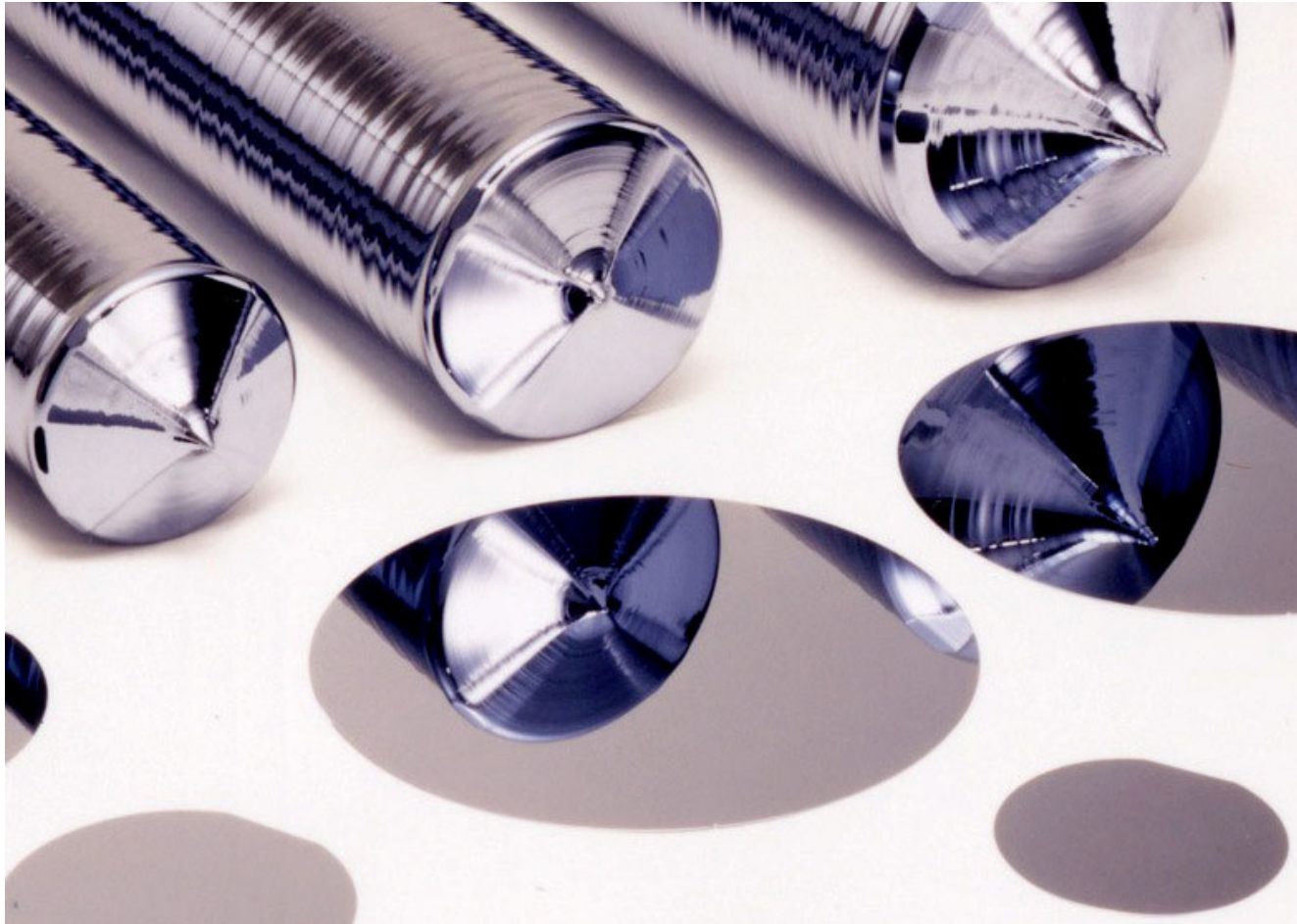


COMPOSANTS SEMI-CONDUCTEURS

I) Formation de bandes

P.A. Besse

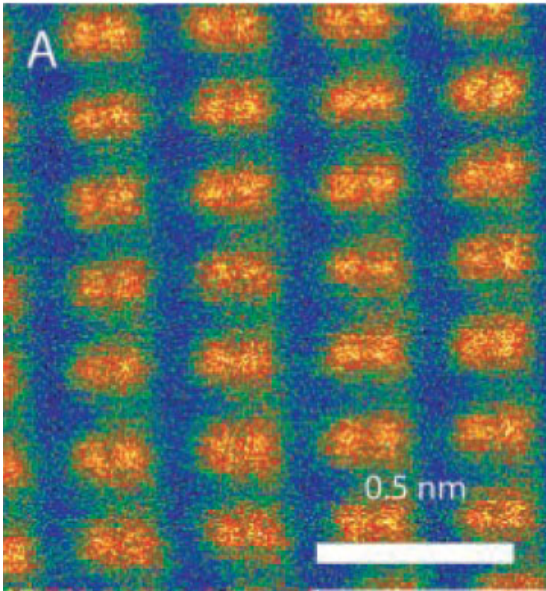
EPFL



Composition et propriétés des plaquettes de silicium ?

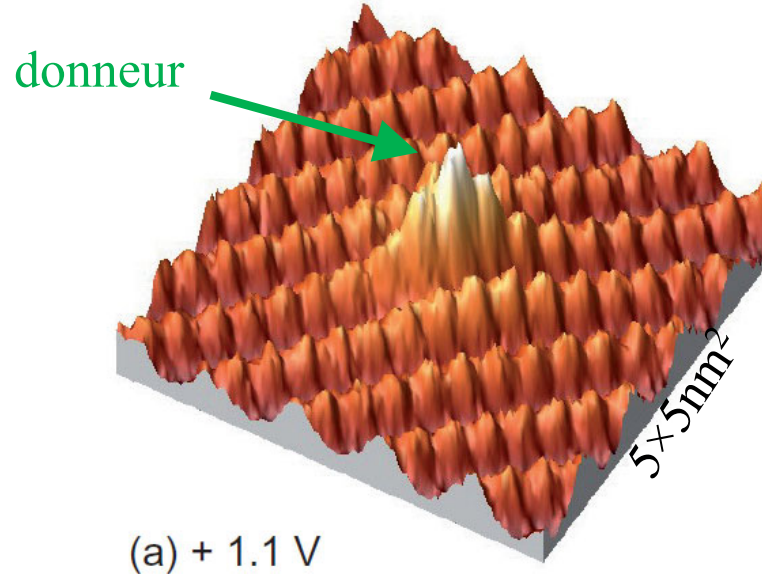
Réseau cristallin: images STM (Scanning Tunnel Microscope)

Silicium
[112]-orientation



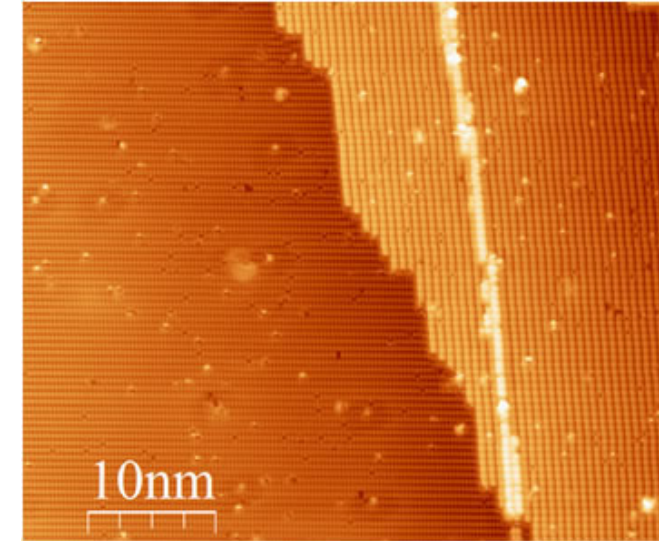
P.D.Nellist et al. « Direct Sub-Angstrom Imaging of a Crystal Lattice», Science, Vol. 305, 2004, p. 1741

N-doped Si
(111)-2×1 surface



C.Sürgers et al., «Electronic disorder of P- and B-doped Si at the metal–insulator transition investigated by scanning tunnelling microscopy and electronic transport», New Journal of Physics 15 (2013)

Silicium
(100)-surface



<http://www.nist.gov/pml/div683/grp02/abdm.cfm>

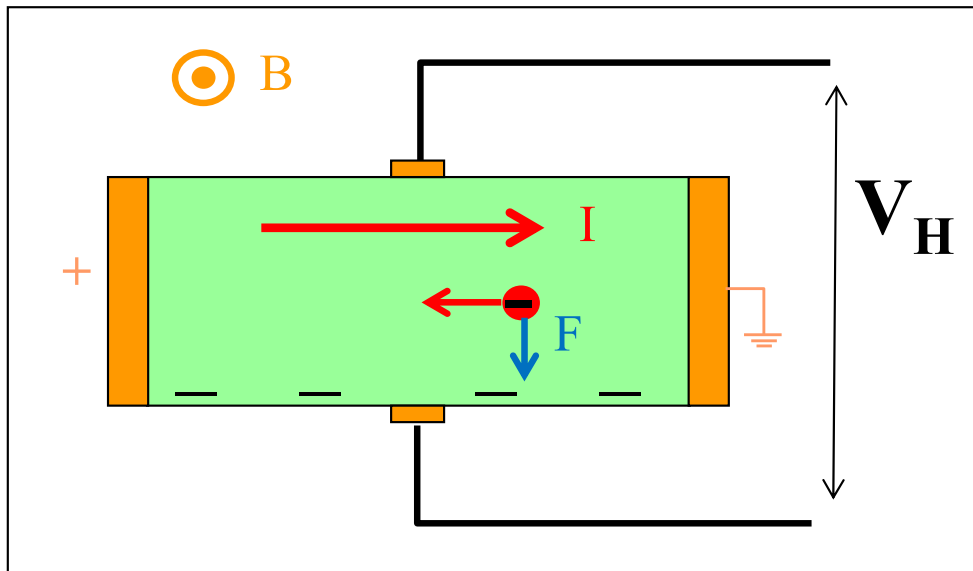


Le silicium et un réseau cristallin, on peut le décrire par des «modes globaux» et interpréter les porteurs libres comme des «paquets d'ondes» dans ce réseau.

Motivation:
Effet Hall →
charges libres positives ou négatives

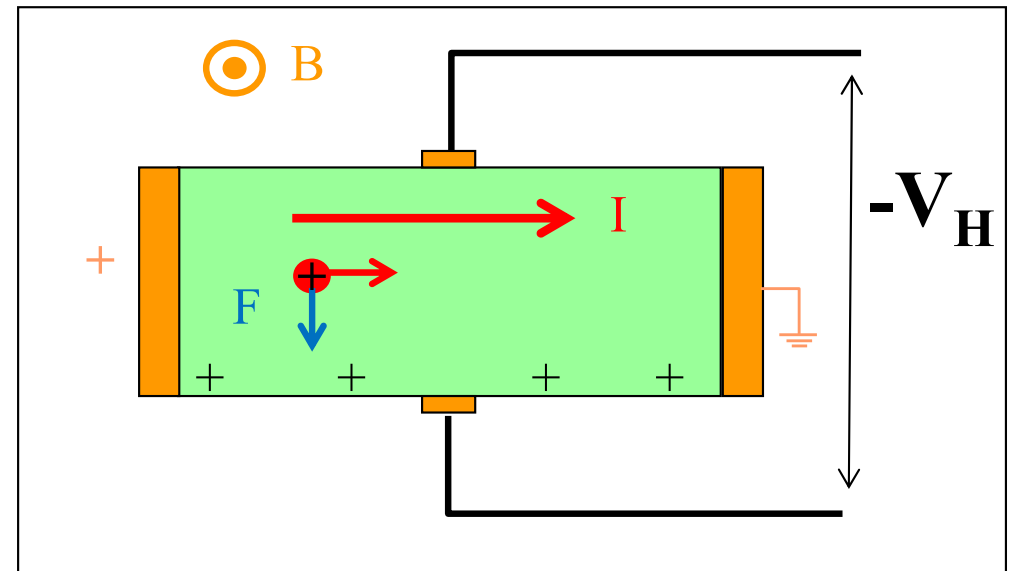
Dopé au phosphore ou à l'arsenic

Courant porté par des charges négatives



Dopé au bore

Courant porté par des charges positives

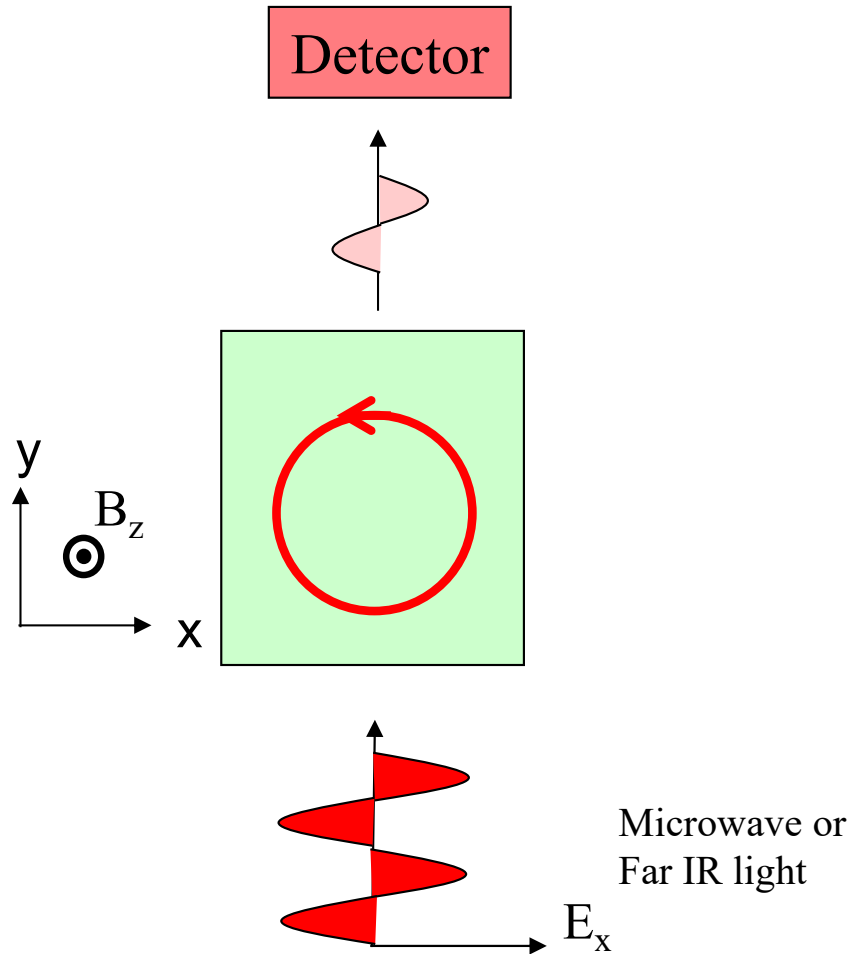


$$\vec{F} = q\vec{v} \times \vec{B} \cong \vec{I} \times \vec{B}$$

Le signe de la tension de Hall V_H dépend des charges porteuses du courant

Les deux signes de la tension de Hall sont possibles et dépendent du choix de dopant !!!

Masses des porteurs dans le cristal résonance cyclotronique



Dans une cavité résonante:

- Champ B statique
- Champ E haute fréquence ω_0

Le champ B est varié.

$\omega_c = \omega_0 \rightarrow$ Résonance
 $\rightarrow$ Absorption d'énergie à la fréquence de résonance.

La masse effective perpendiculaire à B est déterminée.

Fréquence cyclotron:

$$\omega_c = \frac{qB}{m}$$

[Animation et principe du cyclotron](#)

Motivation: masses anisotropiques

Résonance cyclotronique dans le silicium

Dresselhaus, Phys. Rev. Vol. 98, (1955), pp. 368-384

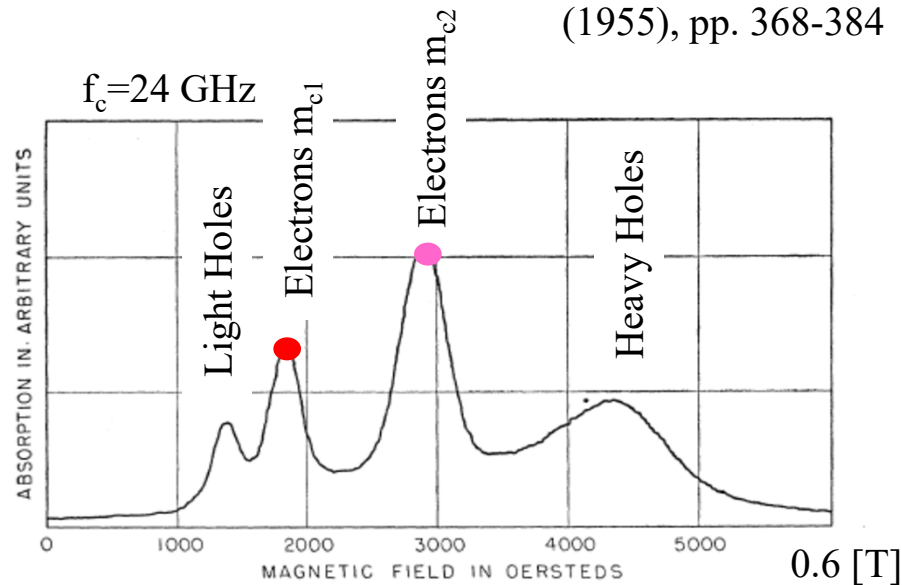


FIG. 3. Typical cyclotron resonance results in silicon near 24 000 Mc/sec and 4°K: static magnetic field orientation in a (110) plane at 30° from a [100] axis.

- Plusieurs résonances
- Masses proches de celle de l'électron
- Masses variables selon l'orientation du wafer dans le champ magnétique

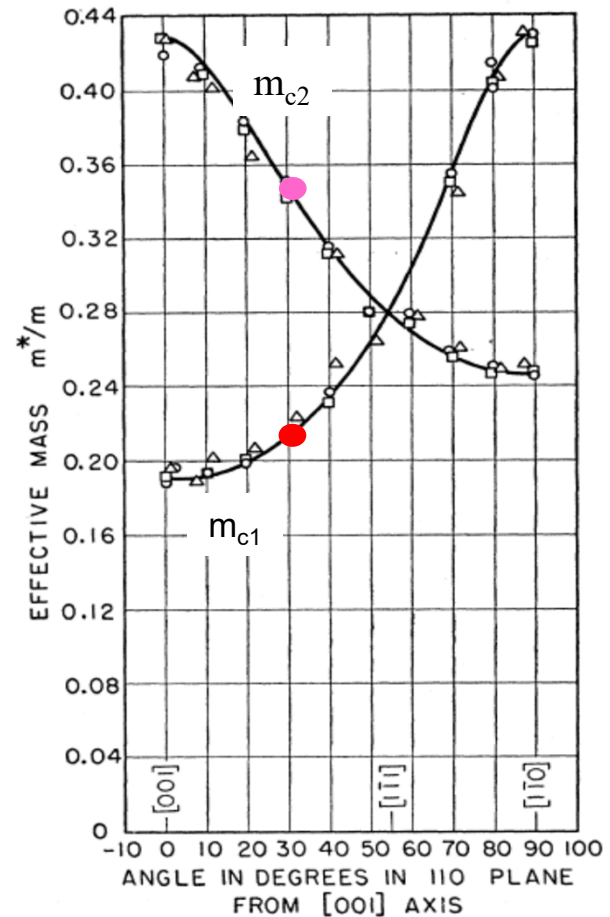


FIG. 6. Effective mass of electrons in silicon at 4°K for magnetic field directions in a (110) plane; the theoretical curves are calculated from Eq. (38), with $m_l = 0.98m$; $m_t = 0.19m$.

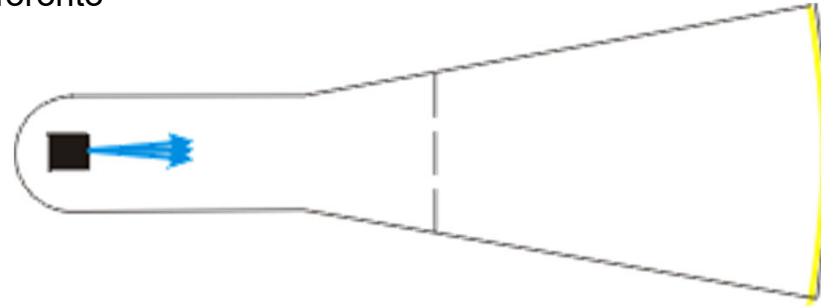
Particule

ou/et

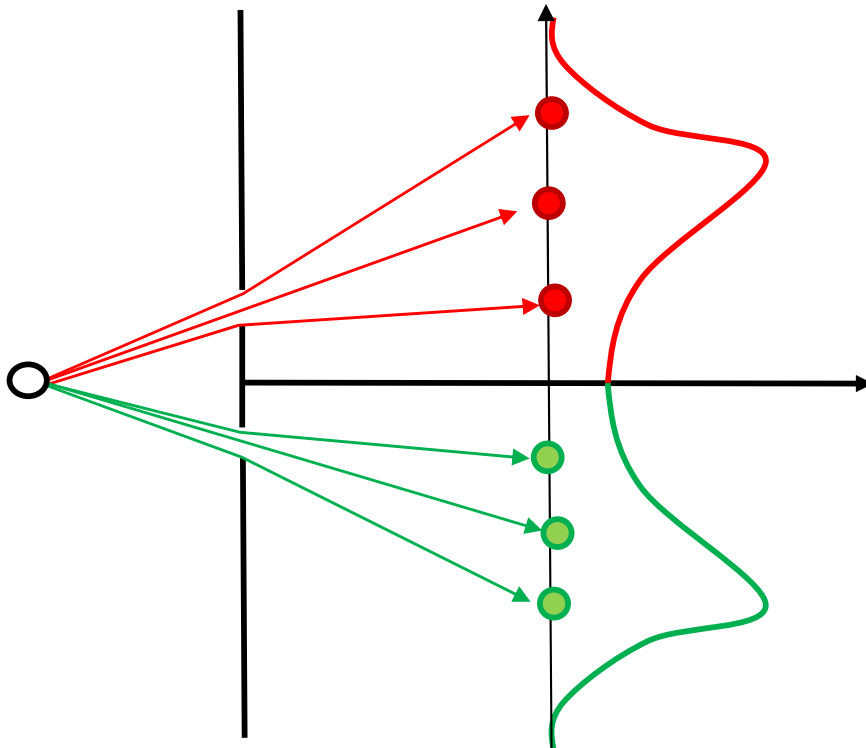
Onde ??

Interférences d'électrons: (fentes de Young électroniques)

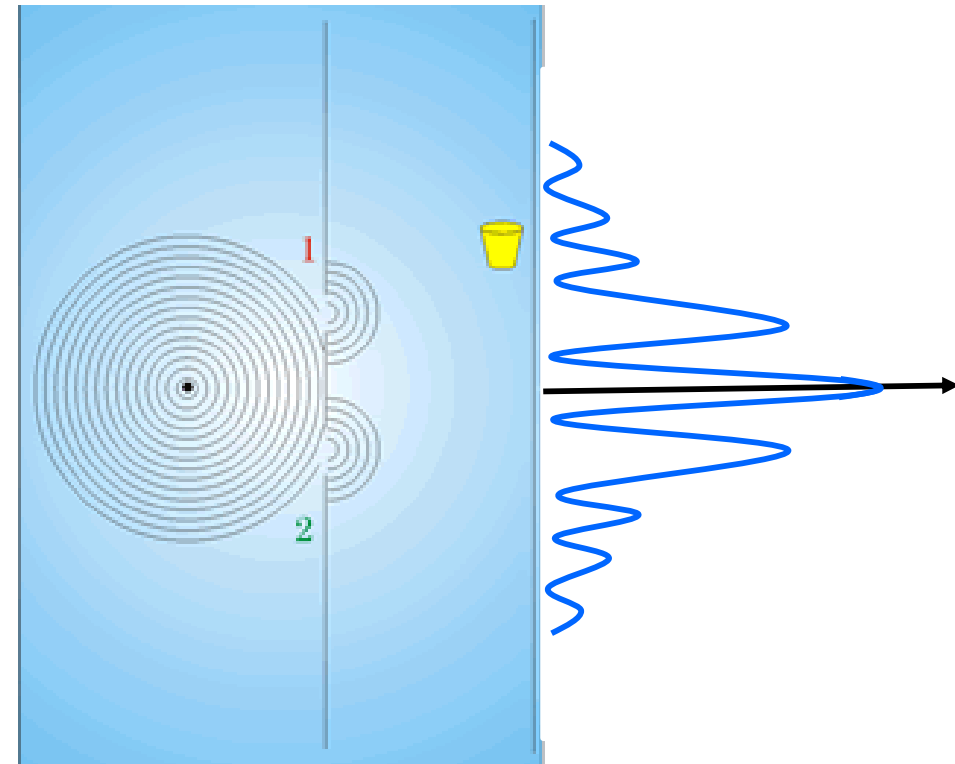
Inspiré de D. M. Harrison, Univ. of Toronto



Hypothèse «particules»



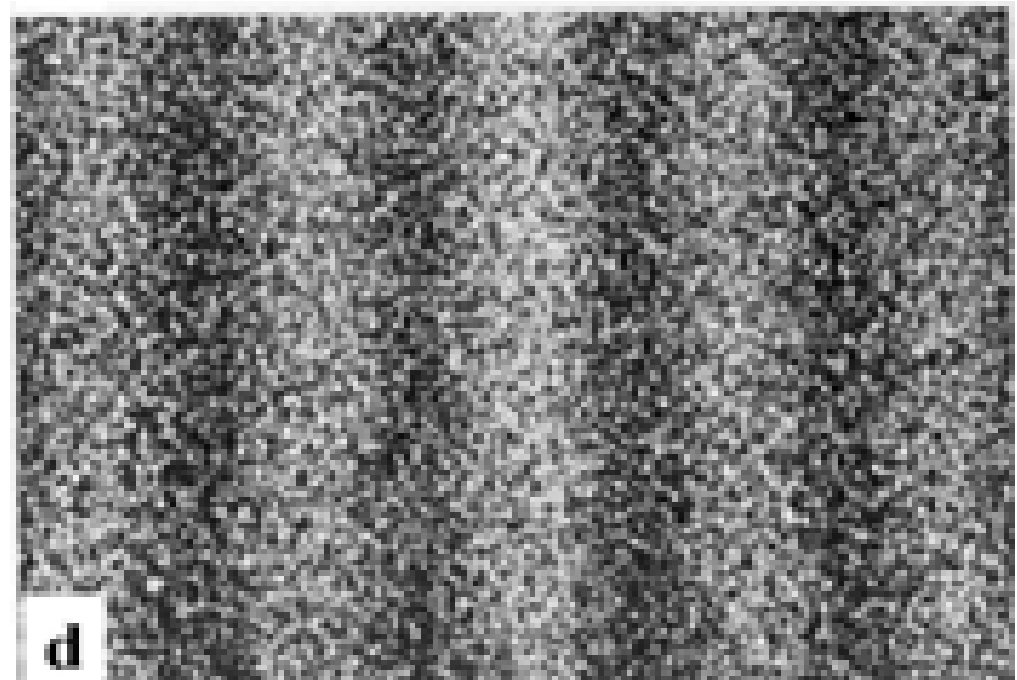
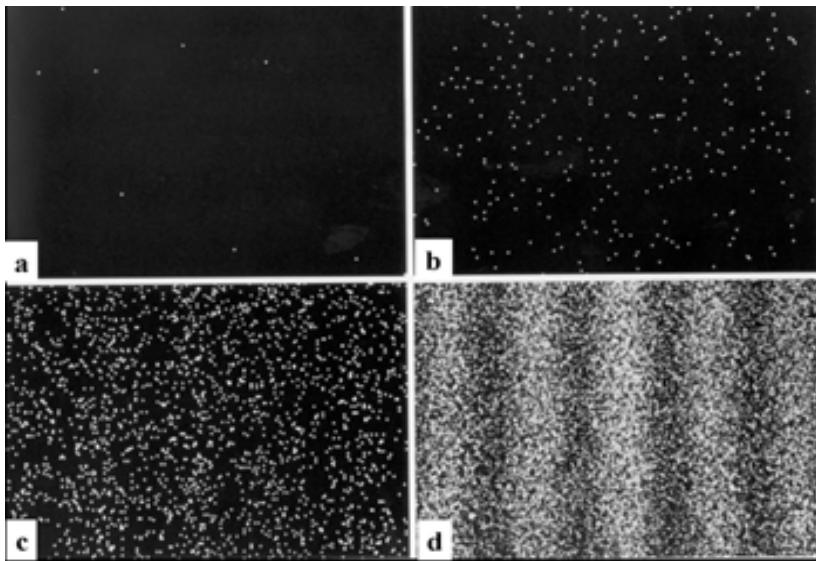
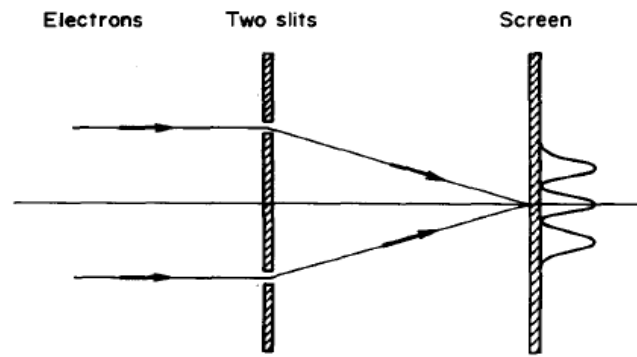
Hypothèse «ondes»



Particule / Onde

Motivation: interférences d'électrons

Double-slit experiment with single electron



<http://www.hqrd.hitachi.co.jp/em/movie/doubleslite-n.wmv>

A. Tonomura, Am. J. Phys. 57 (2), 1989, pp. 117-120

Interactions → Particules

Propagation → Fonction d'onde

$$\psi(\vec{x}, t) = A \cdot e^{i\vec{K} \cdot \vec{x}} \cdot e^{-i\omega t}$$

Particules:

- Energie E
- Impulsion $\vec{P}$

« Planck »

$$E = \hbar \cdot \omega$$

$$\vec{P} = \hbar \cdot \vec{K}$$

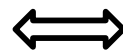
« De Broglie »

Ondes:

- Fréquence $\omega = 2\pi\nu$
- Vecteur d'onde $\vec{K}$
 $|\vec{K}| = 2\pi / \lambda$

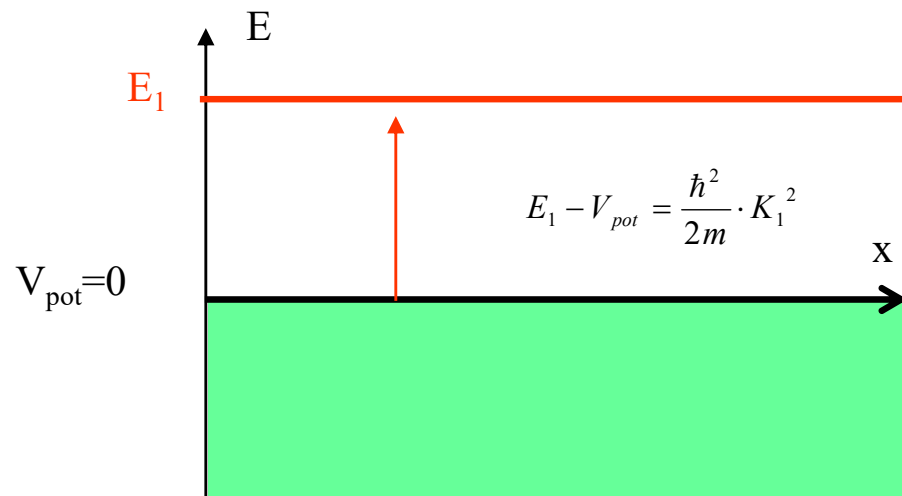
Relation de l'énergie

$$E = \frac{P^2}{2m} + V_{pot}$$



$$\hbar\omega = \frac{(\hbar K)^2}{2m} + V_{pot}$$

Relation de dispersion



$$\psi_1(x, t) = A_1 \cdot e^{iK_1 \cdot x} \cdot e^{-i \frac{E_1}{\hbar} \cdot t}$$

Modes
(Fourier)

Propagation

1) $E_1 > V_{\text{pot}}$

K_1 est réel

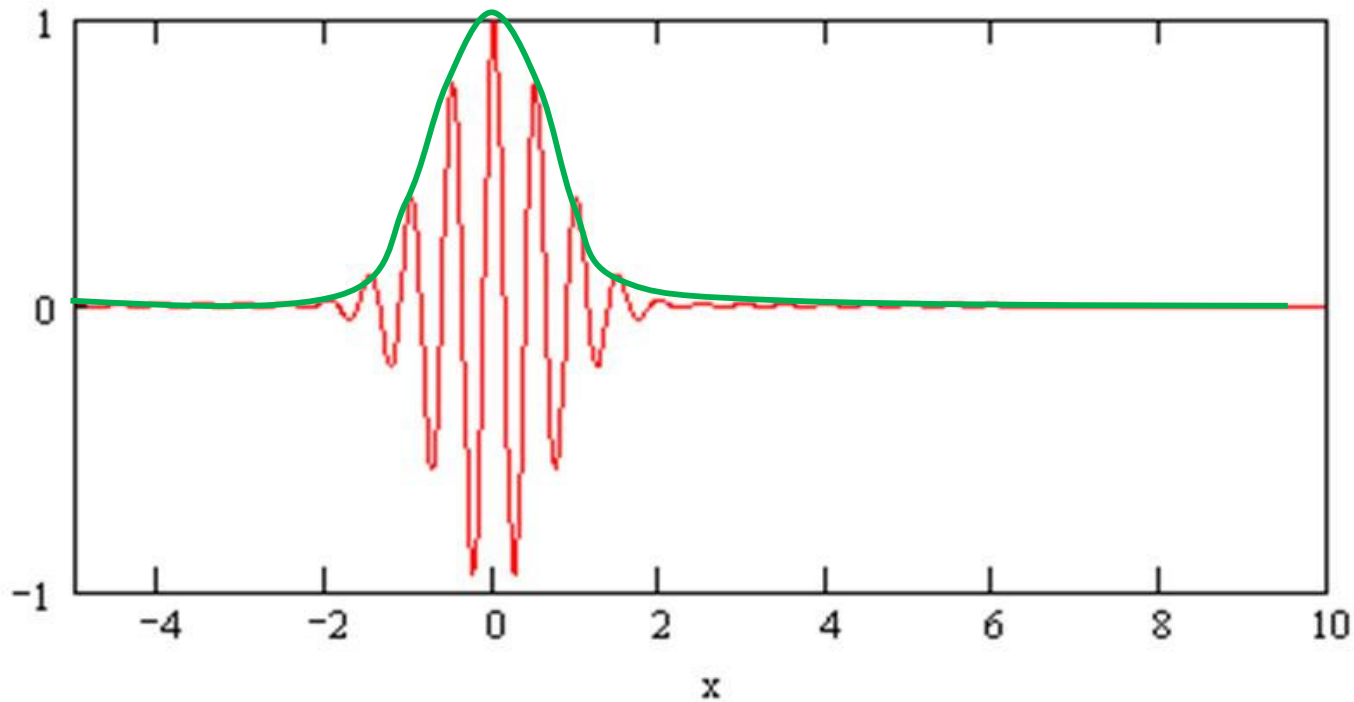
Il existe un continuum d'ondes planes de la forme sinus et cosinus.

2) $E_1 < V_{\text{pot}}$

K_1 est imaginaire

Les ondes sont évanescentes et ne peuvent donc pas se propager.

Electron libre = «bit»
= porteuse et son enveloppe

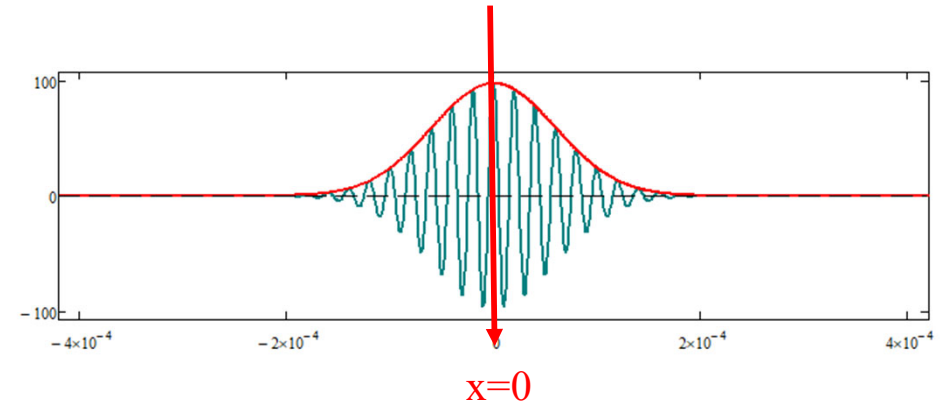


Propagation comme un «paquet d'ondes» autour de la porteuse

Amplitude en t=0

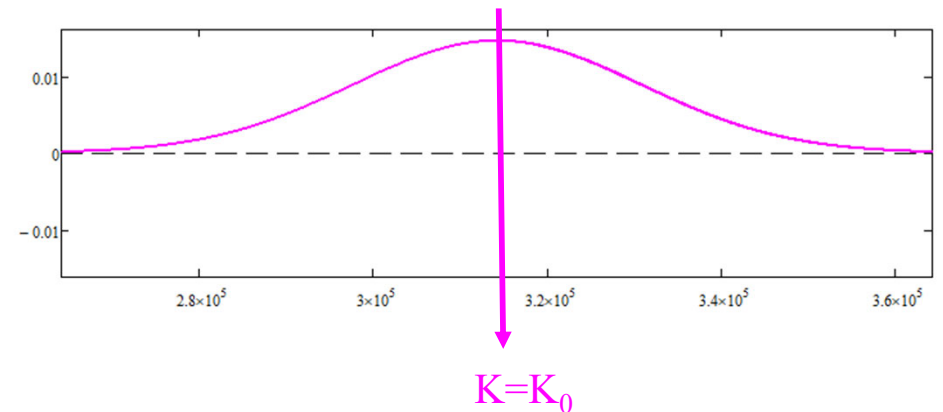
$$|\psi_0(x)\rangle = \left(\frac{1}{\pi \cdot \sigma_0^2} \right)^{1/4} \cdot e^{-\frac{x^2}{2\sigma_0^2}} \cdot e^{iK_0x}$$

enveloppe
Porteuse



Transformée de Fourier en t=0

$$|\tilde{\psi}_0(K)\rangle = \left(4\pi\sigma_0^2 \right)^{1/4} \cdot e^{-\frac{\sigma_0^2(K-K_0)^2}{2}}$$



Variance en x: $\sigma_x^2 = \sigma_0^2$

Variance en K: $\sigma_K^2 = 1 / \sigma_0^2$

Propagation dans l'espace de Fourier

$$|\tilde{\psi}(K, t)\rangle = \left(4\pi\sigma_0^2\right)^{1/4} \cdot e^{-\frac{\sigma_0^2(K-K_0)^2}{2}} \cdot e^{-i\omega t}$$

Propagation

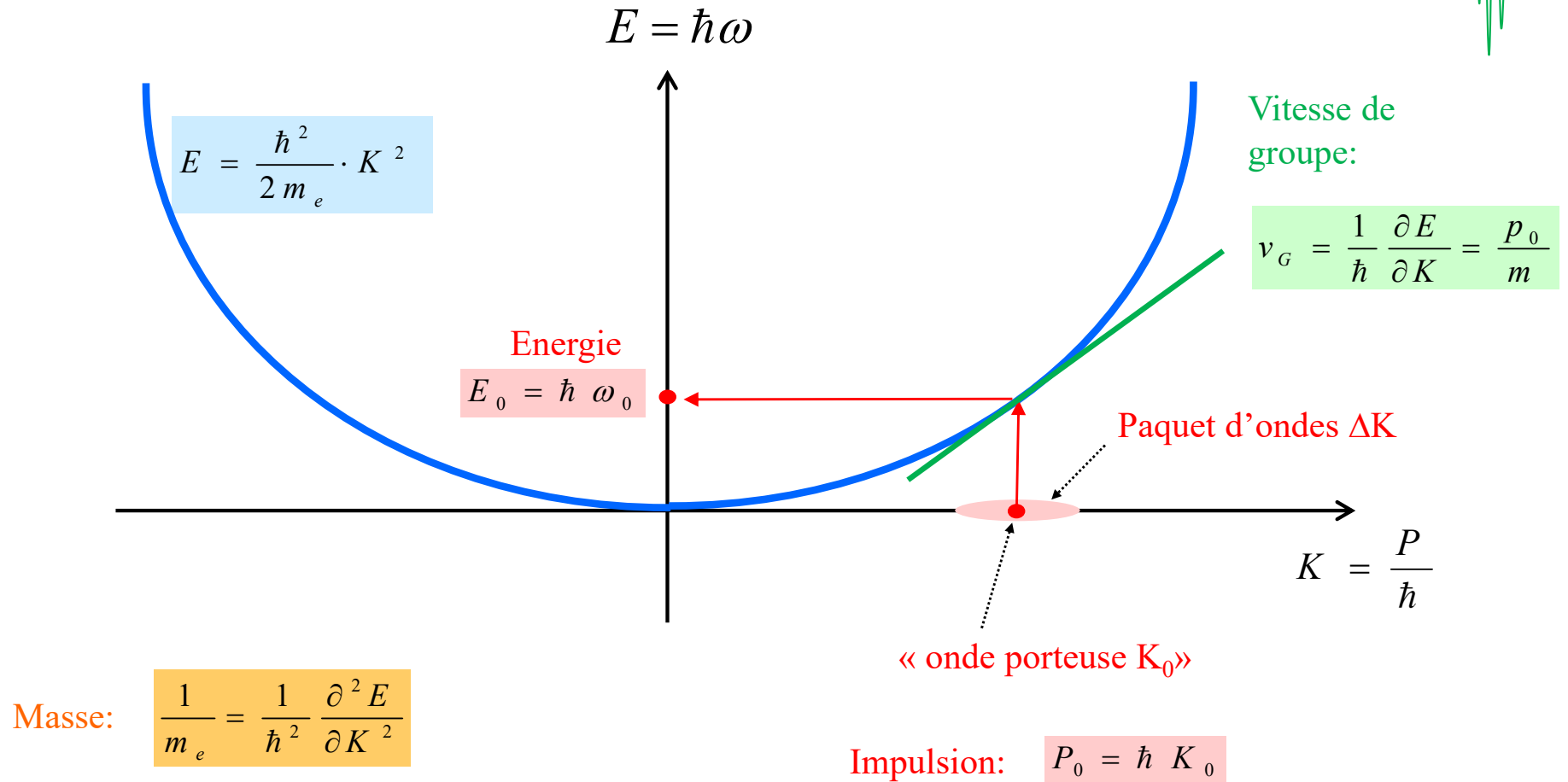
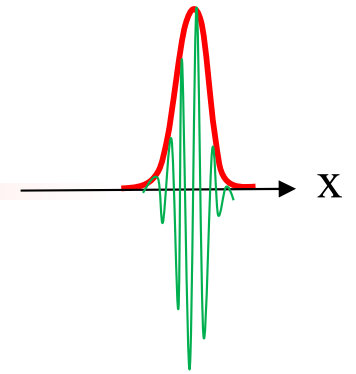
$\hbar\omega = \frac{(\hbar K)^2}{2m}$

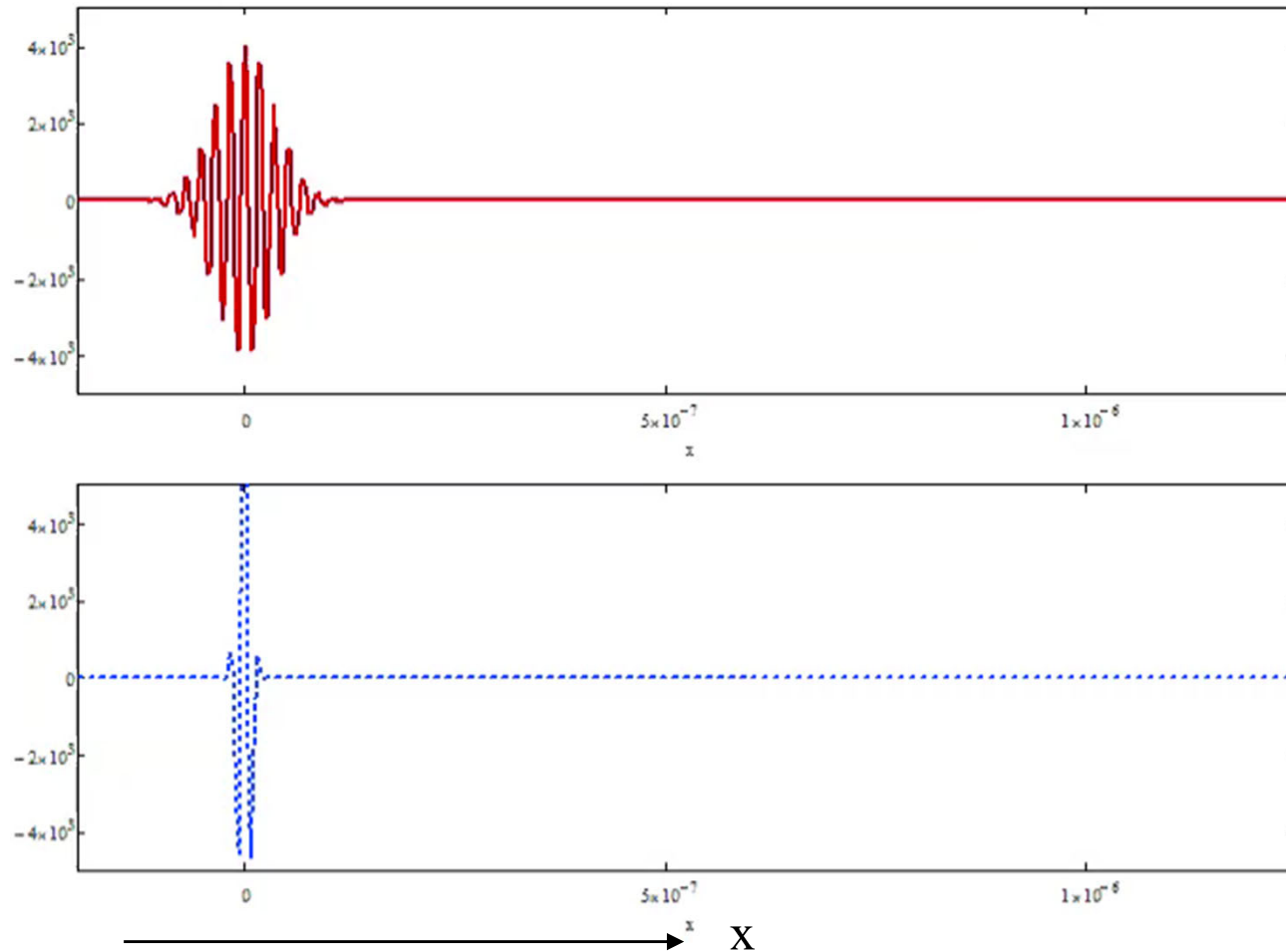
Retour dans l'espace x par transformée de Fourier inverse:

$$|\psi(x, t)\rangle \approx \left(\frac{1}{\pi \cdot \sigma^2}\right)^{1/4} \cdot e^{-\frac{(x-v_G t)^2}{2\sigma^2}}$$

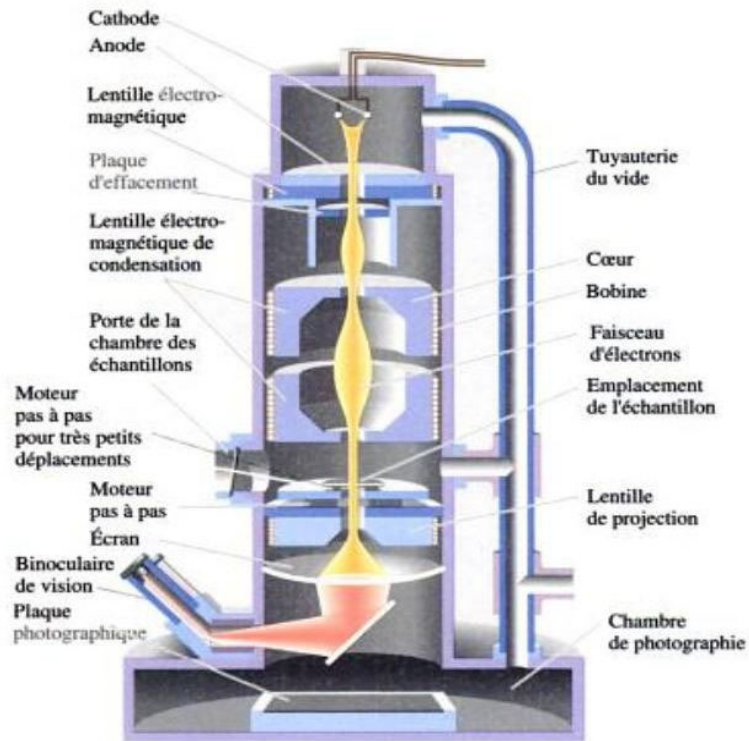
Vitesse de groupe: $v_G \equiv \frac{1}{\hbar} \frac{\partial E}{\partial K} \Big|_{K=K_0} = \frac{\hbar K_0}{m} = \frac{p_0}{m}$

Dispersion: $\sigma = \sigma_0 \cdot \sqrt{1 + \left(\hbar t / m \sigma_0^2\right)^2}$



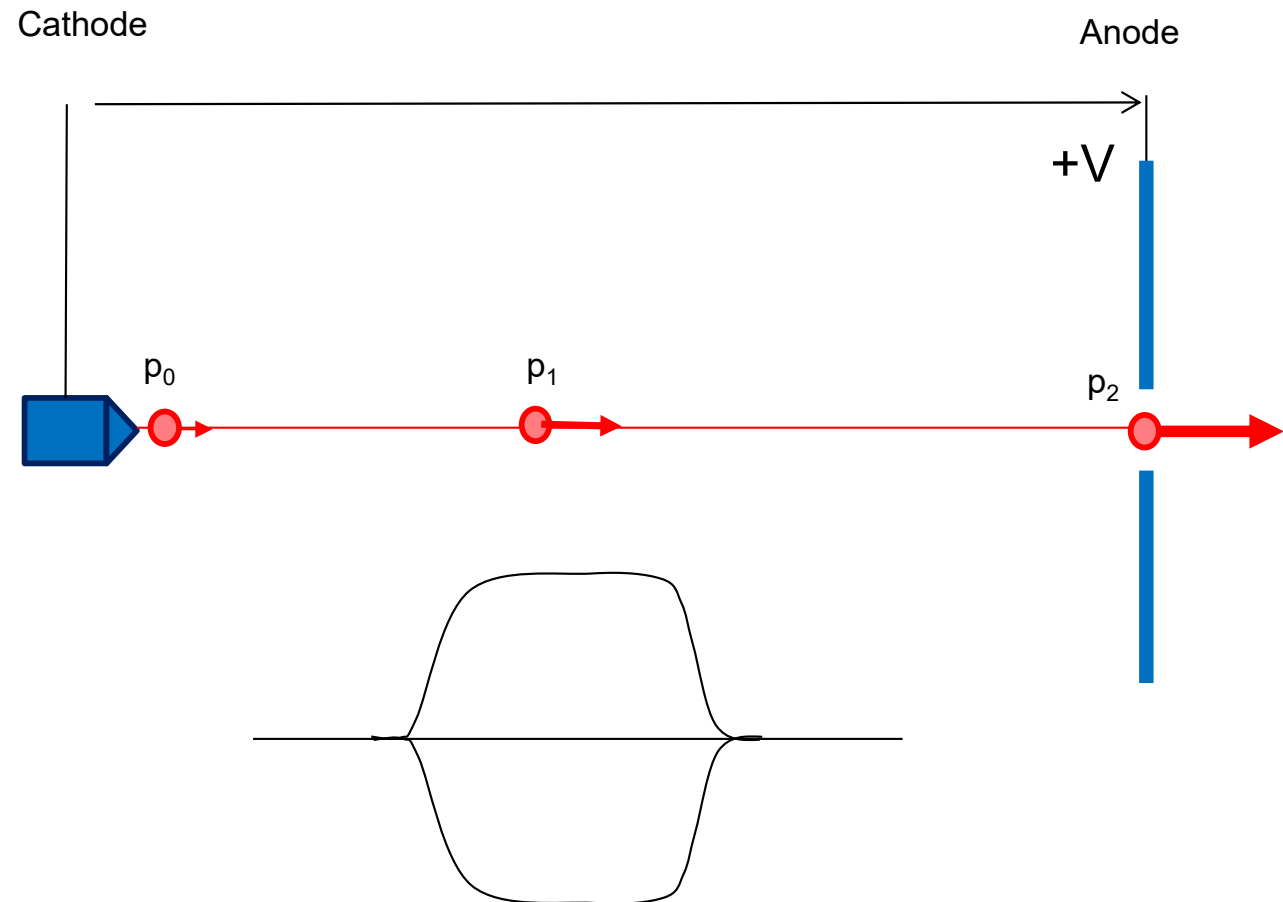


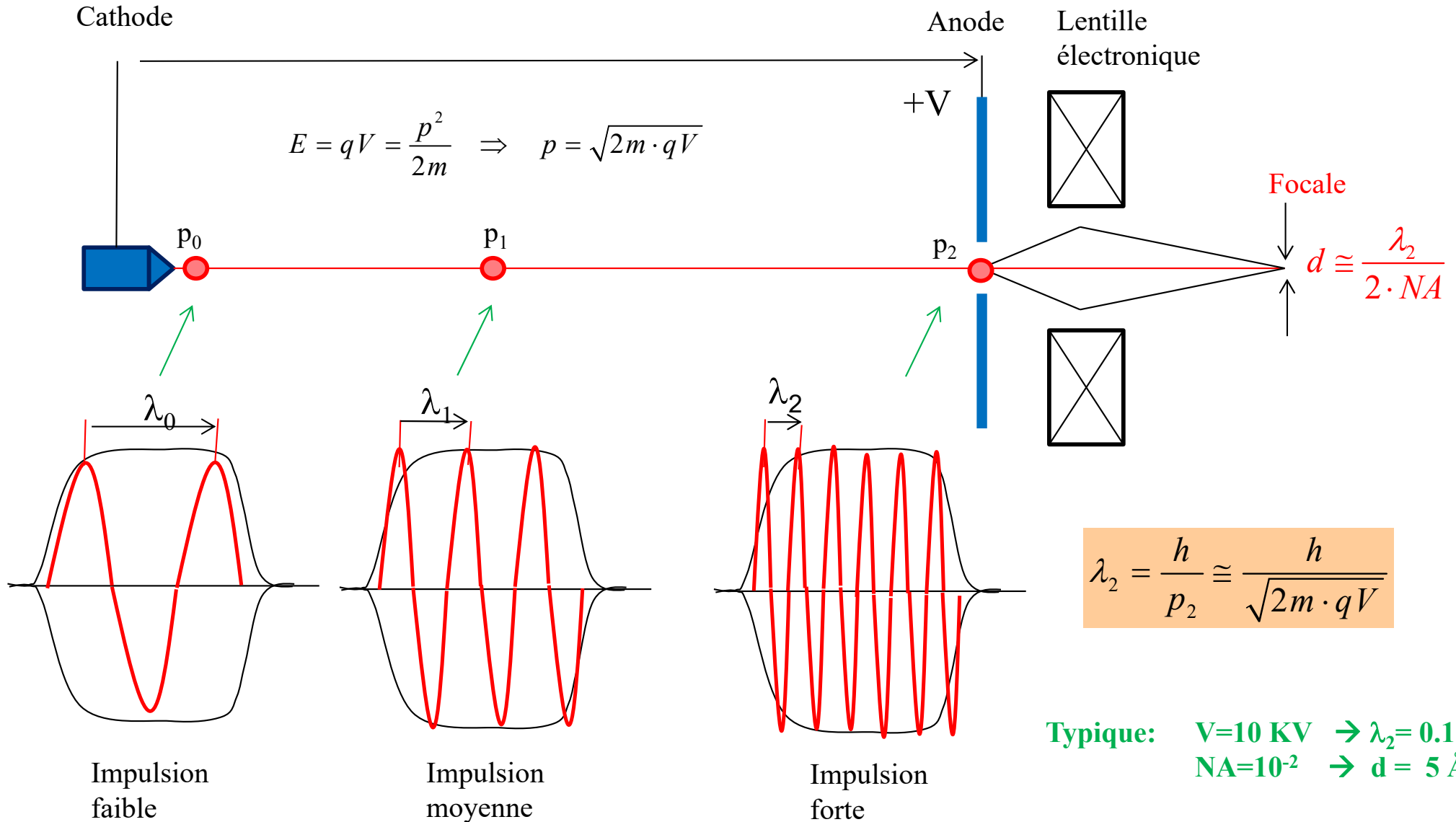
TEM principle



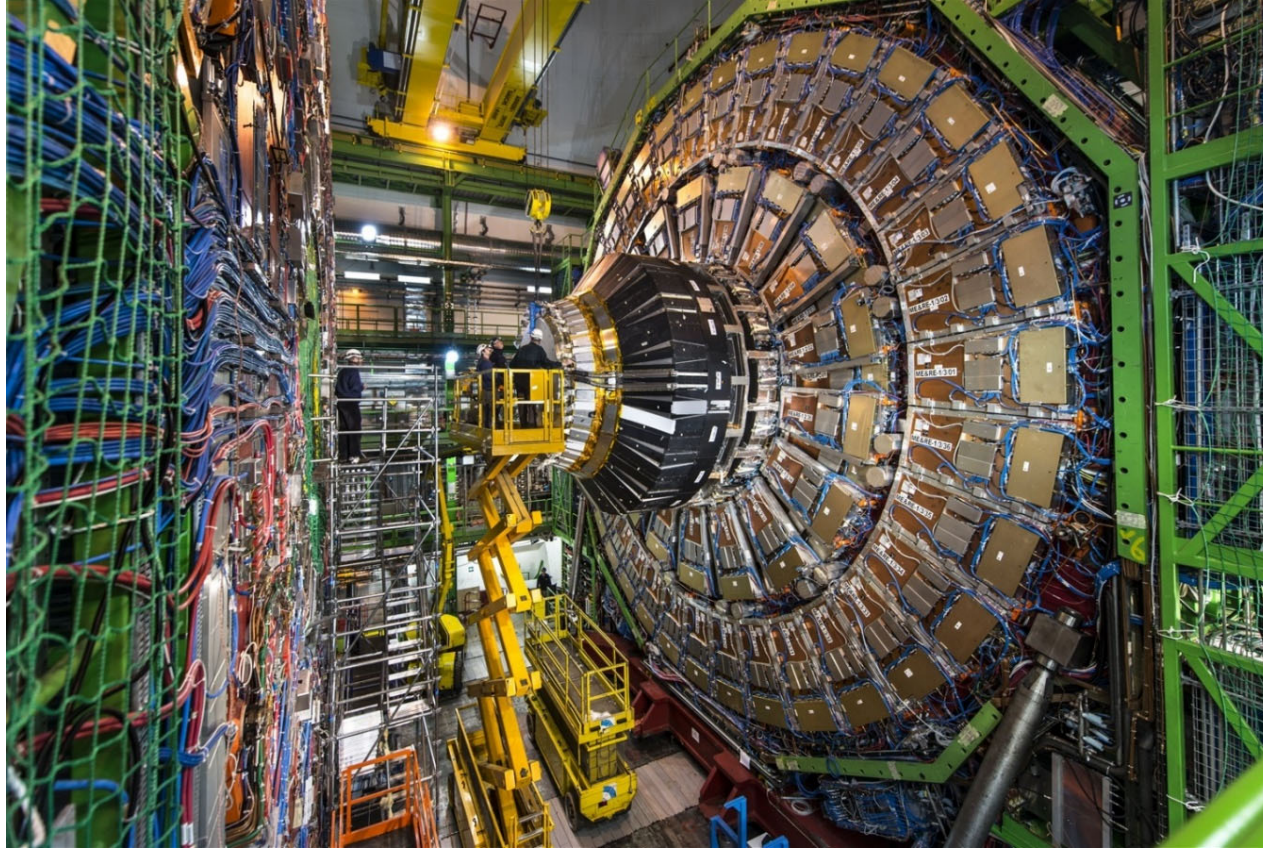
Eugene Hecht, « Physique », p. 1171

Canon à électrons simplifié





Quel est le «microscope» le plus puissant au monde ?



... le LHC (Large Hardron Collider)

$$\lambda_2 = \frac{h}{p_2} \cong \frac{h}{\sqrt{2m \cdot qV}}$$

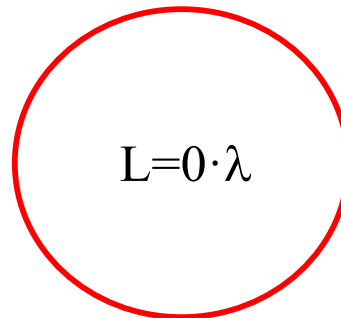
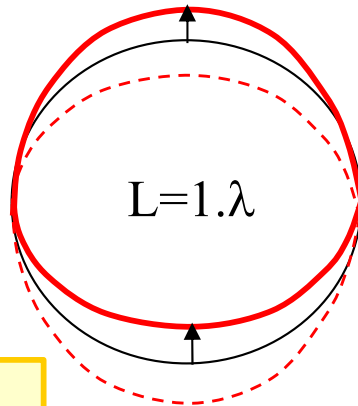
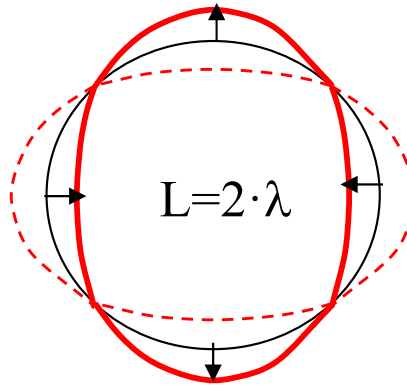
Orbitales

et

Niveaux discrets d'énergie



Nova Physics



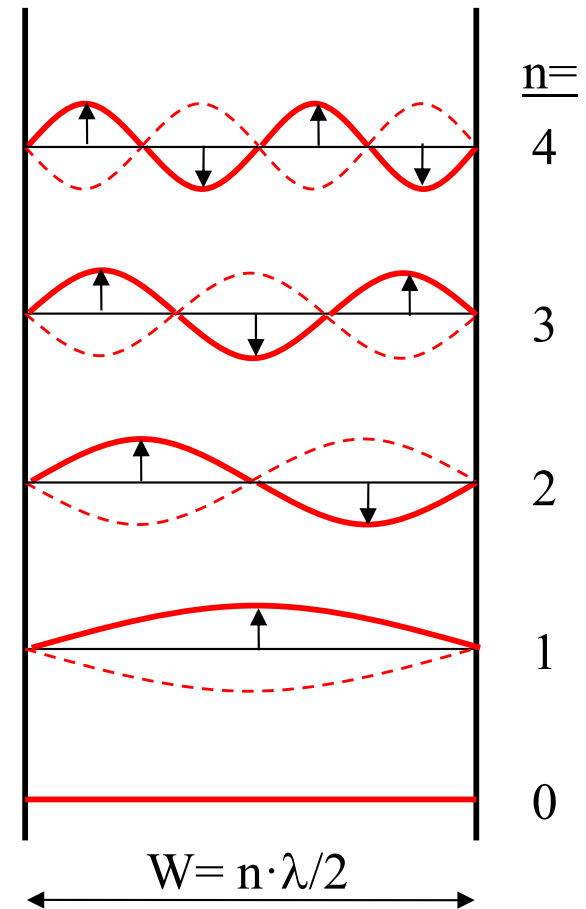
$$L = n \cdot \lambda$$

$$\Rightarrow K \equiv \frac{2\pi}{\lambda} = \left(\frac{2\pi}{L} \right) \cdot n$$

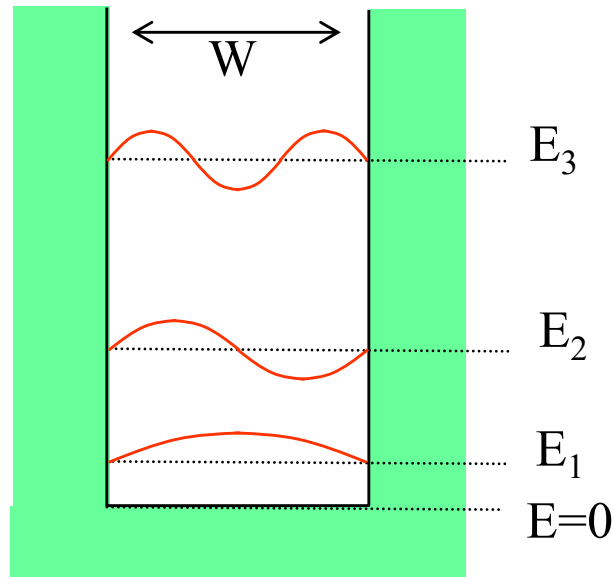
Discret et régulier

$$E = \frac{P^2}{2m} = \frac{\hbar^2 K^2}{2m}$$

$$E = n^2 \frac{\hbar^2 \pi^2}{2mW^2}$$



Puits infini

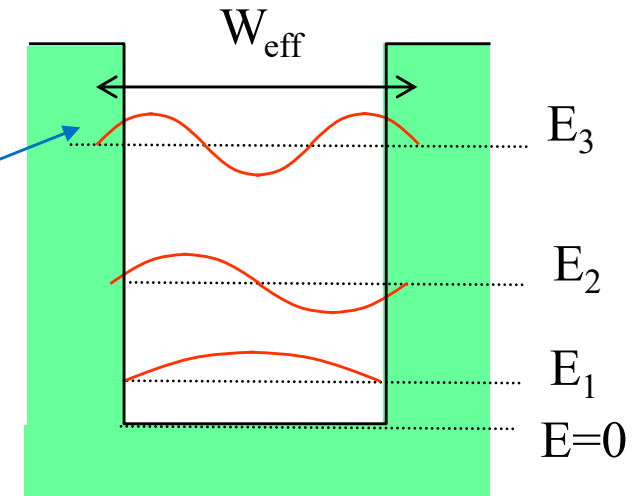


$$n \frac{\lambda}{2} = W$$

$$E_n = \frac{\hbar^2 K^2}{2m} = n^2 \cdot \frac{\hbar^2 \pi^2}{2m W^2}$$

Puits fini

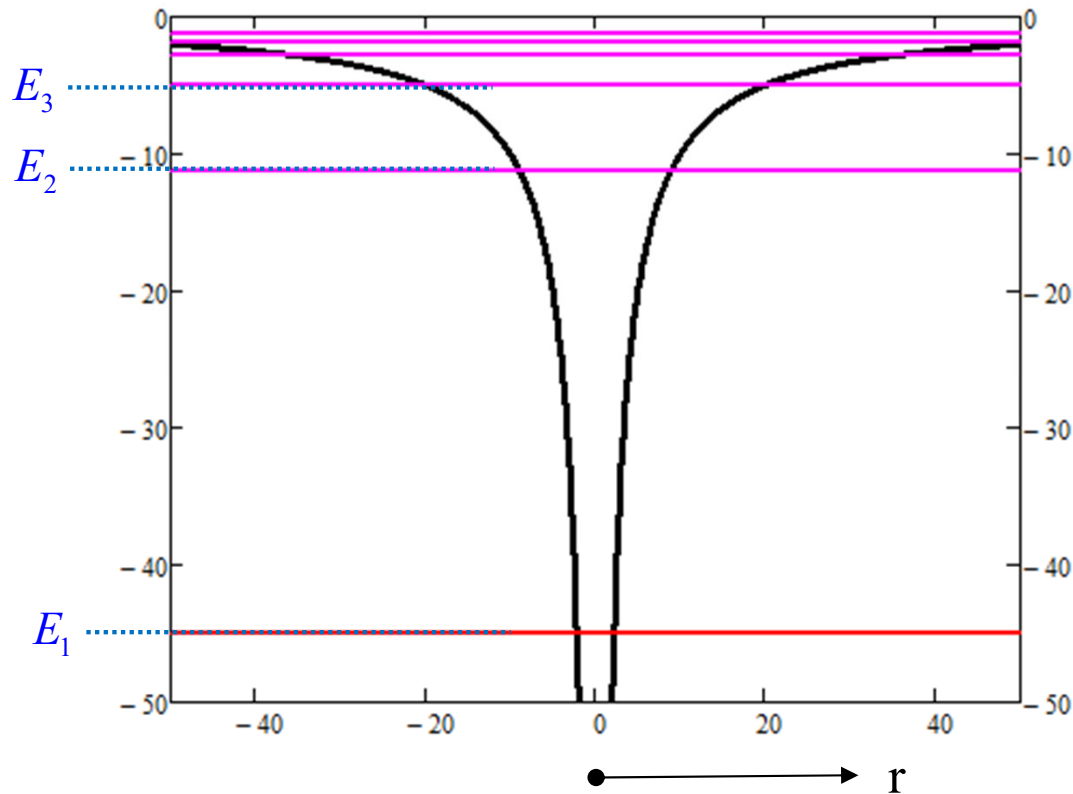
Ondes
évanescentes



Pénétration latérale
surtout pour états supérieurs

« Etats discrets »

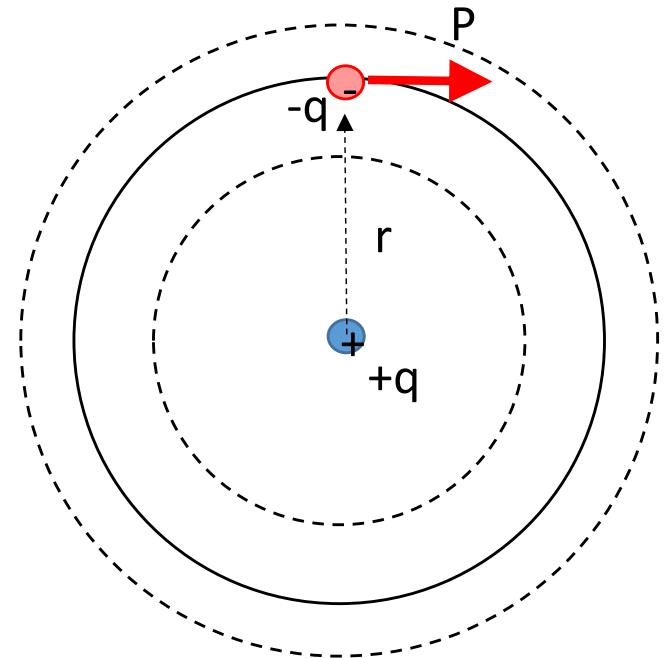
$$E_n \cong n^2 \cdot \frac{\hbar^2 \pi^2}{2m W_{\text{eff}}^2}$$

Potentiel en $1/r$ 

$$E_n \approx -\frac{1}{n^2}$$

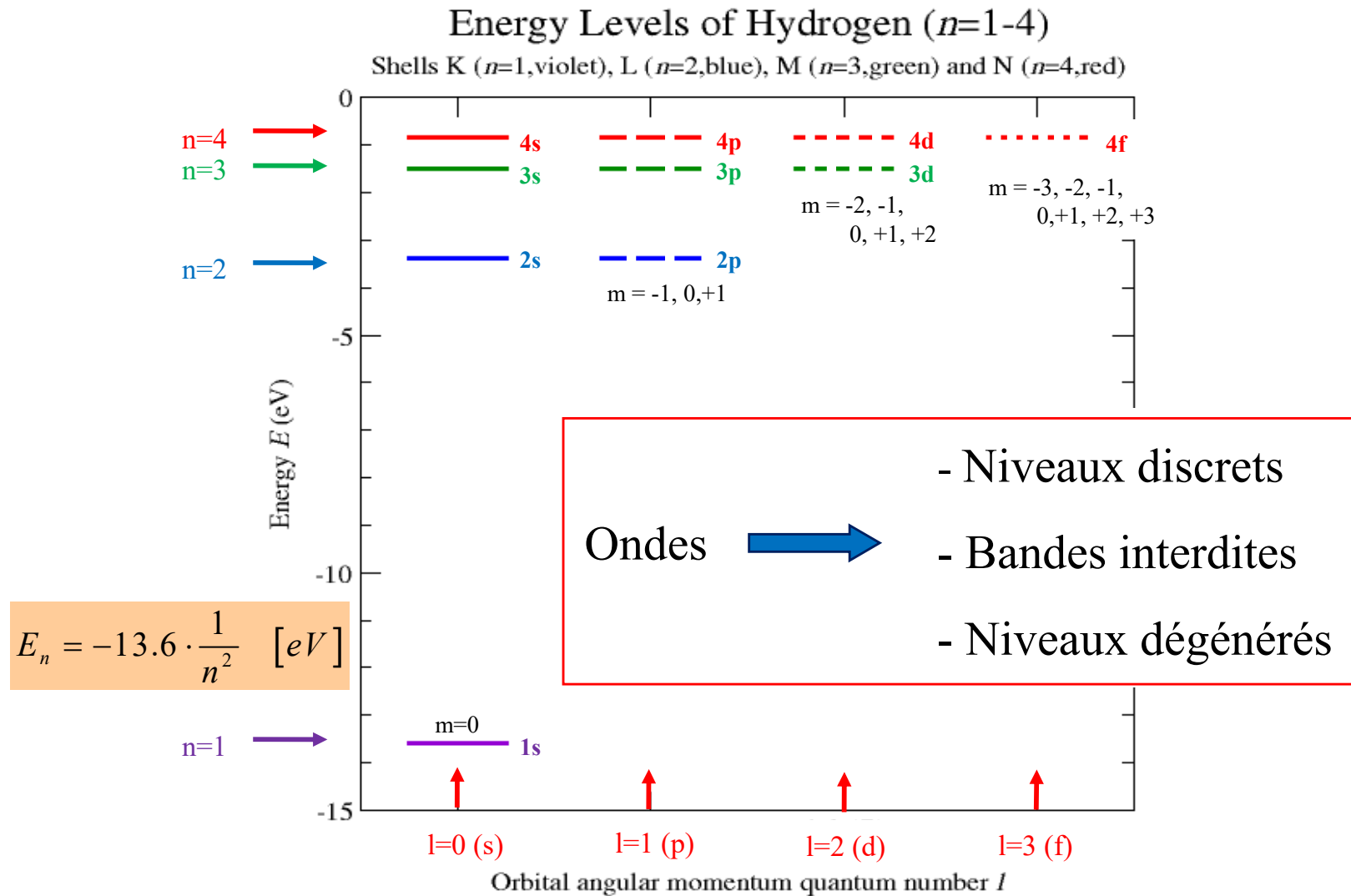
Centrifuge = Coulomb $\frac{v^2}{r} \approx \frac{1}{r^2}$

Onde stable $K \equiv \frac{2\pi}{\lambda} = \left(\frac{2\pi}{L}\right) \cdot n$



**Orbitales discrètes dans
l'atome d'hydrogène**

Niveaux d'énergie de l'hydrogène



http://en.wikipedia.org/wiki/Laplace-Runge-Lenz_vector

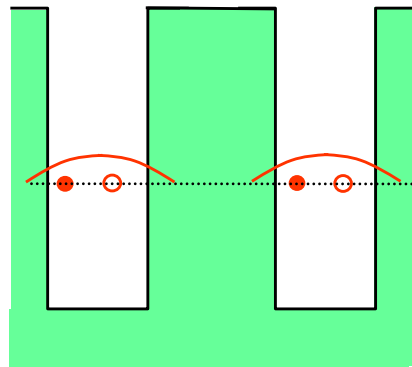
Liaisons covalentes

et

Formation de bandes

Atomes H

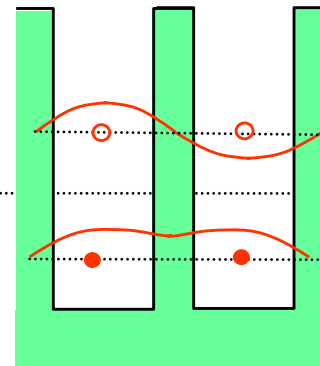
Deux atomes séparés
avec 1 électron chacun



Hybridation

Molécule H₂

Deux atomes proches
avec 1 électron chacun

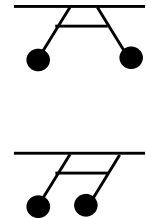


E₂

Anti-liant

E₁

Liant



Deux états identiques:

- localisés
- deux spins possibles par état
- un électron dans chaque puits

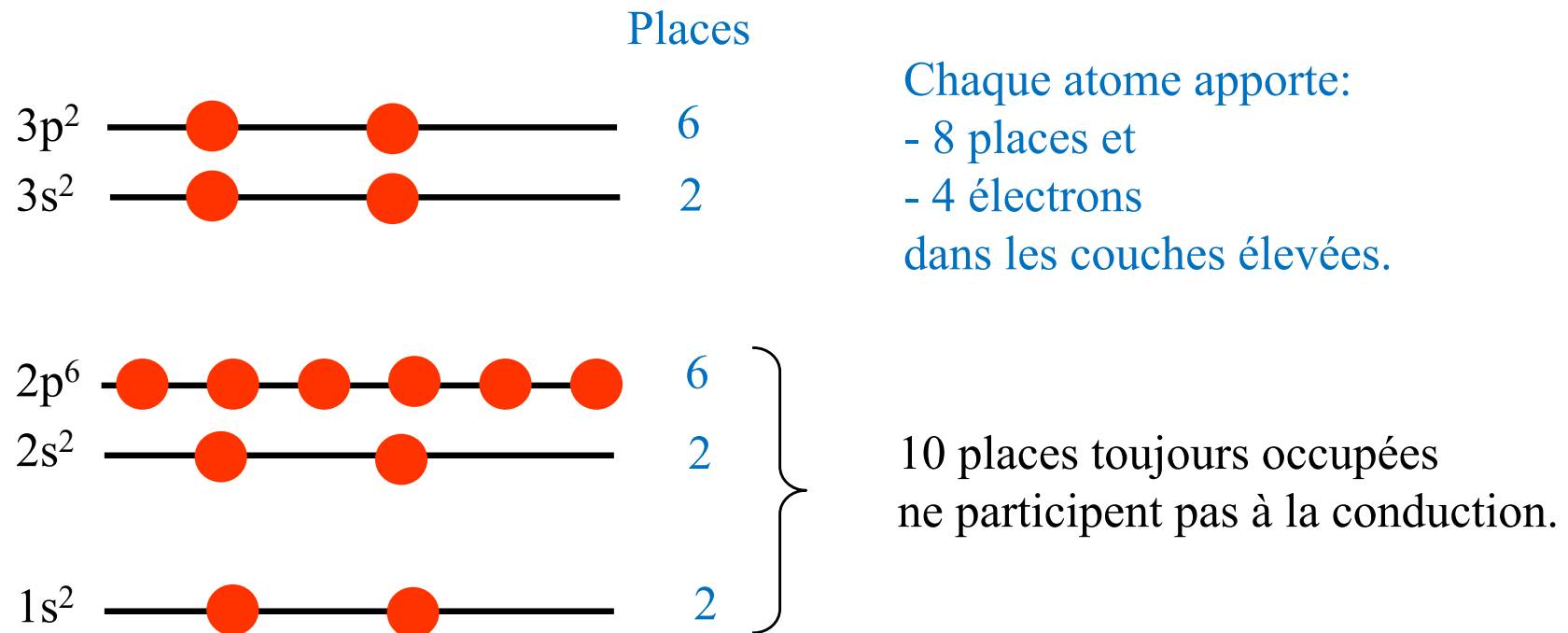
Etat « liant »:

- énergie profonde, occupé par un électron de chaque atome.

Etat « anti-liant »:

- énergie supérieure, libre à basse température

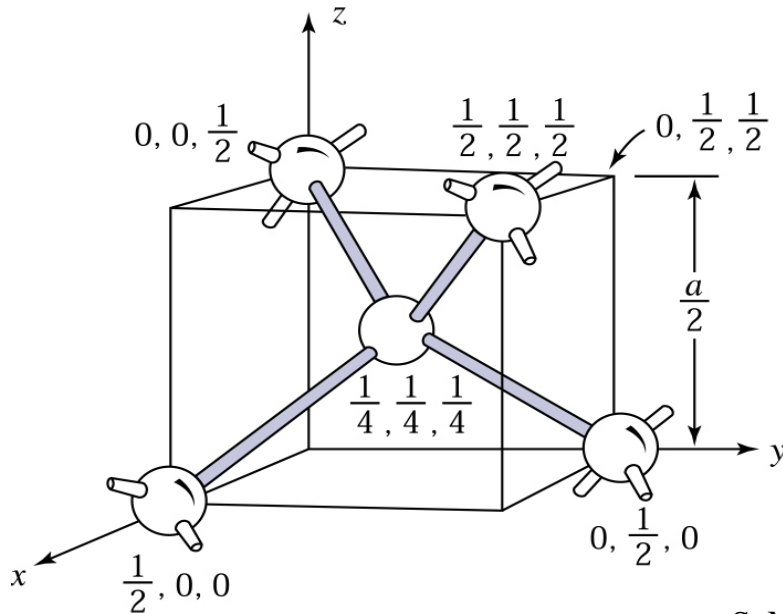
Structure électronique d'un atome isolé.



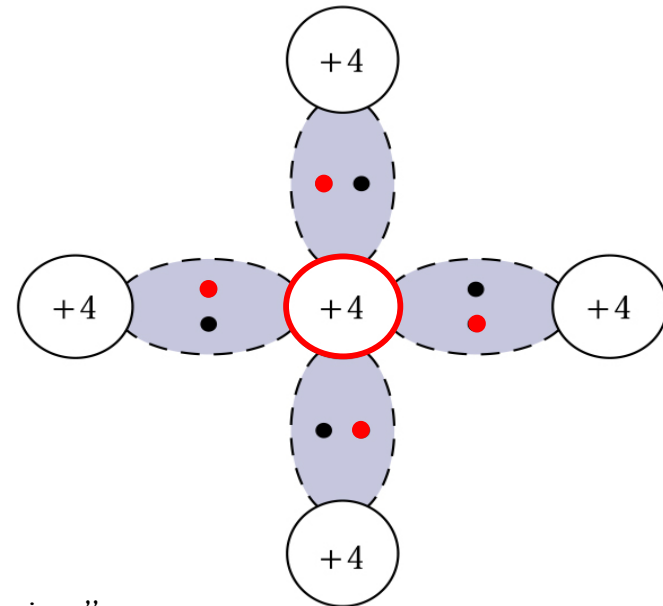
2 atomes =
8 électrons
16 places

→ 4 états liants sp^3 (8 places occupées par 8 électrons)
4 états anti-liants sp^3 (8 places libres à basse température)

Silicium



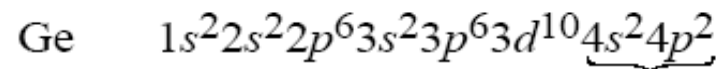
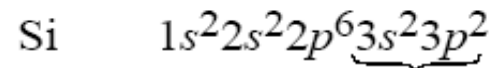
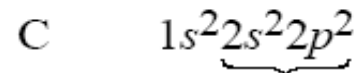
S. M. Sze "Semiconductor Devices"



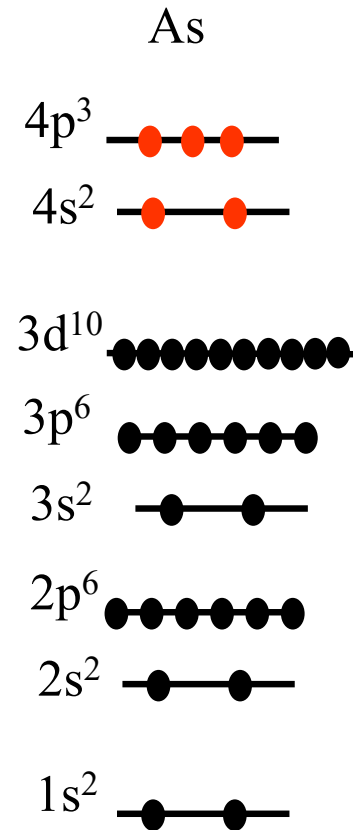
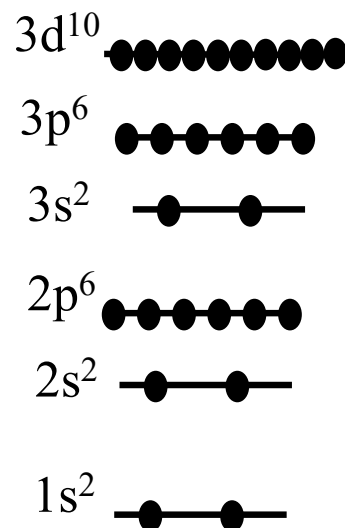
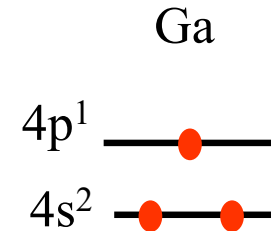
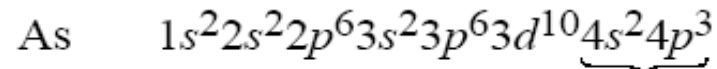
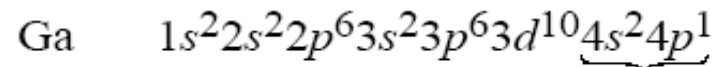


J. Singh: "Semiconductor Devices"

IV Semiconductors



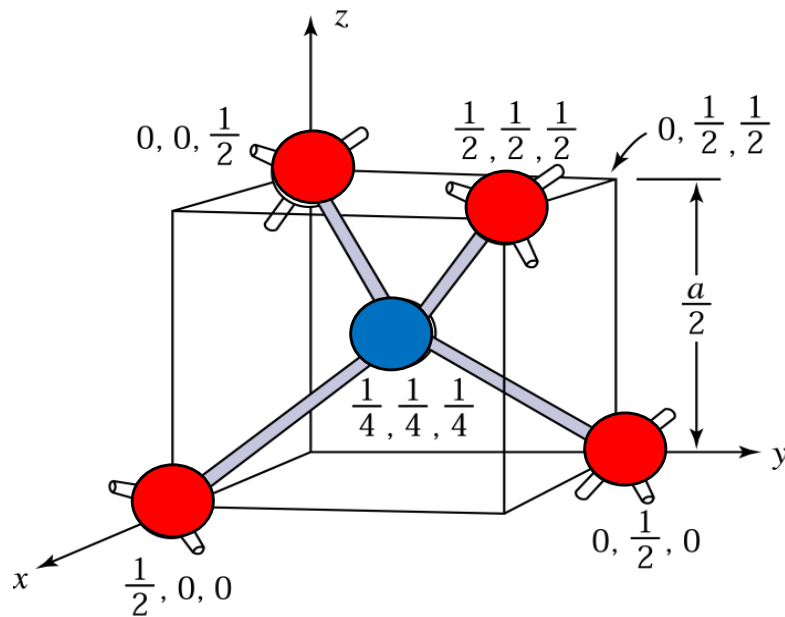
III-V Semiconductors



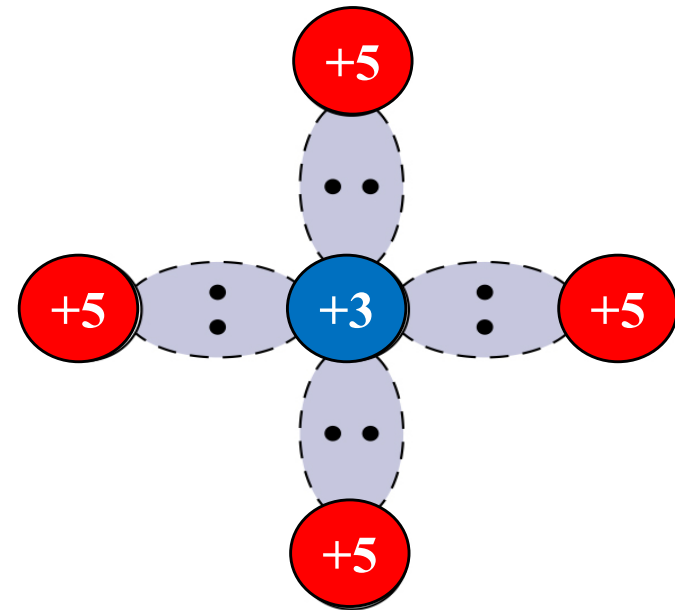
Si = 2 atomes = 8 électrons à placer sur les 4 liaisons tétraédriques

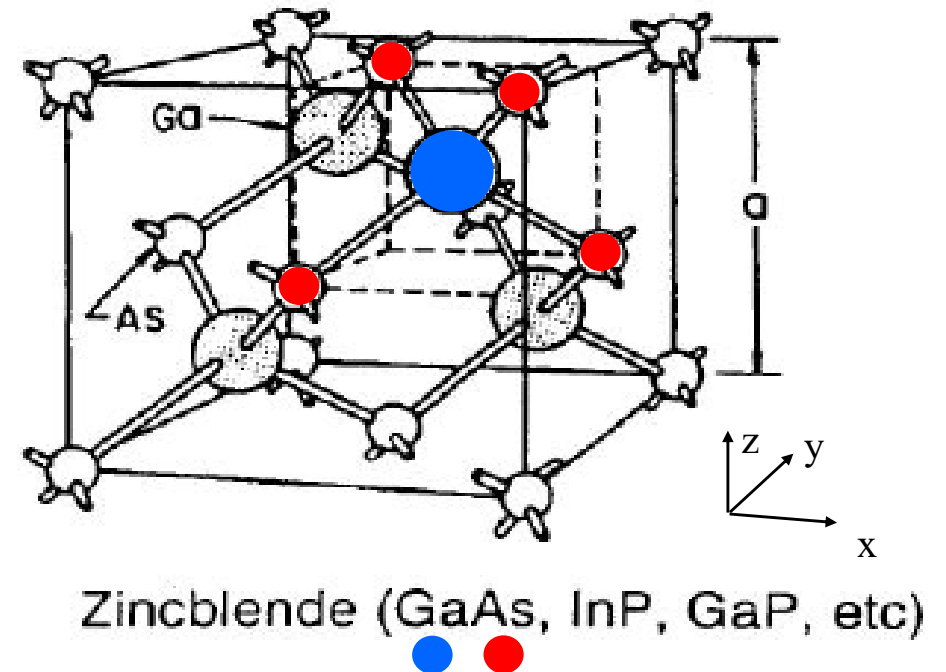
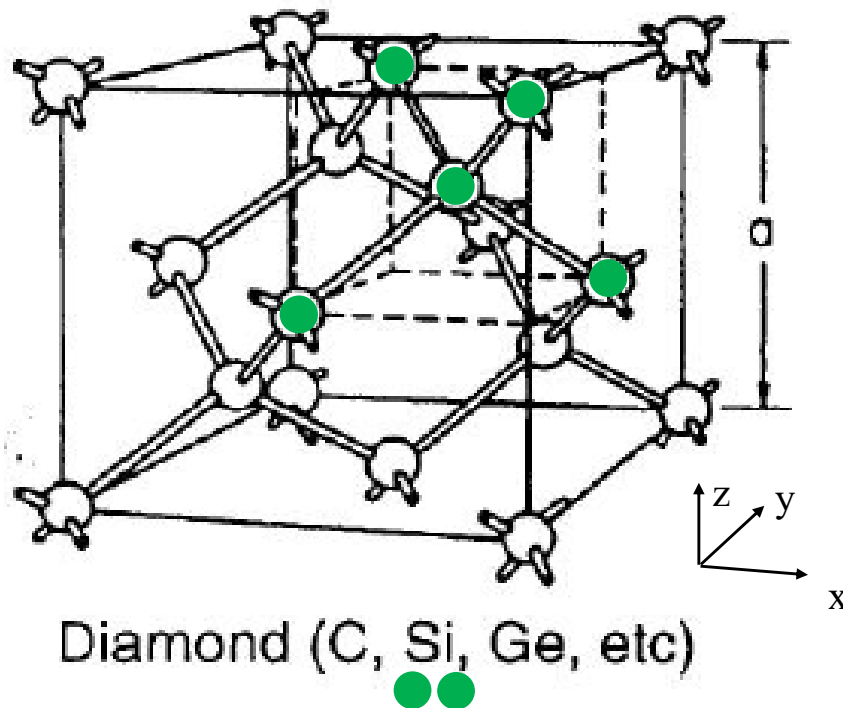
GaAs = 2 atomes = 8 électrons à placer sur les 4 liaisons tétraédriques

GaAs , InP , InGaAs , InGaAsP , ...

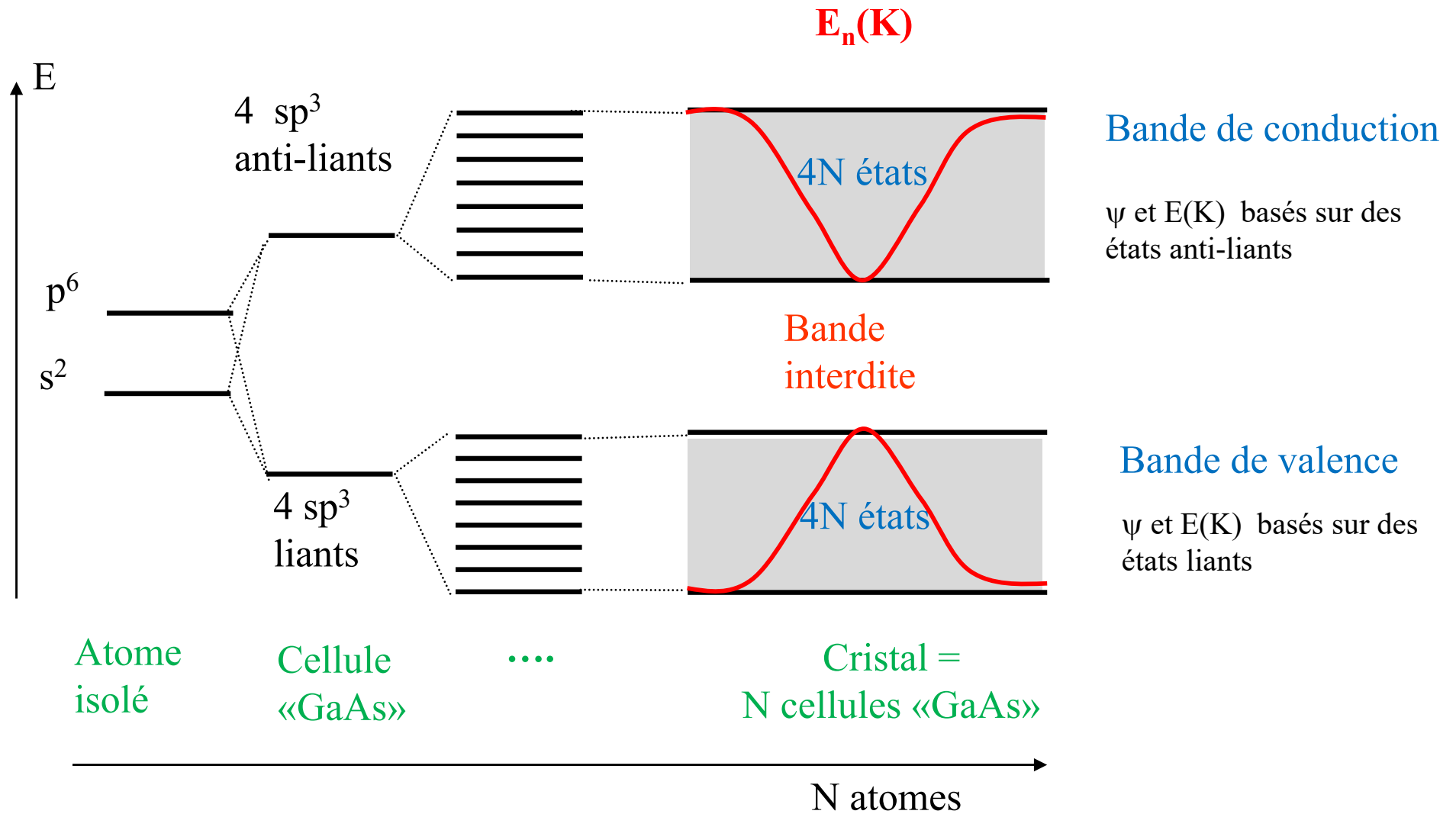


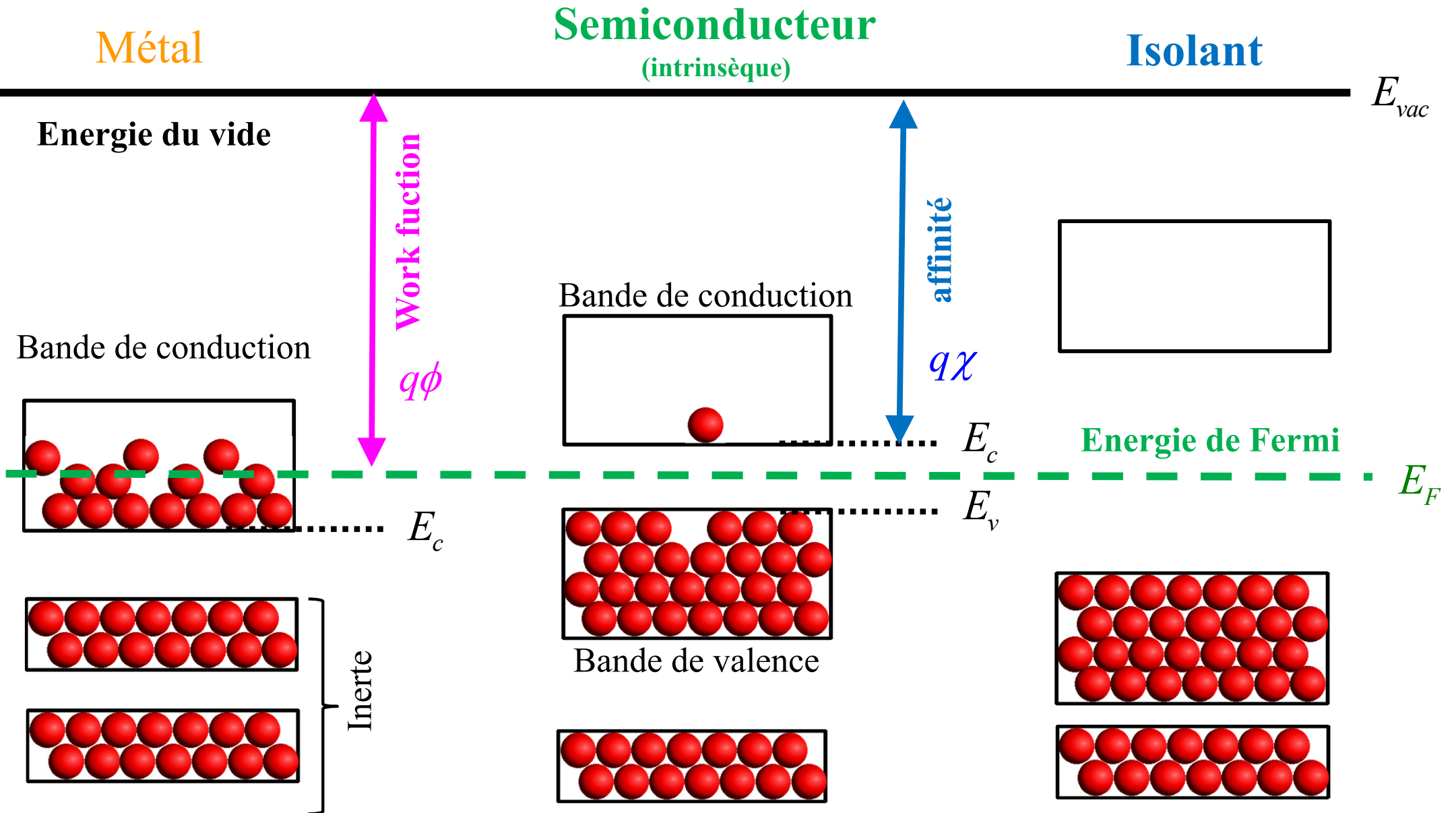
S. M. Sze “*Semiconductor Devices*”





S. M. Sze "Physics of semiconductor devices"





Cas spécifique: silicium à température ambiante

Energie de gap: $E_{g,Si} \equiv E_C - E_V \cong 1.1 [eV]$

Energie thermique: $U_{th} \equiv \frac{kT}{q} \cong 25 [meV]$ à température ambiante

$$E_{g,Si} \gg U_{th}$$

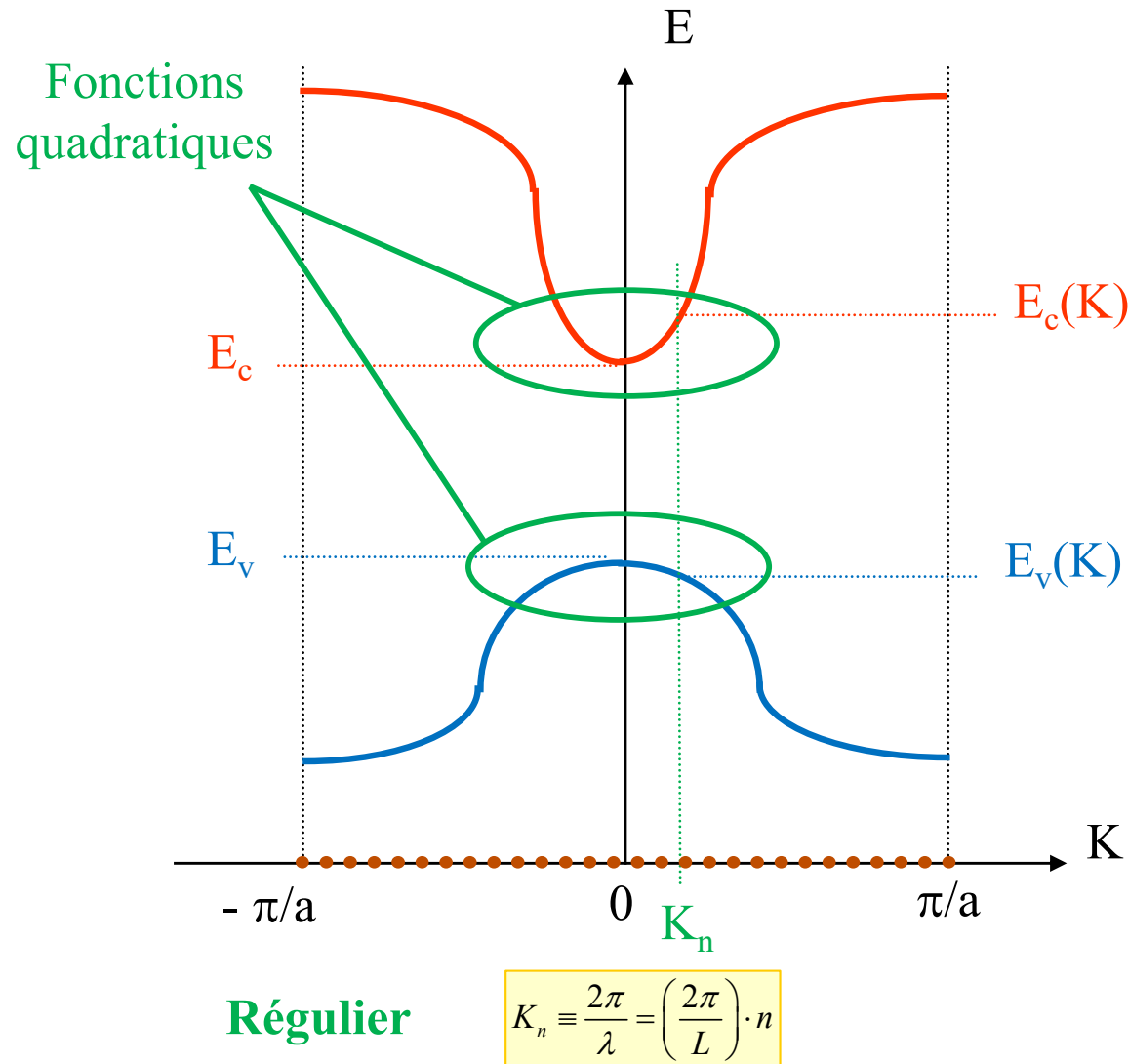


**Le silicium non-dopé à T=300K est un isolant
Il doit être dopé pour devenir semi-conducteur**

Rem:

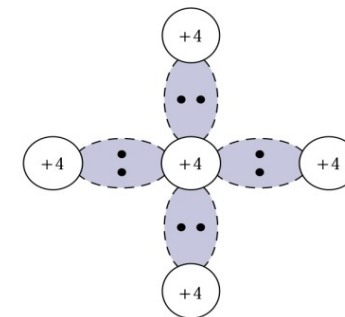
$$n_i \cong 10^{10} [cm^{-3}] \ll N_{dopage} \cong 10^{18} [cm^{-3}] \ll N_{atomes} \cong (10^8)^3 = 10^{24} [cm^{-3}]$$

Semicondcteurs: relation de dispersion $E(K)$



Bande de conduction
basée sur des états libres (anti-liants)

Bande de valence
basée sur des liaisons tétraédriques



S. M. Sze
"Semiconductor
Devices"

Approximation des relations de dispersion: Masses effectives et vitesse de groupe

Développement de Taylor

Conduction:

$$E \cong E_c + \frac{\hbar^2}{2} \vec{K} \cdot \frac{1}{m_n^*} \cdot \vec{K}$$

Masse effective
de la bande de conduction

Valence:

$$E \cong E_v - \frac{\hbar^2}{2} \vec{K} \cdot \frac{1}{m_p^*} \cdot \vec{K}$$

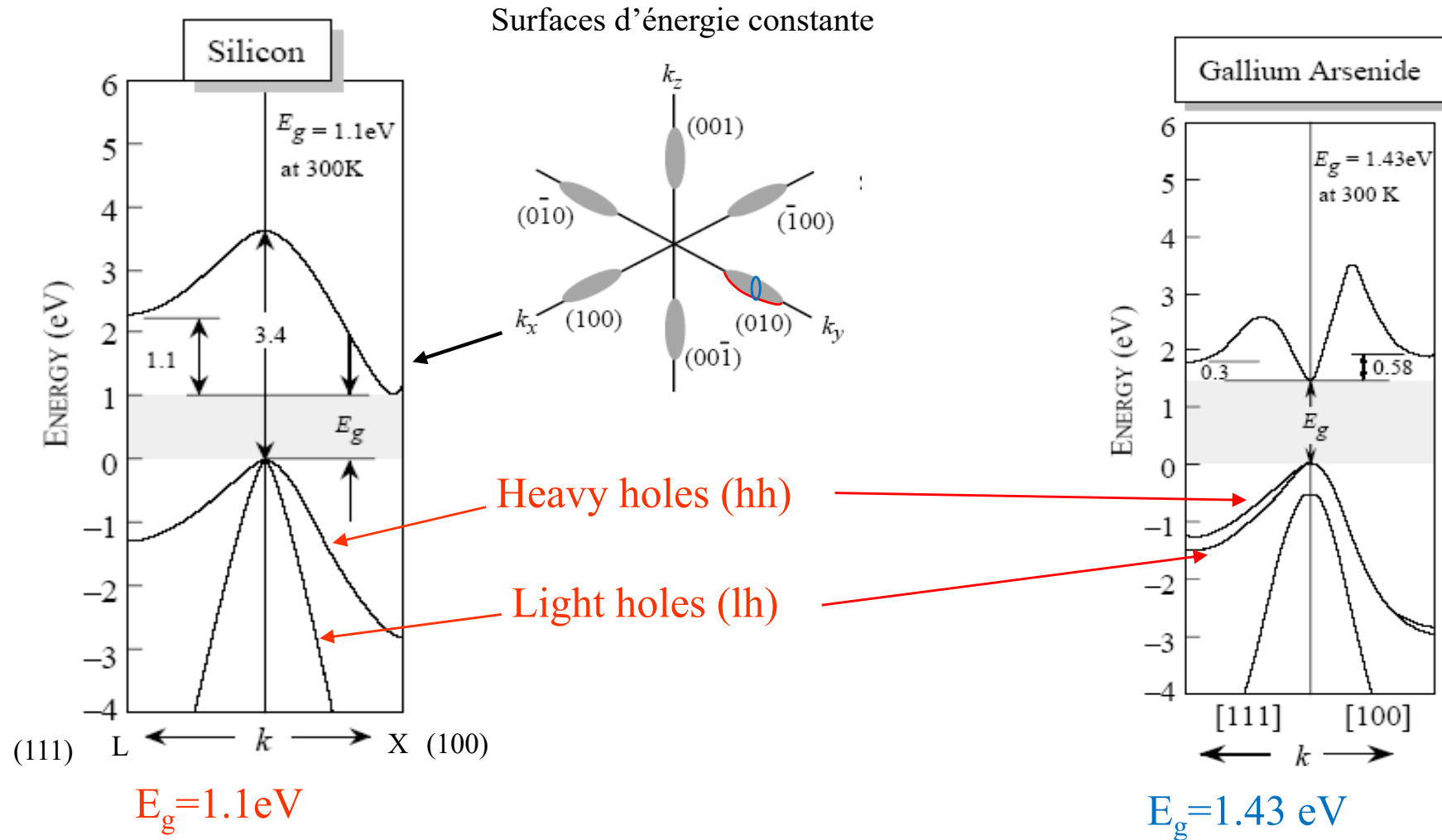
Masse effective
de la bande de valence

Vitesse de groupe:

$$\vec{v}_G = \frac{1}{\hbar} \cdot \overrightarrow{\text{grad}_K}(E)$$

Accélération due à une force F:

$$\vec{a} = \frac{d\vec{v}_G}{dt} = \left(\frac{1}{m^*} \right) \cdot \vec{F} \quad \text{avec} \quad \left(\frac{1}{m^*} \right) \equiv \frac{1}{\hbar^2} \frac{\partial^2}{\partial K^2} E$$



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Material	Bandgap (eV)	Relative Dielectric Constant
C	5.5, I	5.57
Si	1.124, I	11.9
Ge	0.664, I	16.2
SiC	2.416, I	9.72
GaAs	1.424, D	13.18
AlAs	2.153, I	10.06
InAs	0.354, D	15.15
GaP	2.272, I	11.11
InP	1.344, D	12.56
InSb	0.230, D	16.8
CdTe	1.475, D	10.2
AlN	6.2, D	9.14
GaN	3.44, D	10.0
ZnSe	2.822, D	9.1
ZnTe	2.394, D	8.7

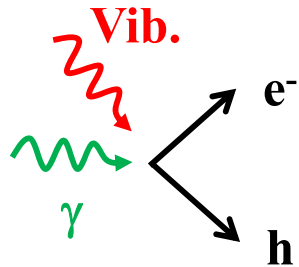
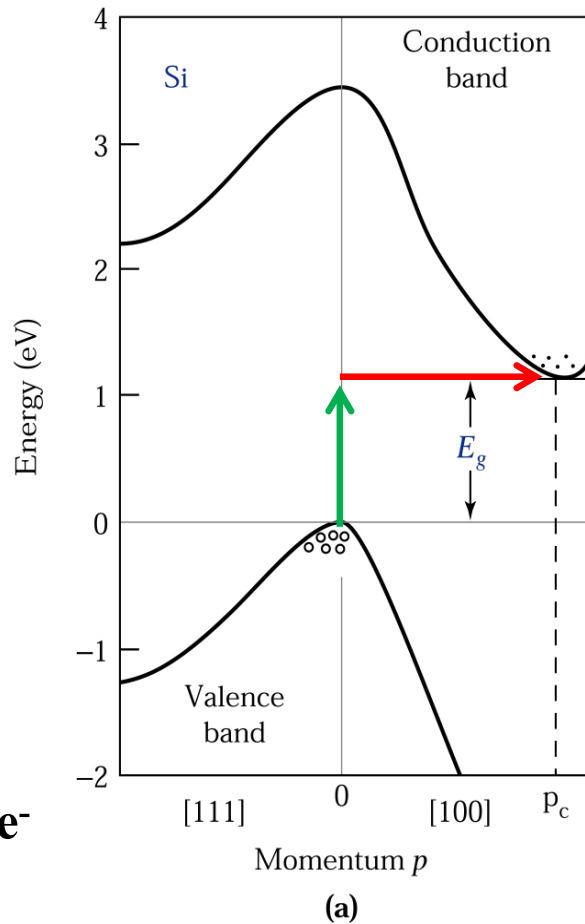
Masses effectives en unité: $m_0 = 0.911 \cdot 10^{-30}$ Kg

PROPERTY	Si	GAAs
Electron effective mass (m_0)	$m_{\text{c}}^* = 0.98$ $m_{\text{v}}^* = 0.19$ $m_{\text{dos}}^* = 1.08$ $m_{\sigma}^* = 0.26$	$m^* = 0.067$
Hole effective mass (m_0)	$m_{\text{hh}}^* = 0.49$ $m_{\text{lh}}^* = 0.16$ $m_{\text{dos}}^* = 0.55$ $m_{\sigma}^* = 0.37$	$m_{\text{hh}}^* = 0.45$ $m_{\text{lh}}^* = 0.08$ $m_{\text{dos}}^* = 0.47$ $m_{\sigma}^* = 0.34$
Bandgap (eV)	$1.17 - \frac{4.37 \times 10^{-4} T^2}{T + 636}$	$1.519 - \frac{5.4 \times 10^{-4} T^2}{T + 204}$
Electron affinity (eV)	4.01	4.07

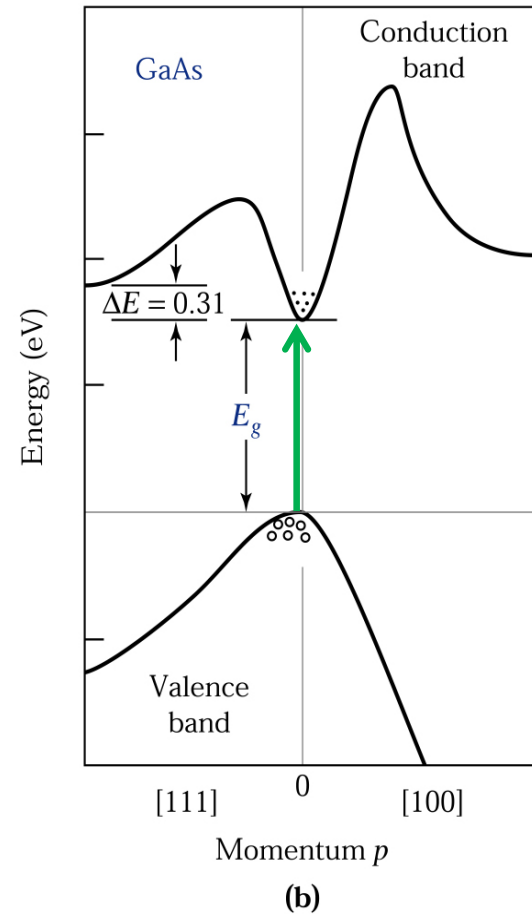
For Si: m_{dos}^* : To be used in calculating density of states, position of Fermi level
 m_{σ}^* : To be used in calculating response to electric field, e.g., in mobility

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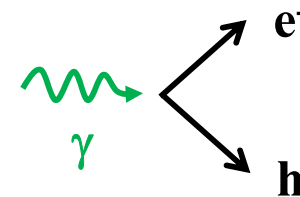
Indirect

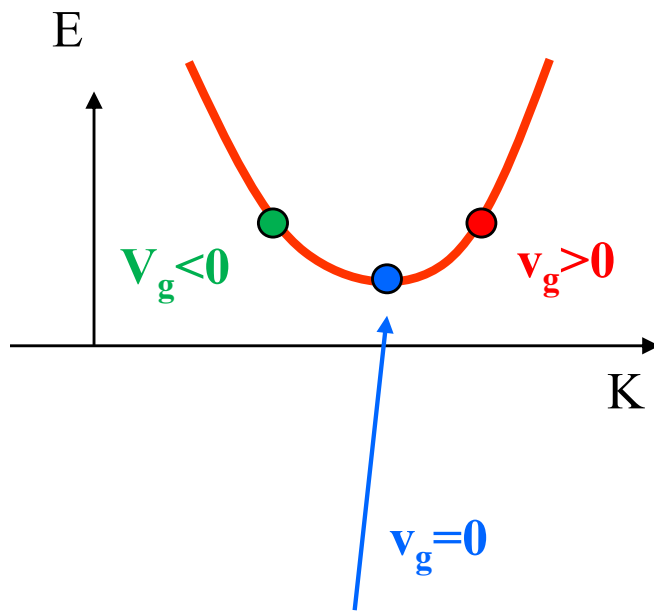


Direct

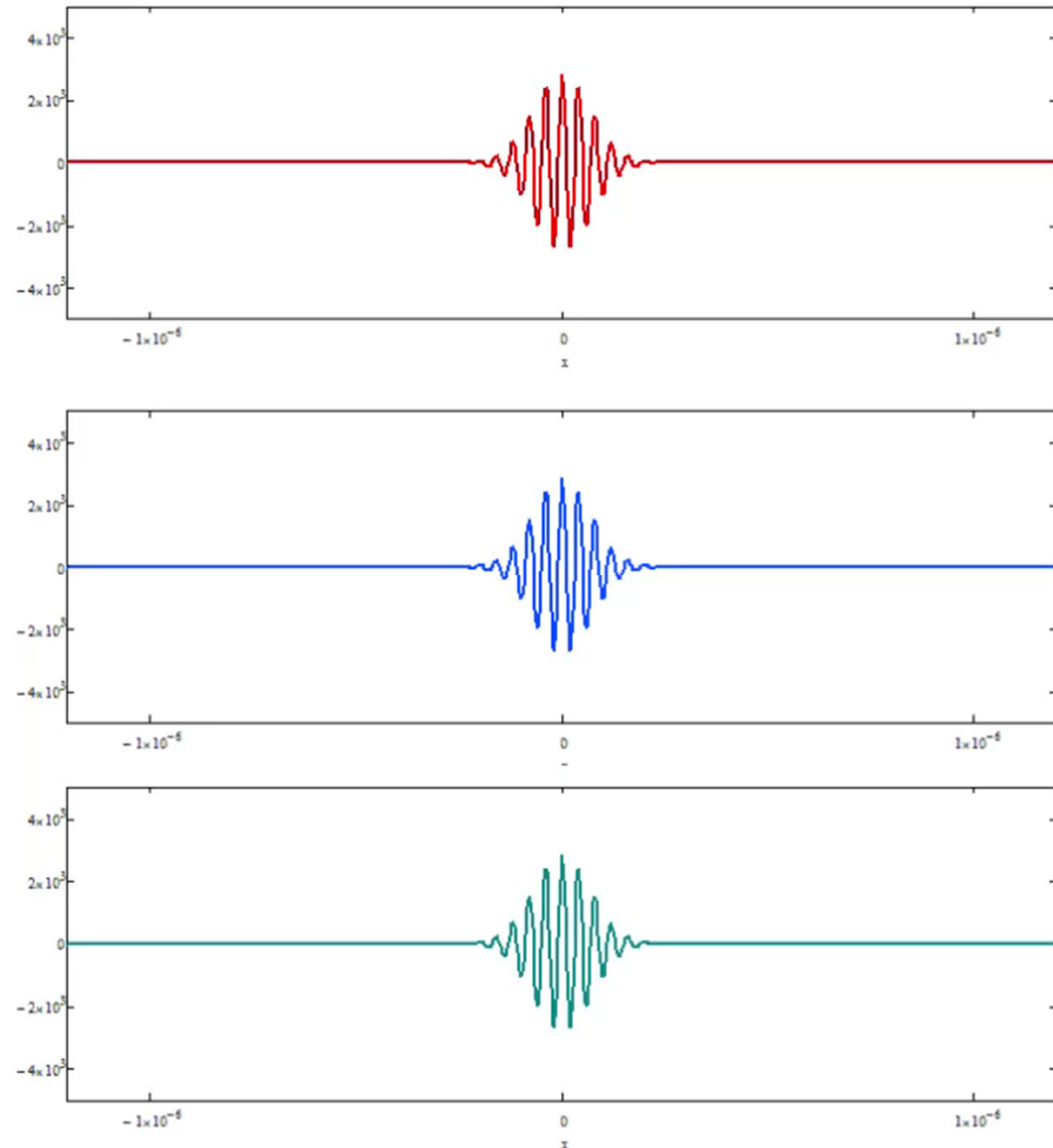


Un semi-conducteur indirect doit utiliser des phonons (vibrations du cristal) pour conserver l'impulsion.



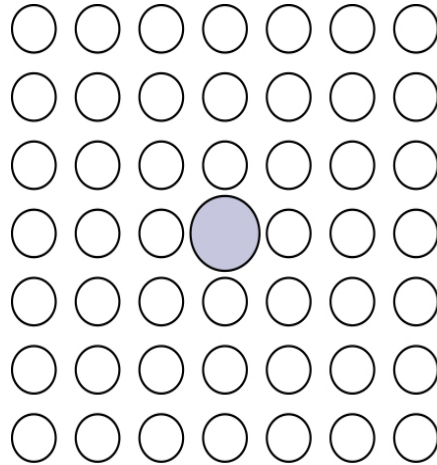


Impulsion non-nulle mais
vitesse de groupe nulle !!

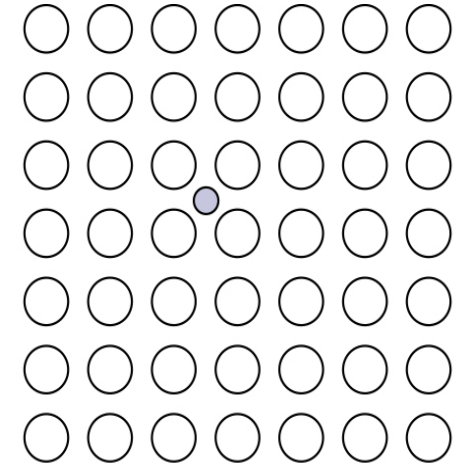


Défauts ponctuels

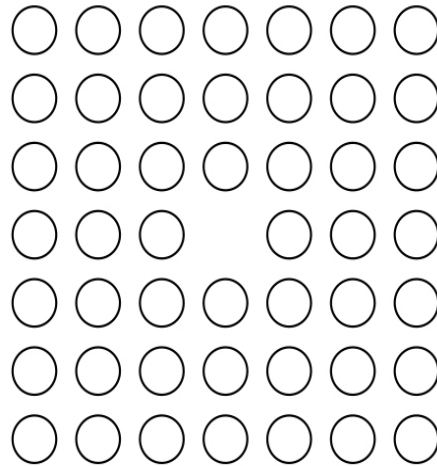
Substitution



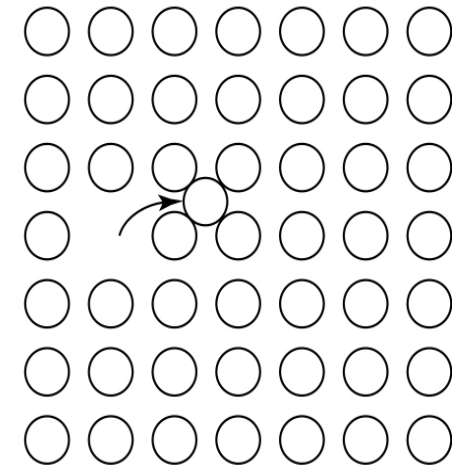
Impureté
interstitielle



Vacance



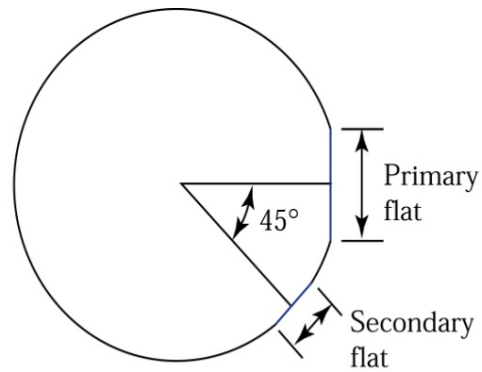
Défaut de
Frenkel



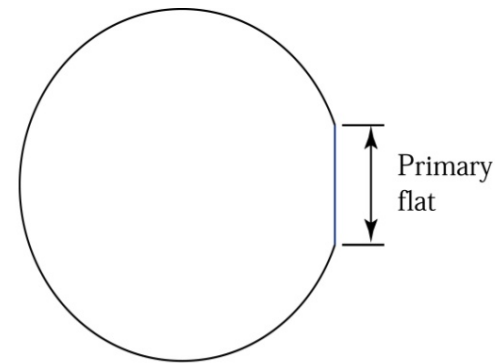
S. M. Sze
“Semiconductor Devices”



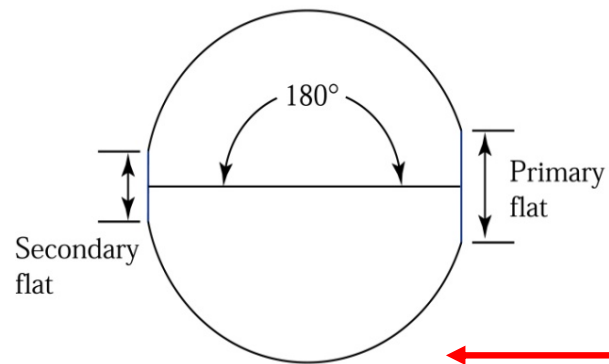
S. M. Sze “*Semiconductor Devices*”



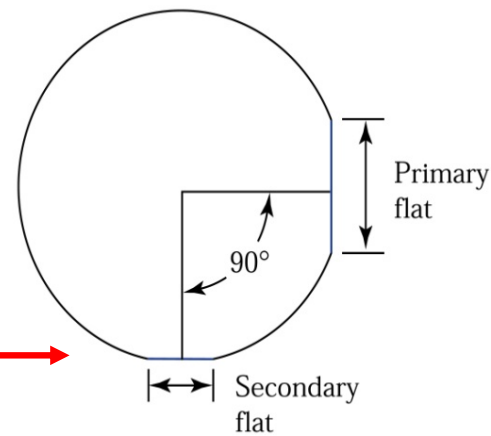
$\{111\}$ *n*-type



$\{111\}$ *p*-type



$\{100\}$ *n*-type



$\{100\}$ *p*-type

$[011]$



Des questions de réflexion sont en fin de chaque script. Elles couvrent les notions fondamentales de chaque chapitre et vous aident à préparer l'examen oral final.

Répondez aux questions 1.1, 1.2 et 1.5

1.1	Qu'appelle-t-on la relation de dispersion d'une particule ? Exprimez-la pour une particule dans le vide. Comment peut-on déterminer graphiquement la vitesse de groupe et la masse effective de la particule à partir de cette relation ?
1.2	Considérez un atome « A » avec trois électrons sur deux niveaux d'énergie. Dessinez le schéma d'énergie de la cellule « AA » contenant deux atomes « A ». Expliquez la formation de bandes dans un monocristal basé sur cette cellule « AA ».
1.5	À l'aide du schéma d'énergie, expliquez l'absorption optique dans un gaz et dans un semi-conducteur monocristallin.