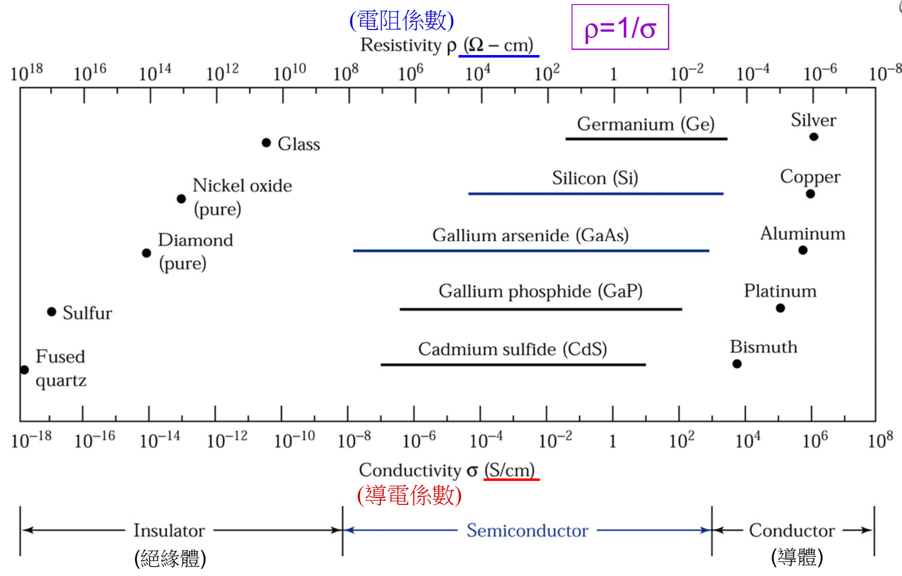
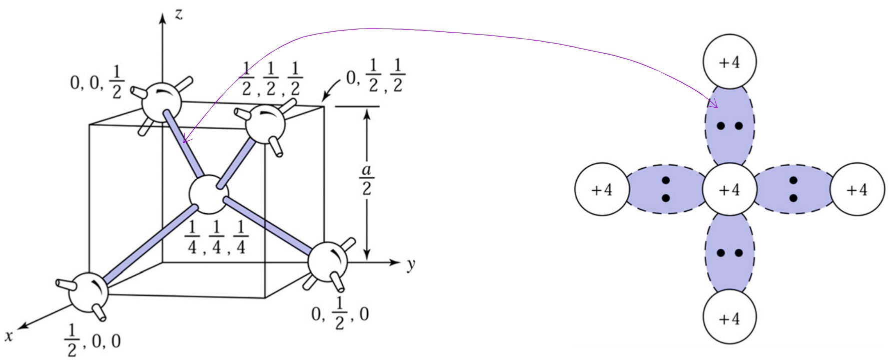
Semiconductor Basics

(半導體基礎)



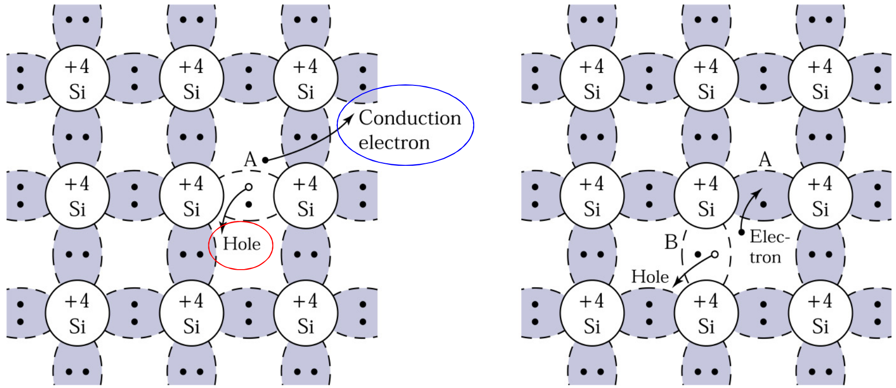
Conduction Electron (導電電子) and Hole (電洞)

◆ The electrons shared for atomic bonding in semiconductors can not freely move!



◆ ***Intrinsic*** (本質的) ***semiconductor***: a pure semiconductor without *doping* (摻雜).

∴ Intrinsic semiconductor ≡ Undoped (未摻雜的) semiconductor.

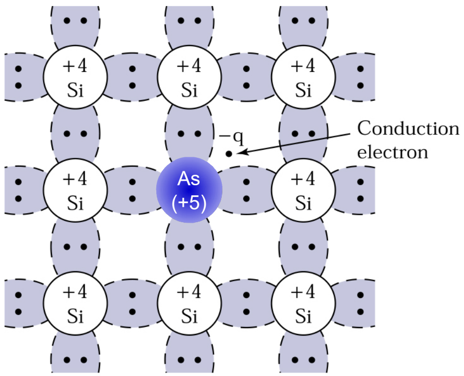


T > 0 K (絕對零度)

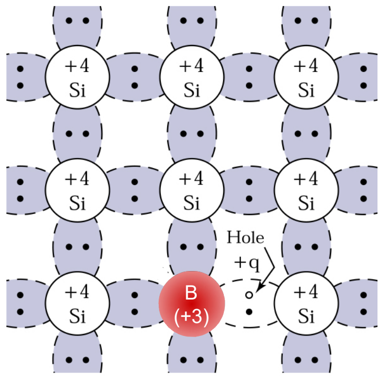
Electron (電子): a particle of a negative charge (–1.6×10^{-19} C).

Hole (電洞): a fictitious (虛構的) particle of a positive charge (+1.6×10^{-19} C).

- ***Extrinsic*** (外質的) ***semiconductor***: a semiconductor doped with impurity atoms (雜質原子).
  ∴ Extrinsic semiconductor ≡ Doped (摻雜的) semiconductor.
- The impurity atoms are called *dopants* (摻雜物) when they are used for doping.
- 2 types of dopants:
  - ***donor*** (施體) for n-type semiconductors, and
  - ***acceptor*** (受體) for p type semiconductors.

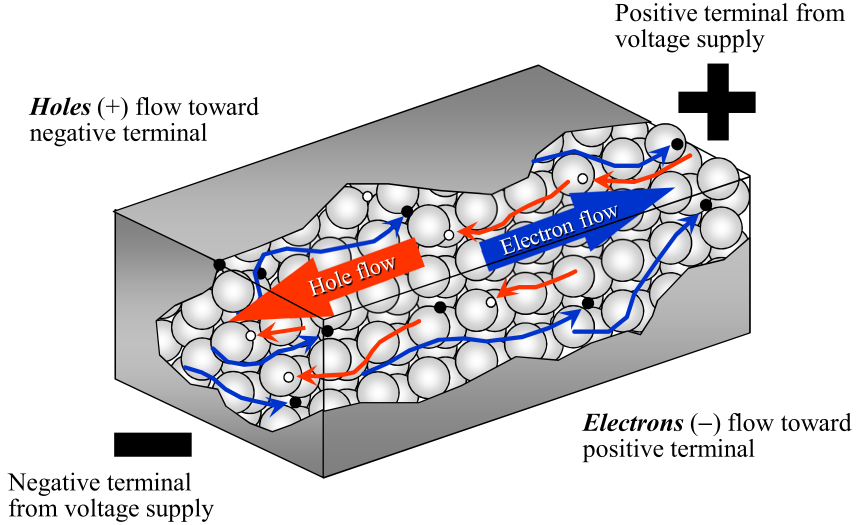


n-type Si with donor (As)



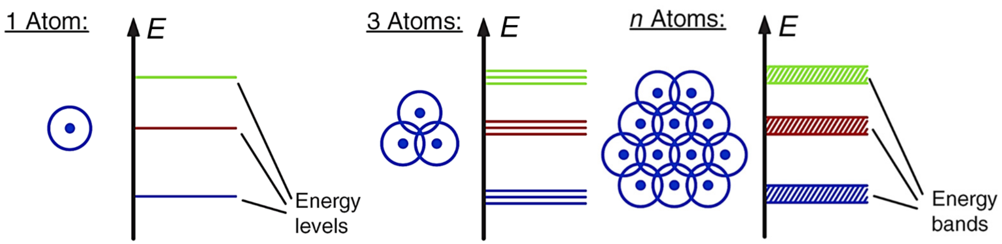
p-type Si with acceptor (B)

Flow of Carriers (載子) in Semiconductor



Energy Band (能帶)

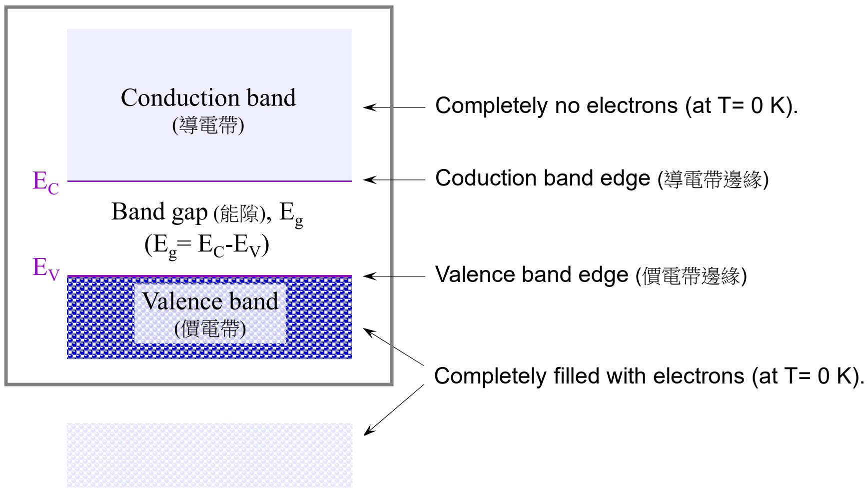
Formation of energy bands in solid



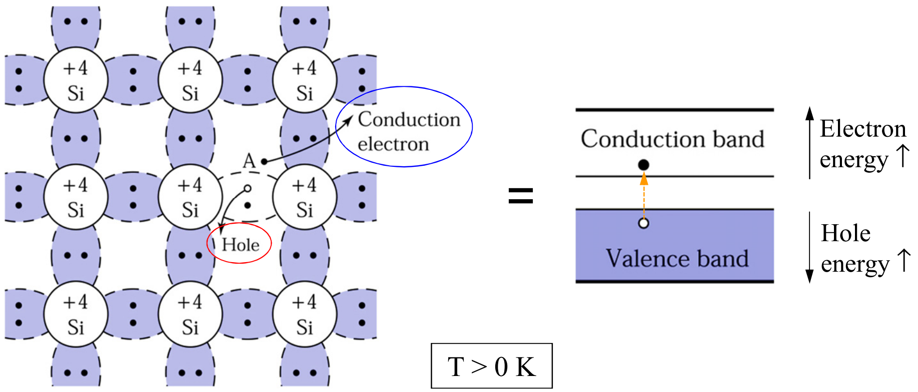
For a solid, a large amount of closely-located energy levels form an energy band.

Energy band diagram (能帶圖) of a semiconductor

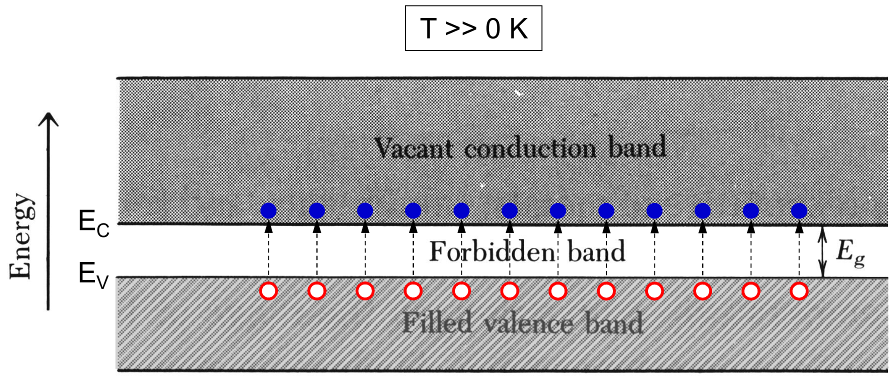
Energy band diagram (能帶圖) ➔ E-x relation



- Electron (電子): a particle of a negative charge (–1.6×10^{-19} C).
  Hole (電洞): a fictitious (虛構的) particle of a positive charge (+1.6×10^{-19} C).
- Free electrons are in the conduction band and holes are in the valence band.

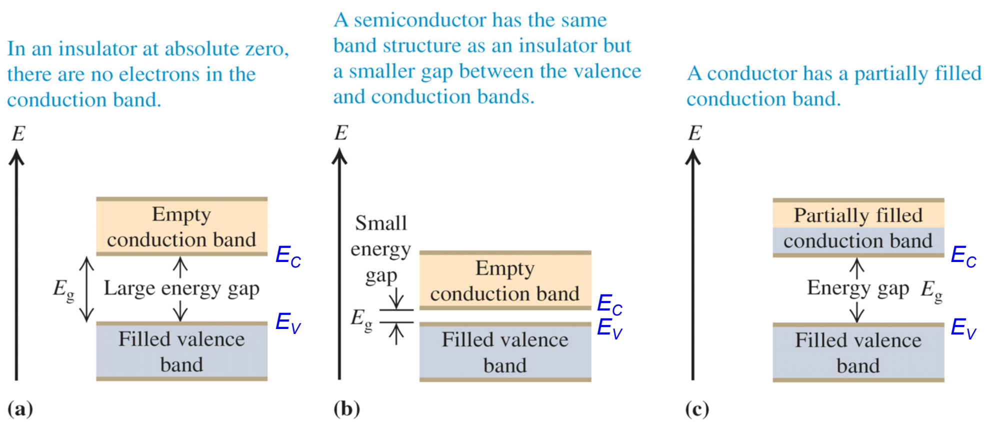


- As T ↑↑, more electrons are *thermally excited* (熱激發) from the valence band to the conduction band.
- Electron concentration (電子濃度) ***n*** = Hole concentration (電洞濃度) ***p***.



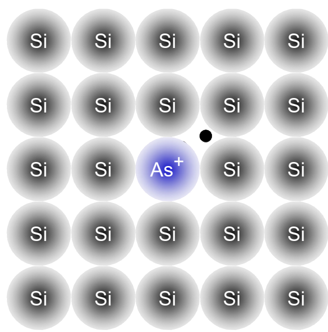
Band gap & electron occupancy (電子佔居) at 0 K

Insulator (絕緣體) | Semiconductor | Conductor (導體)

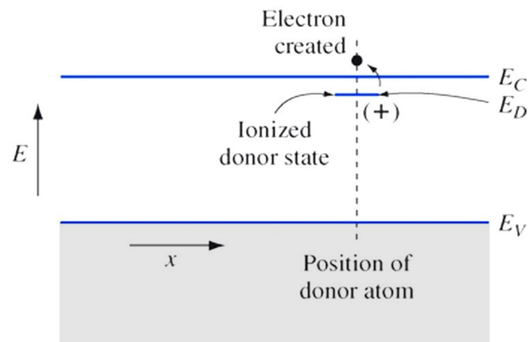


Extrinsic semiconductor: when a donor atom is present …..

- Donor (or, Donor-like) level:
  if filled by an electron → electrically neutral (電中性)
  if empty → positively charged (帶+電)

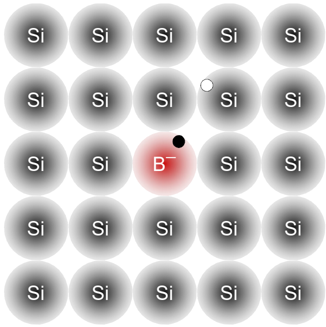


- **Activation energy** (活化能量), or **Ionization energy** (離子化能量)
  $E_d \equiv E_C - E_D$

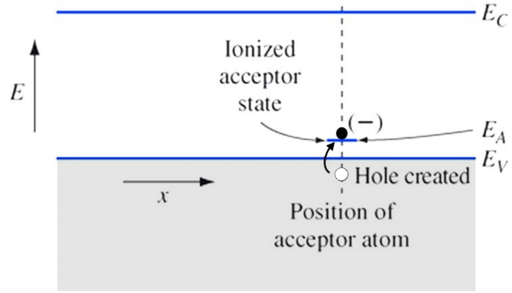


Extrinsic semiconductor: when an acceptor atom is present …..

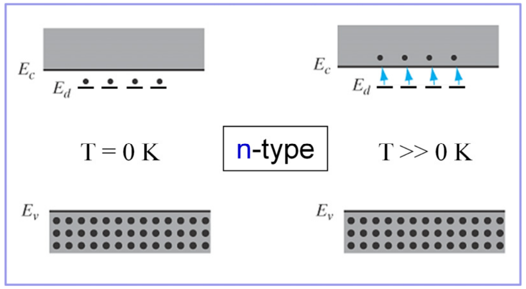
- Acceptor (or, Acceptor-like) level:
  if filled by an electron → negatively charged (帶−電)
  if empty → electrically neutral (電中性)

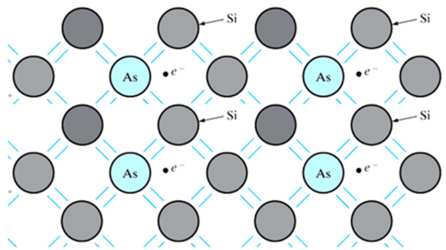


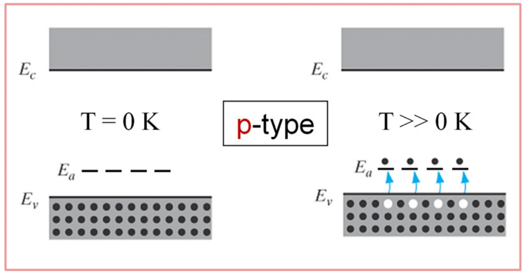
- **Activation energy** (活化能量), or **Ionization energy** (離子化能量)
  $E_a \equiv E_A - E_V$

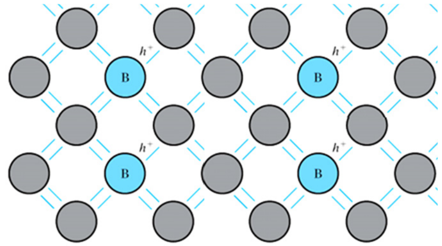


When a large number of dopant atoms are present …..









Carrier Concentration at Thermal Equilibrium (熱平衡)

- Carrier concentration (載子濃度):
  Electron concentration (電子濃度), n
  Hole concentration (電洞濃度), p
- For a practical semiconductor:

  $\boldsymbol{n = N_C \cdot F_{1/2}\left(\frac{E_F-E_C}{kT}\right)}$ & $\boldsymbol{p = N_V \cdot F_{1/2}\left(-\frac{E_F-E_V}{kT}\right)}$

  where N_C is *effective density of states in the conduction band* (導電帶有效能態密度),
  N_V is *effective density of states in the valence band* (價電帶有效能態密度),
  $F_{1/2}(x)$ is Fermi integral (費米積分) with $n = 1/2$,

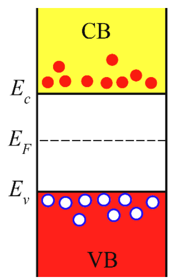
  Fermi integral: $F_n(x) = \frac{2}{\sqrt{\pi}} \int_0^\infty \frac{y^n}{1+\exp(y-x)} dy$ (with $n > -1$)
  In the case of calculating carrier concentration, we have $n = 1/2$.

  E_F is Fermi level (費米準位),
  k is Boltzmann's constant (波茲曼常數) ($= 8.62\times10^{-5}$ eV/K $= 1.38\times10^{-23}$ J/K),
  T is absolute temperature (絕對溫度).

$n = N_C \cdot F_{1/2}\left(\frac{E_F-E_C}{kT}\right)$ where N_C is *effective density of states in the conduction band.*
$p = N_V \cdot F_{1/2}\left(-\frac{E_F-E_V}{kT}\right)$ where N_V is *effective density of states in the valence band.*

- If $\boldsymbol{E_C - 3kT > E_F > E_V + 3kT}$, semiconductor is called ***nondegenerate*** (非簡併的).

$$n = N_C\, F_{1/2}\left(\frac{E_F - E_C}{kT}\right) \approx N_C \exp\left(\frac{E_F - E_C}{kT}\right)$$
$$p = N_V\, F_{1/2}\left(-\frac{E_F - E_V}{kT}\right) \approx N_V \exp\left(-\frac{E_F - E_V}{kT}\right)$$
$$\therefore\ n\,p = N_V N_C \exp\left(-\frac{E_C - E_V}{kT}\right) = N_V N_C \exp\left(-\frac{E_g}{kT}\right)$$

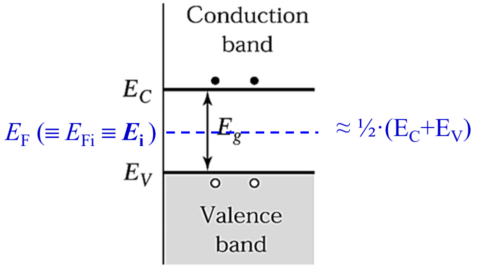


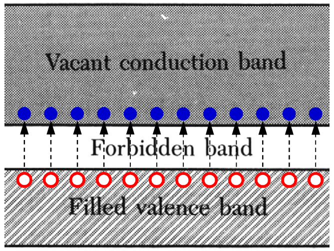
$n = N_C\, e^{(E_F-E_C)/kT}$
$p = N_V\, e^{-(E_F-E_V)/kT}$
$n \cdot p = N_C N_V\, e^{-E_g/kT}$

Intrinsic (i.e., undoped) semiconductors

- $n = p \equiv n_i$, where n_i is called ***intrinsic carrier concentration*** (本質載子濃度).
  $\Rightarrow n \cdot p = n_i \cdot n_i = n_i^2$
  But, an intrinsic semiconductor is nondegenerate. (*See its E_F to be calculated below.*)
  $\Rightarrow n \cdot p = N_C N_V e^{-E_g/kT}$
  ∴ The above two equations give $n_i = (N_C N_V)^{1/2} e^{-E_g/2kT}$.
- $n = p \Rightarrow N_C e^{(E_F-E_C)/kT} = N_V e^{-(E_F-E_V)/kT}$
  ∴ ***Intrinsic Fermi level*** (本質費米準位) is given by
  $E_F (\equiv E_{Fi} \equiv E_i) = ½ \cdot (E_C+E_V) + ½ \cdot kT \cdot \ln(N_V/N_C)$
  $\approx ½ \cdot (E_C+E_V)$

$n = N_C e^{(E_F-E_C)/kT}$
$p = N_V e^{-(E_F-E_V)/kT}$
$n \cdot p = N_C N_V e^{-E_g/kT}$
$= n_i^2$



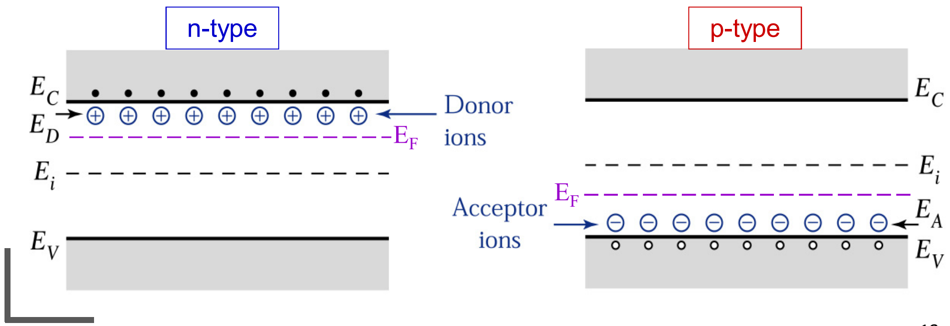


Extrinsic (i.e., doped) semiconductors

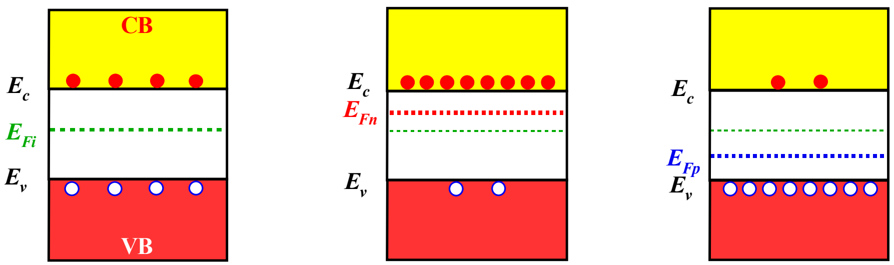
(N_D: donor concentration (施體濃度) & N_A: acceptor concentration (受體濃度))
If N_D or N_A is not very high, giving the semiconductor nondegenerate, then we have:

- ***Complete ionization*** (完全離子化): as shown in the figure below.
- If doped with N_D (>> n_i) ⇒ n-type
  Majority carrier (多數載子) $n \approx N_D$ ⇒ $E_F - E_C \approx kT \cdot \ln(N_D/N_C)$
  Minority carrier (少數載子) $p = N_V e^{-(E_F-E_V)/kT}$ or $p = n_i^2/n$
- If doped with N_A (>> n_i) ⇒ p-type
  Majority carrier (多數載子) $p \approx N_A$ ⇒ $E_F - E_V \approx kT \cdot \ln(N_V/N_A)$
  Minority carrier (少數載子) $n = N_C e^{(E_F-E_C)/kT}$ or $n = n_i^2/p$

$n = N_C e^{(E_F-E_C)/kT}$
$p = N_V e^{-(E_F-E_V)/kT}$
$n \cdot p = N_C N_V e^{-E_g/kT}$
$= n_i^2$



Intrinsic	N-type	P-type
n = p	n >> p	n << p
$n \cdot p = n_i^2$	$n \cdot p = n_i^2$	$n \cdot p = n_i^2$

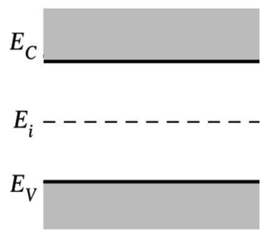


Summary of formulas (for both intrinsic & extrinsic cases)

When the semiconductor is nondegenerate:

- $n = N_C e^{(E_F-E_C)/kT} = N_C e^{(E_i-E_C)/kT} e^{(E_F-E_i)/kT}$
  $= n_i e^{(E_F-E_i)/kT}$
  $p = N_V e^{-(E_F-E_V)/kT} = N_V e^{-(E_i-E_V)/kT} e^{-(E_F-E_i)/kT}$
  $= n_i e^{-(E_F-E_i)/kT}$
  $n \cdot p = n_i^2$ ← ***Mass action law***
- $E_F - E_C = kT \cdot \ln(n/N_C)$
  $E_F - E_V = kT \cdot \ln(N_V/p)$
  or
  $E_F - E_i = kT \cdot \ln(n/n_i)$
  $E_F - E_i = kT \cdot \ln(n_i/p)$
- For a doped semiconductor:
  If n type ⇒ $n \approx N_D$ & $p = n_i^2/n$
  If p type ⇒ $p \approx N_A$ & $n = n_i^2/p$

$n = N_C e^{(E_F-E_C)/kT}$
$p = N_V e^{-(E_F-E_V)/kT}$
$n \cdot p = N_C N_V e^{-E_g/kT}$
$= n_i^2$



Symbols for undoping & doping concentration

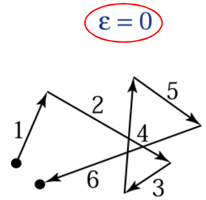
Examples: n^+-Si, p^{++}-Si, n-GaAs, p^--GaAs, i-GaAs

N_D: Donor concentration (施體濃度)
N_A: Acceptor concentration (受體濃度)

N_D or N_A	Degenerate ?	N-type	P-type
> 10^{19} cm^{-3}	Degenerate	n^{++}	p^{++}
10^{18} ~ 10^{19} cm^{-3}	~ Degenerate	n^+	p^+
10^{17} ~ 10^{18} cm^{-3}	Nondegenerate	n	p
10^{15} ~ 10^{17}	Nondegenerate	n^-	p^-
0 (Intrinsic)	Nondegenerate	i	i

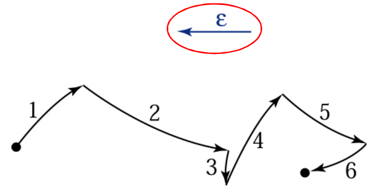
Drift (漂移)

- When $\mathscr{E} = 0$, carriers undergo random thermal motion only
  ⇒ Zero net displacement over a sufficiently long period of time.



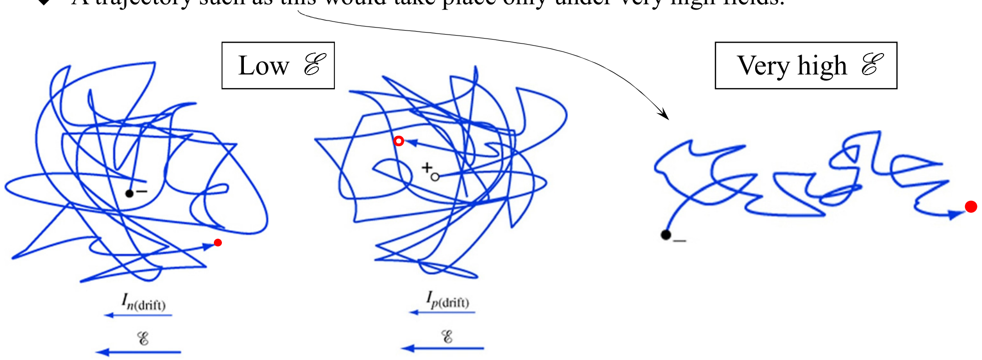
- Average thermal velocity (平均熱速度), v_{th}
  v_{th} ~ 10^7 cm/s @ 300 K
  (More precisely: $\frac{1}{2}m^* v_{th}^2 = 3 \cdot \frac{1}{2}kT$)
- ***Mean free path*** (平均自由路徑), l
  $l = v_{th} \cdot \tau_c$ (~1000 Å @ 300 K)
- ***Mean free time*** (平均自由時間), or
  Collision time (碰撞時間), or
  Relaxation time (鬆弛時間)
  $\tau_c = l / v_{th}$ (~10^{-12} s = 1 ps @ 300 K)

- When $\mathscr{E} \neq 0$, carriers have combined motion due to random thermal motion and an applied electric field.
  ⇒ Non-zero net displacement, so-called ***drift***.



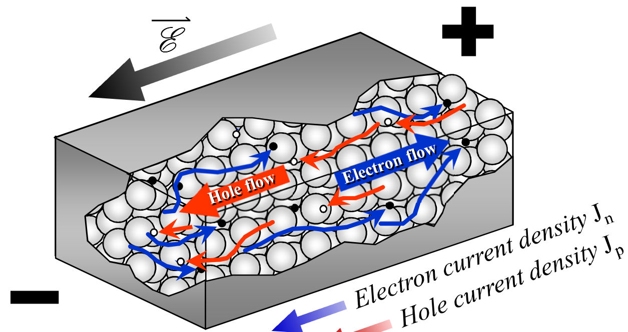
Drift Velocity (漂移速度) and Mobility (遷移率)

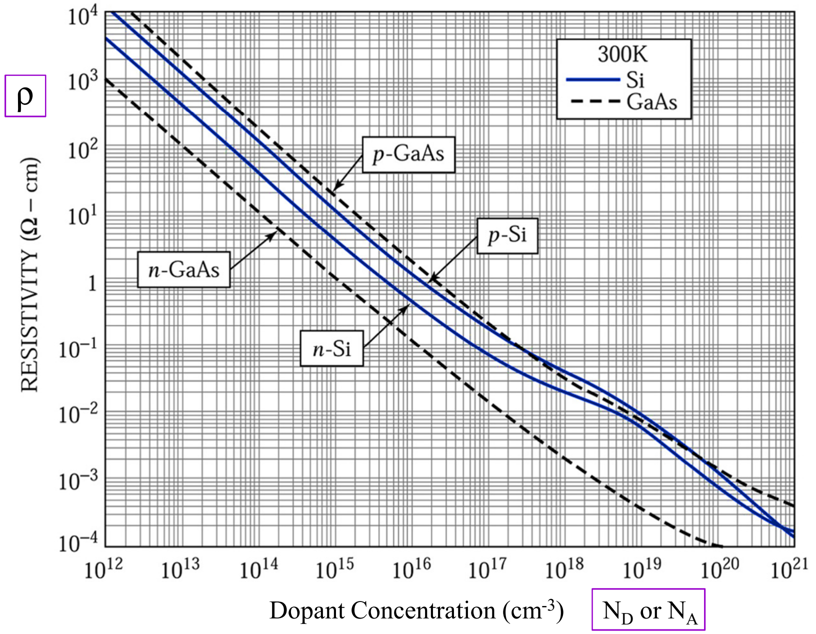
- ***Drift velocity*** (漂移速度) $v = \mu \cdot \mathscr{E}$, where $\mathscr{E}$ is the electric field.
  Mobility (遷移率) $\mu \equiv (q \cdot \tau_c)/m^*$, where m^* is the effective mass of the carriers.
  ($f \cdot t = m \cdot v \;\Rightarrow\; -q\mathscr{E} \cdot \tau_c = m \cdot v \;\Rightarrow\; v = -(q\tau_c/m)\,\mathscr{E}$)
- In most of the semiconductors, electrons have higher mobility than holes (i.e., $\mu_n > \mu_p$) due to their smaller effective mass.
- Under low fields, drift velocity is much smaller than thermal speed (i.e., $v_d << v_{th}$).
- A trajectory such as this would take place only under very high fields.



Drift current (漂移電流)

- ***Drift current density*** (漂移電流密度): $\mathbf{J = J_n + J_p}$
  $\mathbf{J = J_n + J_p = nqv_n + pqv_p = q(n \cdot \mu_n + p \cdot \mu_p)\,\mathscr{E} \equiv \sigma \cdot \mathscr{E}}$
- ***Conductivity*** (導電係數 or 導電率): $\sigma = q(n \cdot \mu_n + p \cdot \mu_p)$ (in $\Omega^{-1} \cdot cm^{-1}$)
  − for n-type (n >> p) ⇒ $\sigma \approx q \cdot n \cdot \mu_n$
  − for p-type (p >> n) ⇒ $\sigma \approx q \cdot p \cdot \mu_p$
- ***Resistivity*** (電阻係數 or 電阻率): $\rho = 1/\sigma$ (in $\Omega \cdot$cm)





Resistivity versus doping concentration for Si and GaAs at 300 K.

Diffusion (擴散)

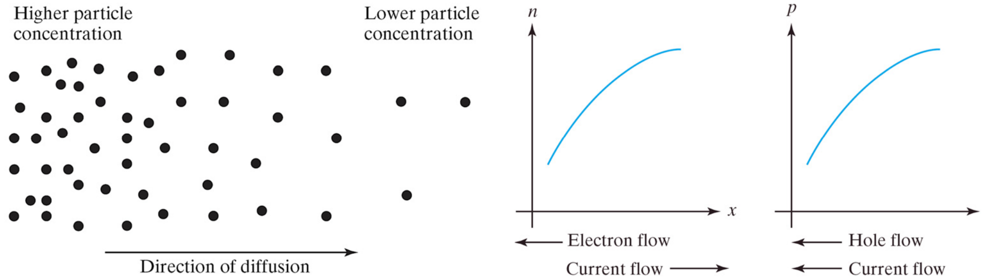
- If the carrier concentration is not uniformly distributed in space, the carriers can ***diffuse*** (擴散) even without expericing an electric field.
- ***Diffusion current density*** (擴散電流密度):

Electrons: $\mathbf{J_n = q \cdot D_n \cdot \frac{dn}{dx}}$

Holes: $\mathbf{J_p = -q \cdot D_p \cdot \frac{dp}{dx}}$

$q = 1.6 \times 10^{-19}$ C

where D (= $v_{th} \cdot l$) is the ***diffusion coefficient*** (擴散係數) (or ***diffusivity*** (擴散率)).



Einstein Relation (愛因斯坦關係)

$$D = \left(\frac{kT}{q}\right) \cdot \mu$$

- $J_n = qD_n(\partial n/\partial x)$ is one-dimensional.
  $\therefore \frac{1}{2} m_n v_{th}^2 = \frac{1}{2} kT \Rightarrow v_{th}^2 = kT/m_n$
- Use $\begin{cases} l = v_{th}\tau_c \\ \tau = \mu m^*/q \end{cases}$ ← from $\mu = q\tau/m^*$

$$\Rightarrow D_n = v_{th} l = v_{th}(v_{th}\tau_c) = v_{th}^2 \left(\frac{\mu_n m_n}{q}\right) = \left(\frac{kT}{m_n}\right)\left(\frac{\mu_n m_n}{q}\right)$$

$\Rightarrow$ $\mathbf{D_n = (kT/q)\mu_n}$ for electrons
$\mathbf{D_p = (kT/q)\mu_p}$ for holes
} Einstein relation

High-Field Effects (高電場效應)

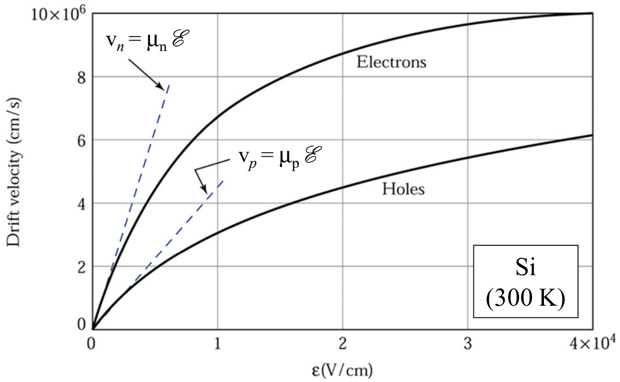
- At high electric fields, many effects may occur.
- Two important effects among them are:
  1) ***Drift velocity saturation*** (漂移速度飽和)
  2) ***Impact ionization*** (衝擊離子化)

Drift Velocity Saturation (漂移速度飽和)

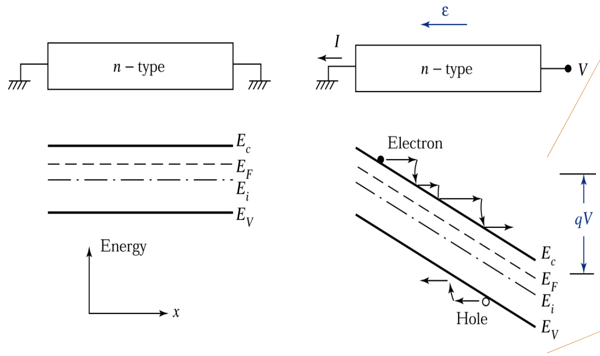
- Real drift velocity is represented by an empirical expression (經驗式)

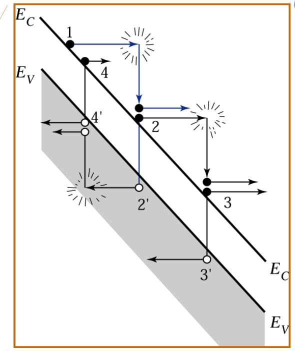
  $v = \mu_0 \mathscr{E} / [1 + (\mu_0 \mathscr{E}/v_s)^{\gamma}]^{1/\gamma}$ ← for Si & Ge

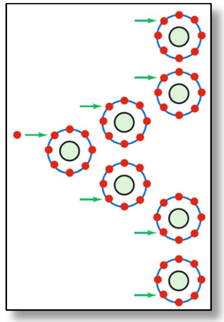
  where μ_0 is the ***low-field mobility*** (低電場遷移率),
  v_s is the ***saturation velocity*** (飽和速度), and
  γ is a factor (2 for electrons; 1 for holes).



Impact Ionization (衝擊離子化)







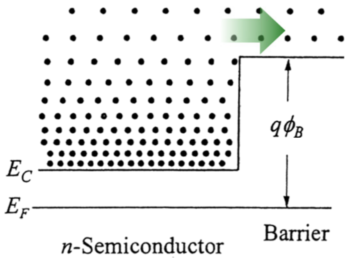
- ***Impact ionization*** (衝擊離子化), or ***Avalanche multiplication*** (累增放大)
- $\frac{1}{2} m_1 v_s^2 = E_g + 3 \cdot \frac{1}{2} m_1 v_f^2$

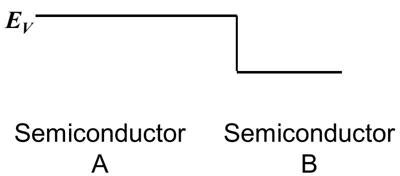
  $m_1 v_s = 3 \cdot m_1 v_f$

  $\Rightarrow \frac{1}{2} m_1 v_s^2 = 1.5\, E_g$

  ∴ The required kinetic energy for the ionization process, $E_0 \approx 1.5\, E_g$.

Thermionic Emission (熱離發射)





Tunneling (穿隧)

- In quantum mechanics:

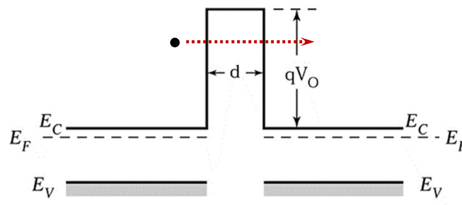
  Transmission coefficient (傳輸係數)

  $$T = \left[1 + \frac{(qV_0 \sinh(\beta d))^2}{4E(qV_0 - E)}\right]^{-1}$$

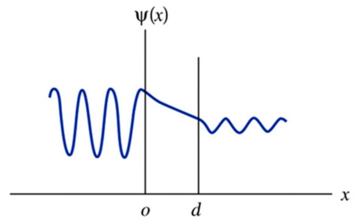
  where $\beta = \sqrt{2m_n(qV_0 - E)}/\hbar$
- If $\beta \cdot d >> 1$ (i.e., V_0↑, or d↑, or E↓)

  $\Rightarrow T \approx e^{-2\beta d} = e^{-2d\sqrt{2m_n(qV_0 - E)}/\hbar}$

  ⇒ T is small
- If we want T ↑, we need d ↓, qV_0 ↓, E ↑, m^* ↓



(a)



(b)

(a) Band diagram of a semiconductor potential barrier with a distance *d*.
(b) Schematic representation of the wave function across the potential barrier.