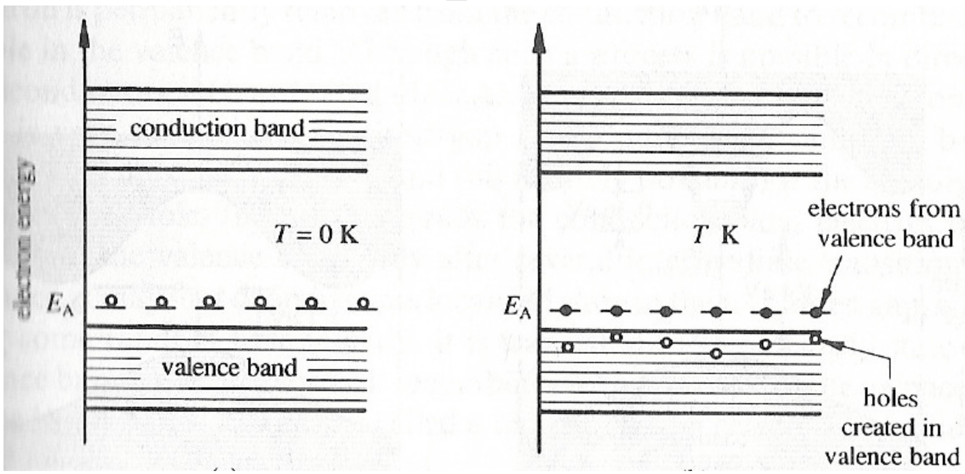




- p-type semiconductors (trivalent impurities)

All 3 electrons participate in bonding

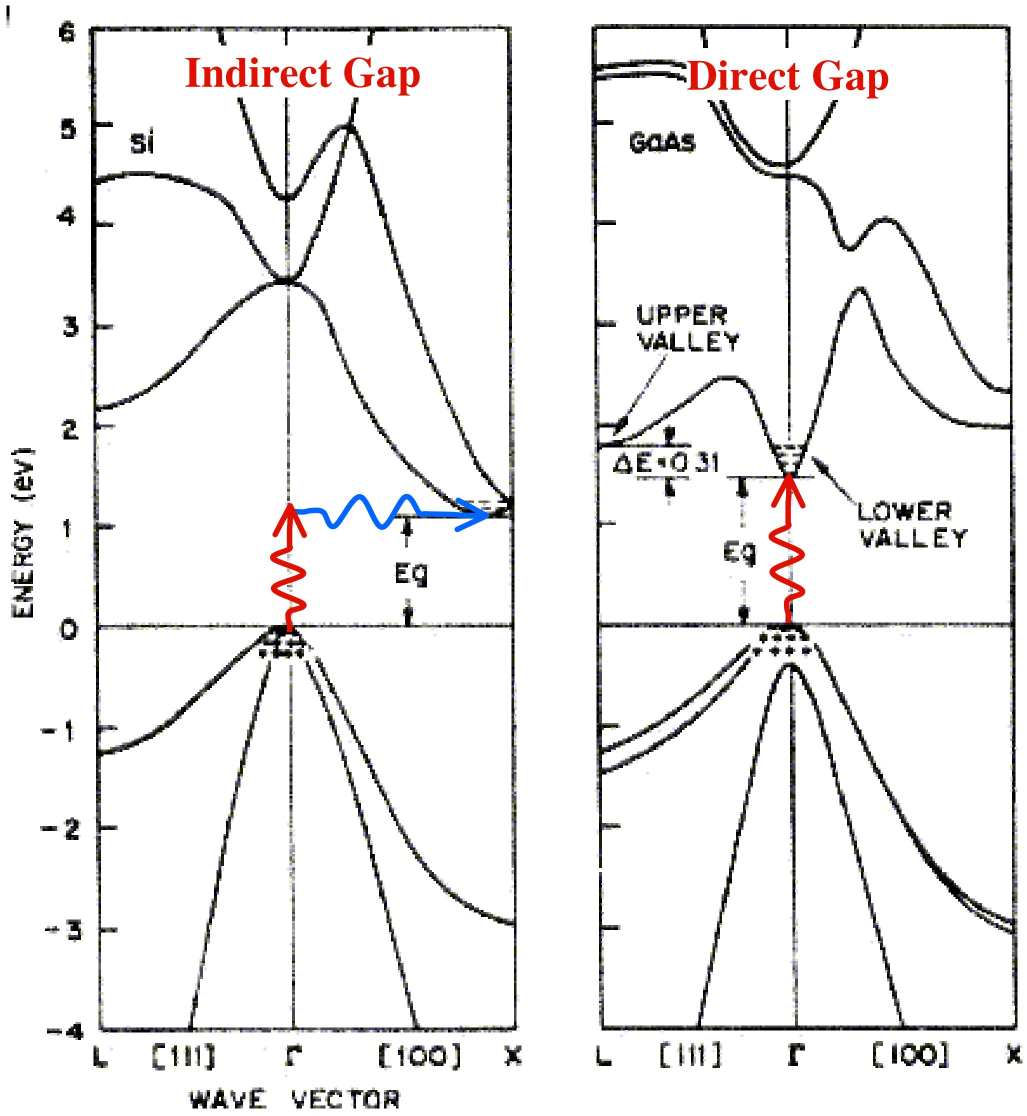




Electron Processes in Real sC

- Direct and indirect gap sC

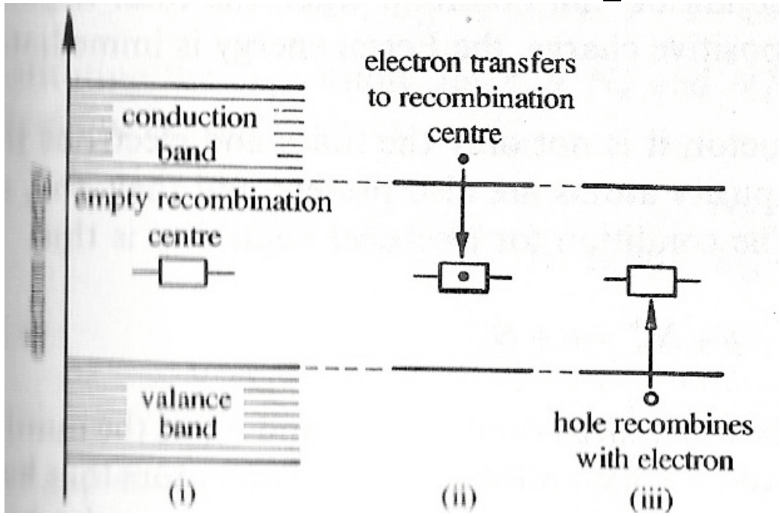
The minimum separation cannot be reached optically.



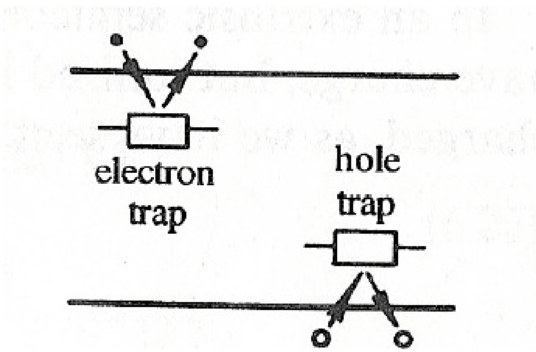
The minimum separation can be reached optically (by means of a photon).

Electron Processes in Real sC

- Recombination (permanent loss of a carrier)
  - Possible in direct-gap sC's but marginally probable in indirect-gap sC's. Intermediate steps are required.



- Trapping (temporary removal of a carrier on localized states)

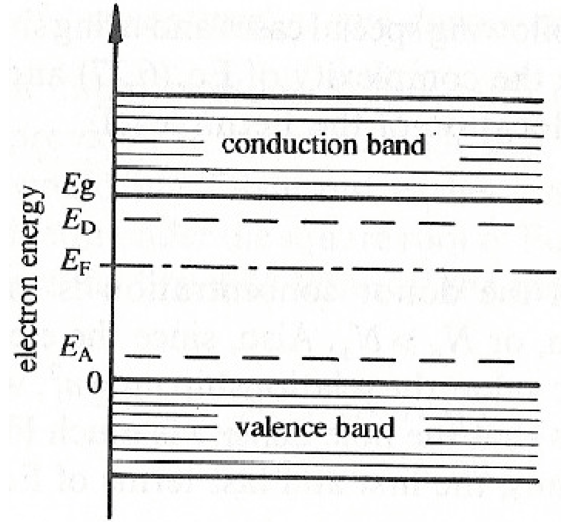


Density of carriers in extrinsic sC

- General considerations:
  - Electrical neutrality:

holes + ionized donors = electrons + ionized acceptors

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



  - n and p were already found
  - Concentration of ionized impurities:

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

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

  - Replacing on neutrality condition

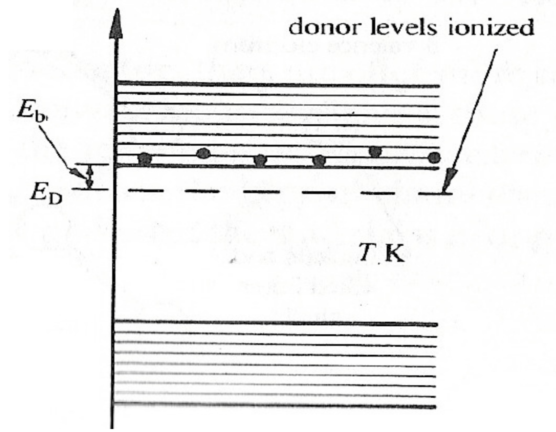
$$N_v \exp(-E_F/kT) + \frac{N_d}{1+\exp[-(E_D - E_F)/kT]} = N_c \exp[-(E_g - E_F)/kT] + \frac{N_a}{1+\exp[(E_A - E_F)/kT]}$$

which can be solved for E_F

Density of carriers in extrinsic sC

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

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



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

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

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

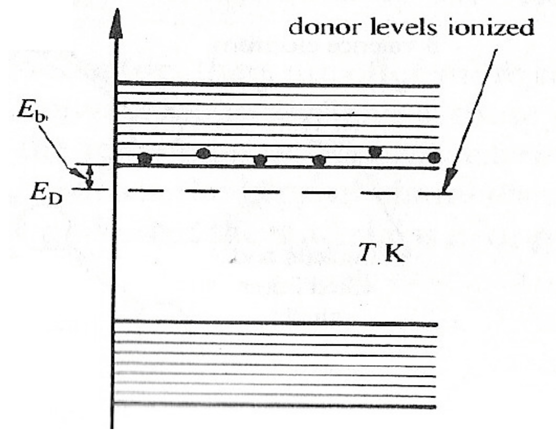
$$\Rightarrow \quad \exp(E_F/kT) \simeq \frac{2(N_d/N_c)^{1/2}\exp[(E_g - E_D)/2kT]}{2\exp(-E_D/kT)} \quad \Rightarrow \quad \boxed{E_F = \tfrac{1}{2}(E_g + E_D) + \tfrac{1}{2}kT\log(N_d/N_c)}$$

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

Density of carriers in extrinsic sC

- n-type material:
  - $N_d \gg N_a$ & $n \gg p$

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



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

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

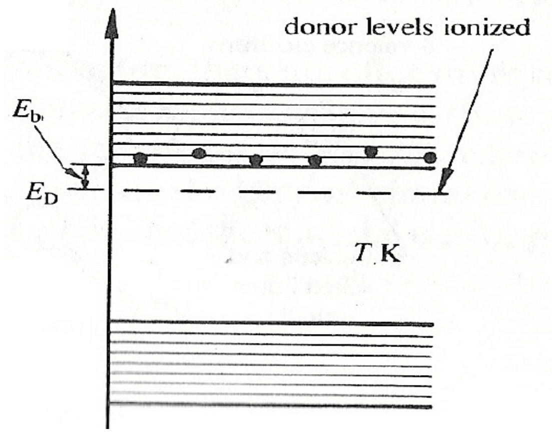
  - T high ($\exp[(E_D - E_g)/kT] \ll 1$) & N_d large ($N_d/N_c \ll 1$)

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

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

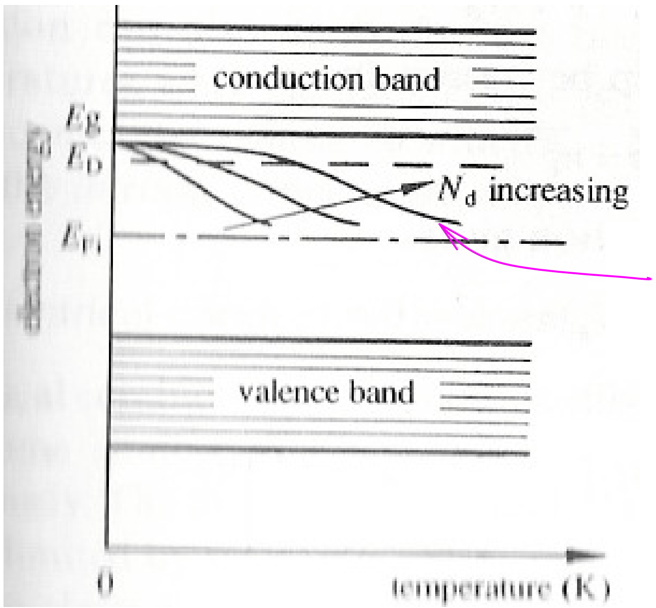
Density of carriers in extrinsic sC

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



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

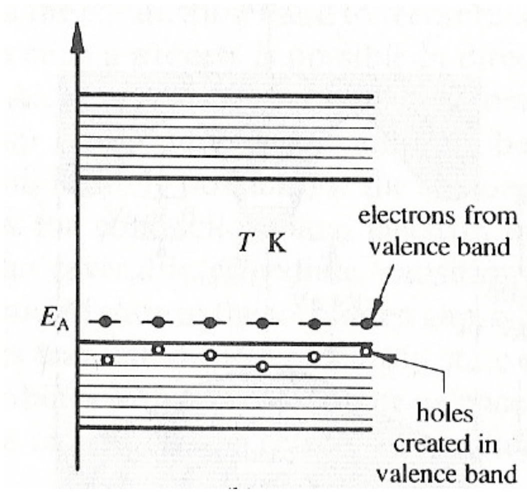
$$\Rightarrow \quad \exp(E_F/kT) = \frac{-1 + \{1 + (4N_d/N_c)\exp[(E_g - E_D)/kT]\}^{1/2}}{2\exp(-E_D/kT)}$$



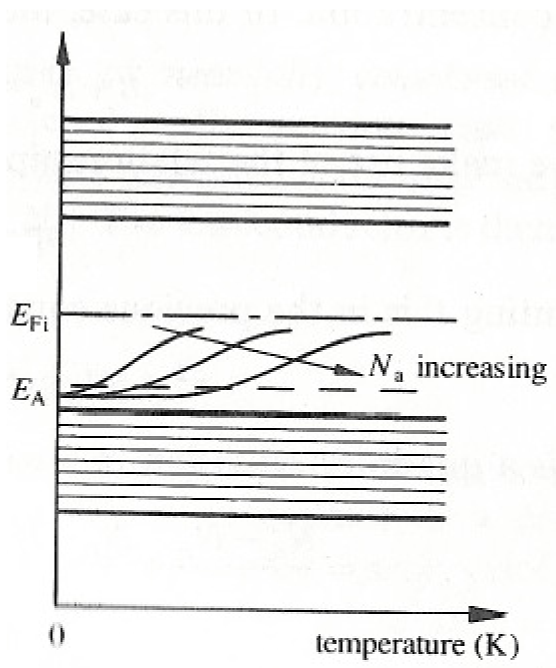
position of E_F

Density of carriers in extrinsic sC

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



  - Idem as before



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

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

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

Electrical conduction in sC.

- Conductivity
  - In a sC we have e^-'s and h^+'s moving:

$$J_e = ne\mu_e \mathscr{E}$$

$$J_h = pe\mu_h \mathscr{E}$$

$$\Rightarrow \quad J = J_e + J_h = \underbrace{e(n\mu_e + p\mu_h)}_{\sigma}\mathscr{E}$$

  - In a n-type sC (n>>p):

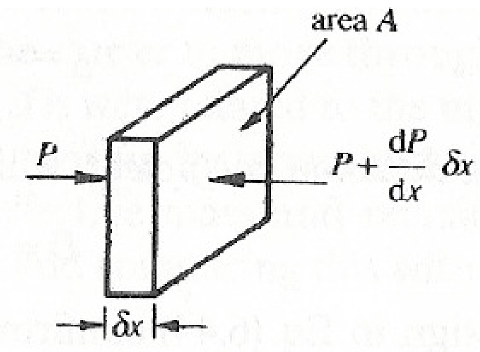
$$\sigma_n \simeq en\mu_e \simeq eN_d\mu_e$$

  - In a p-type sC (p>>n):

$$\sigma_p \simeq ep\mu_h \simeq eN_a\mu_h$$

Electrical conduction in sC.

- Diffusion of charge carriers
  - In general, diffusion occurs when concentration gradients are present.
  - In a neutral gas with gradient in the x direction:



Overall force on the elemental volume

$$\left[P(x)-\left(P+\frac{dP}{dx}\delta x\right)\right]A=-\frac{dP}{dx}\delta xA$$

Average force on each particle

$$F_D=-\frac{1}{N}\frac{dP}{dx}$$

- v_D due to electrical force $e\mathscr{E}$ (see Chap. 4):

$$v_{Dx}=-(e\tau_r/m)\mathscr{E}_x$$

- v_D due to F_D:

$$v_D=-\frac{\tau_r}{M}\frac{1}{N}\frac{dP}{dx}\xrightarrow{P=NkT}v_D=-\frac{\tau_r kT}{M}\frac{1}{N}\frac{dN}{dx}$$

Electrical conduction in sC.

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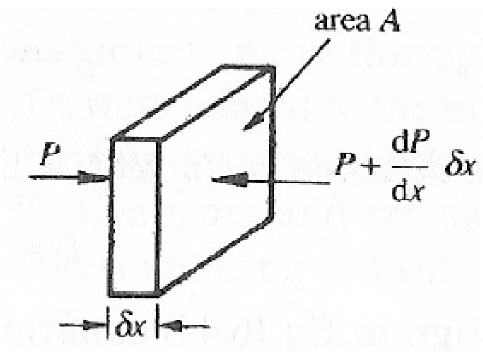

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Average force on each particle

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- v_D due to electrical force $e\mathscr{E}$ (see Chap. 4):

$$v_{Dx}=-(e\tau_r/m)\mathscr{E}_x$$

- v_D due to F_D:

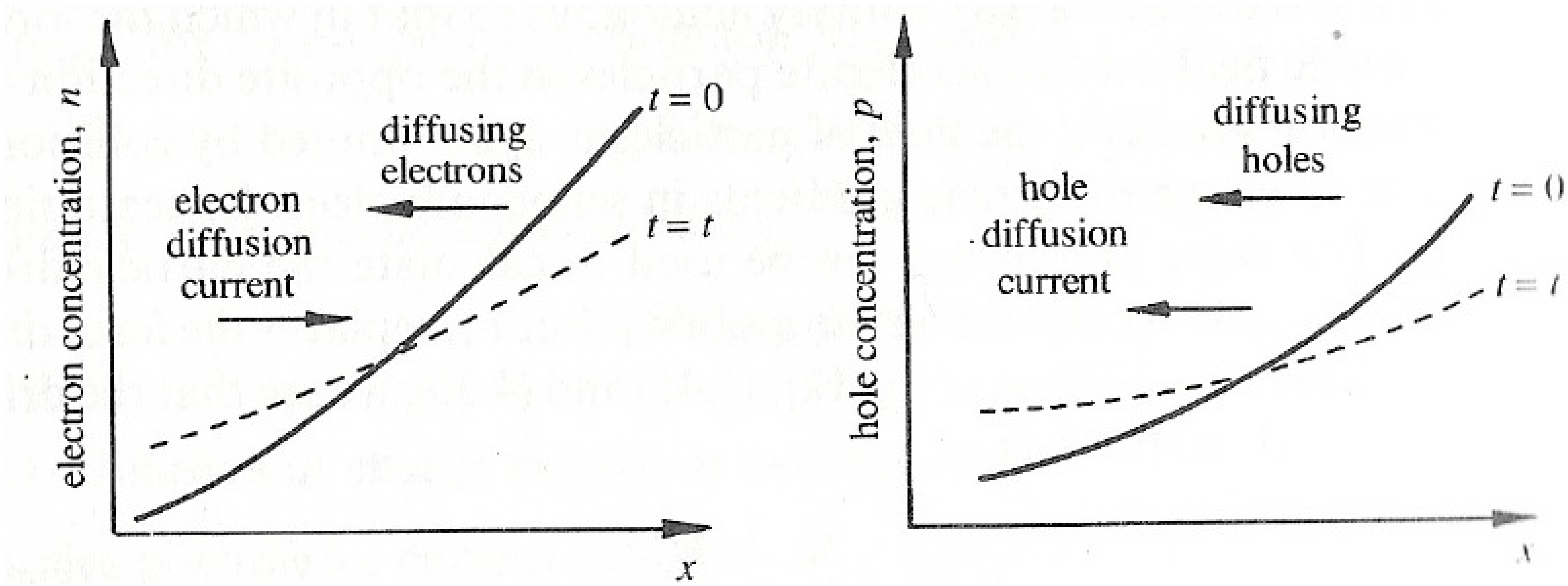
$$v_D=-\frac{\tau_r}{M}\frac{1}{N}\frac{dP}{dx}\xrightarrow{P=NkT}v_D=-\overbrace{\frac{\tau_r kT}{M}}^{D}\frac{1}{N}\frac{dN}{dx}$$

Electrical conduction in sC.

- Diffusion of charge carriers
  - In a sC with a concentration gradient of the e^- and h^+:

$$v_{De} = -D_e \frac{1}{n}\frac{dn}{dx} \qquad v_{D_h} = -D_h \frac{1}{p}\frac{dp}{dx}$$

$$\Rightarrow J_{De} = -nev_D = eD_e\, dn/dx \qquad \Rightarrow J_{Dh} = -eD_h\, dp/dx$$



Electrical conduction in sC.

- Diffusion of charge carriers
  - Diffusion coefficient is related with mobility:

$$D = \frac{\tau_r kT}{M} \xrightarrow{\mu = e\tau_r/m} \begin{array}{l} D_e = (kT/e)\mu_e \\ D_h = (kT/e)\mu_h \end{array} \longrightarrow \boxed{D_e/\mu_e = D_h/\mu_h = kT/e}$$

- Total current flow

$$J_e = ne\mu_e\mathscr{E} + eD_e\nabla n$$

$$J_h = pe\mu_h\mathscr{E} - eD_h\nabla p \xrightarrow{J_h = 0} \mathscr{E} = D_h\nabla p/p\mu_h$$

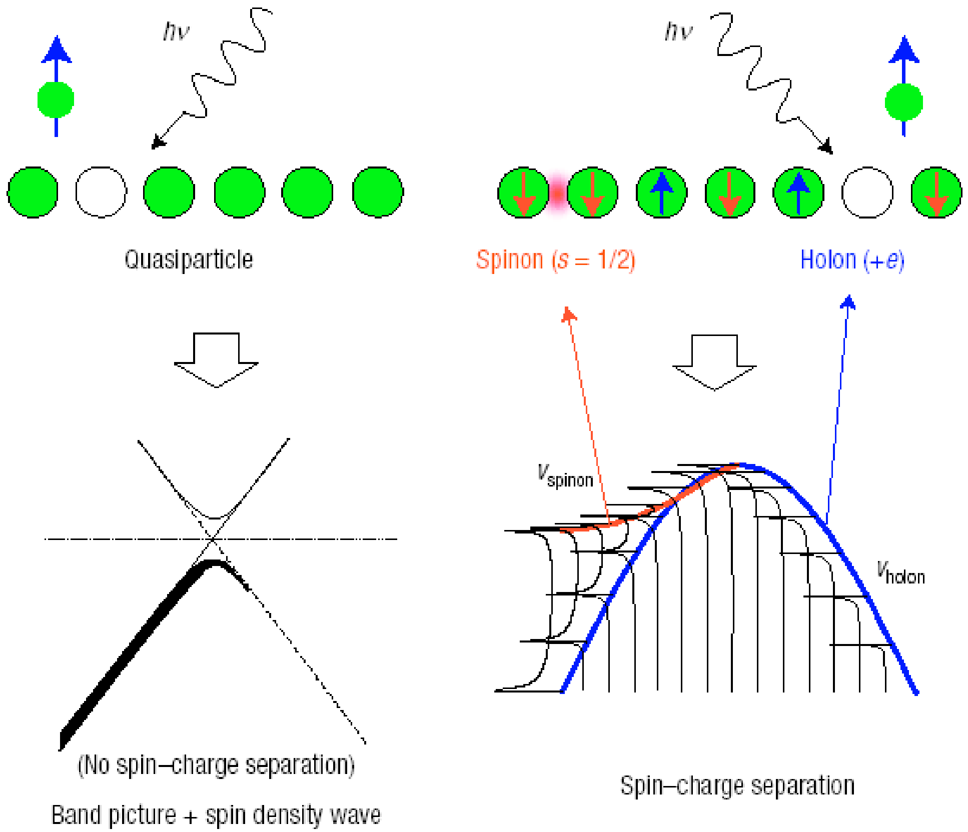
current can be compensated at a particular electrical field

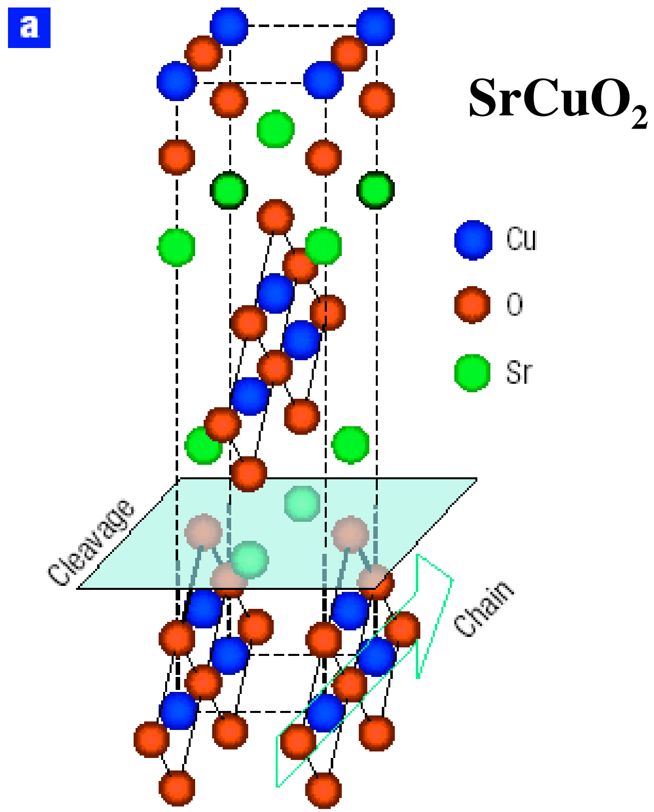
response to electrical field

diffusion

Spin-Charge Separation

- In 1D systems, a collective excitation can be produced such that two new particles form:
  - **Spinon:** spin without charge **Holon:** charge without spin





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