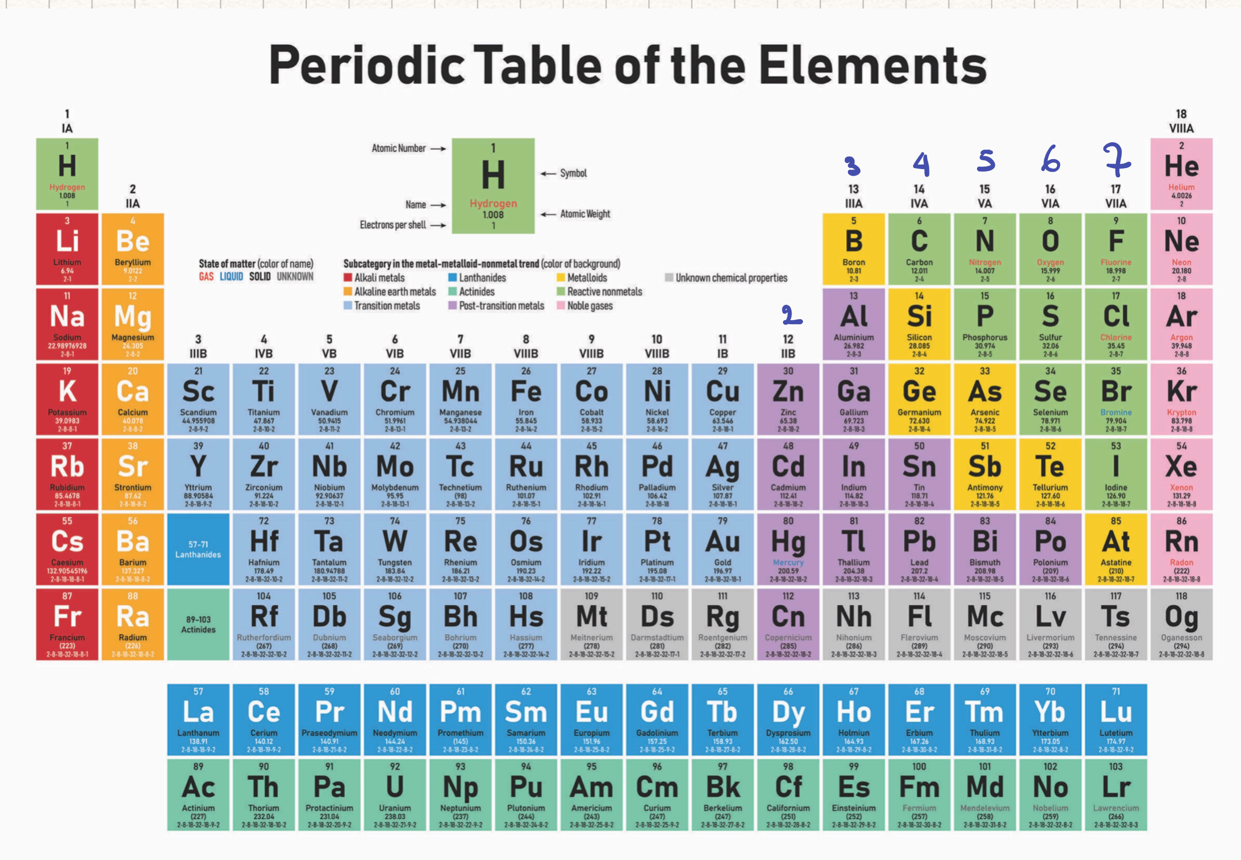
Semiconductors

- transistor
  switchs
  diodes
  photovoltaic cells
  detectors
  thermistors

- Silicon (Si)
- Germanium (Ge)
- Gallium Arsenide (GaAs)

Semiconducto AB



III-V (three-five) semiconductor

GaAs : Gallium arsenide

InSb : Indium antimonide

II-VI (two-six) semiconductor

ZnS : Zinc sulfide

CdS : cadmium sulfide

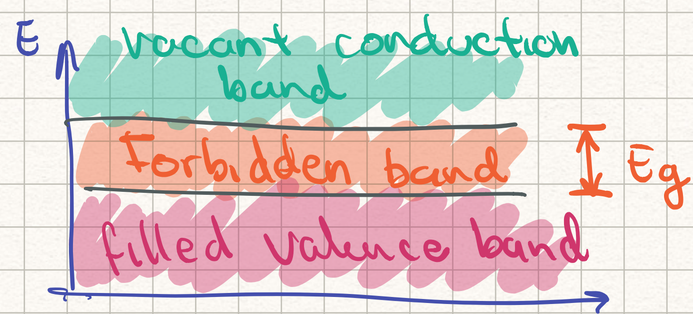
IV - IV (four - four) semiconductor

Si, Ge, SiC : silicon carbide

Band Gap: energy difference between the

- lowest point in the conduction band (conduction band edge)
- highest point in the valence band (valence band edge)

At $T = 0K$



$T > 0$:

- e^- in the valence band jump to the conduction band
- hole (vacancy of electron) left behind by the e^- also contributes to electric cond.

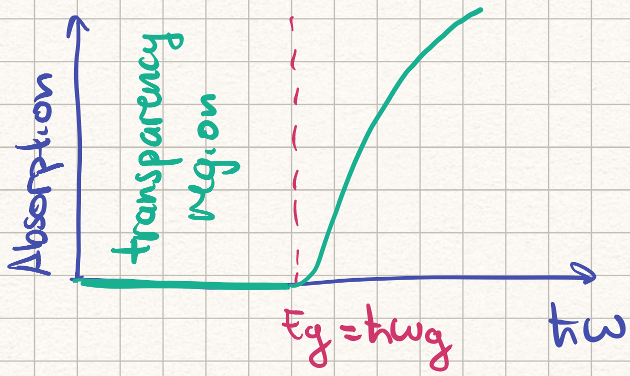
Conductivity is controlled by $E_g / k_B T$

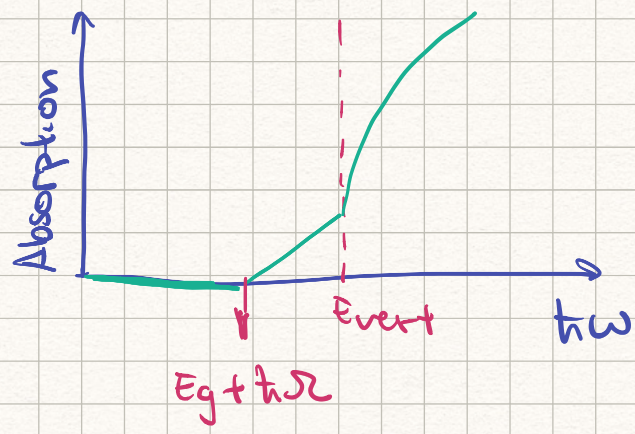
$E_g / k_B T \gg 1$: low carrier concentration

$E_g / k_B T \ll 1$: high carrier concentration

we investigate the band gap optically

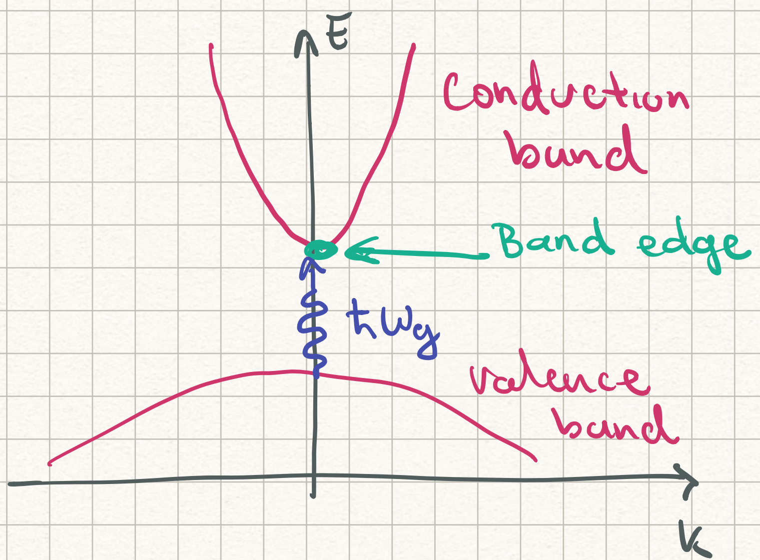
→ light absorption

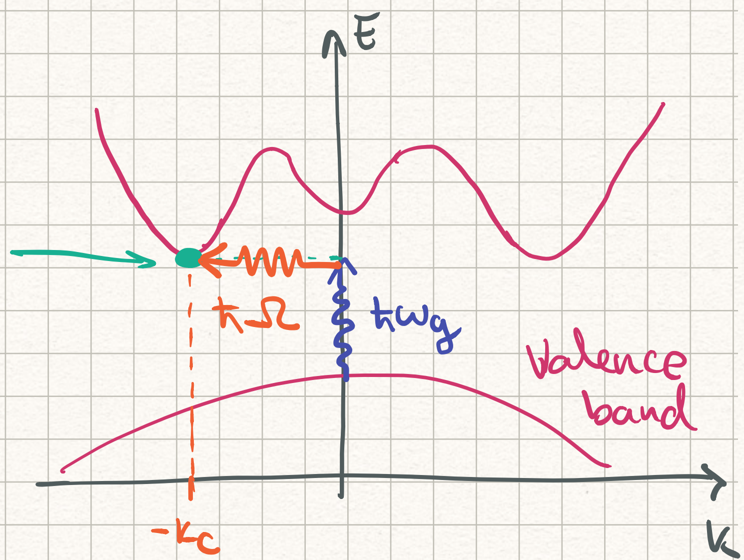




Direct absorption process

Indirect absorption process





1 free electron

1 hole

1 free electron

1 hole

1 phonon with energy $\hbar\Omega$

At $\hbar\omega = E_{vert}$: 1 free electro
1 hole
0 phonons

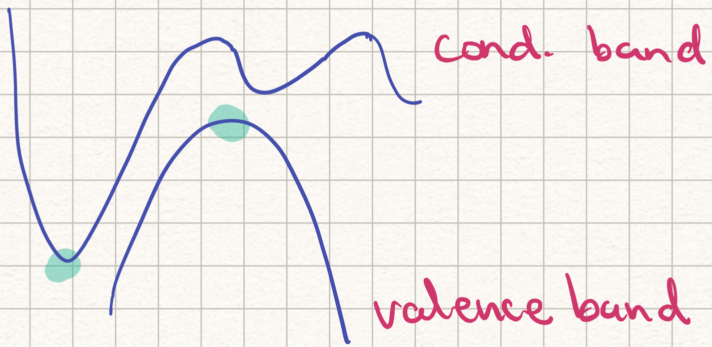
$$k(\text{photon}) = k_e + k(\text{phonon}) = 0$$

$$k(\text{phonon}) = -k_e$$

Direct gap: InSb

Indirect gap: Ge and Si

HgTe and HgSe are semimetal $\Rightarrow E_g < 0$



the band overlap

$E_g < 0$

Eg. of motion of an e^- on an Energy band

The WF near some k ψ_k

$$v_g = \frac{\partial \omega}{\partial k} \qquad \varepsilon = \hbar\omega \qquad \frac{\partial \omega}{\partial k} = \frac{\partial}{\partial k}\left(\frac{\varepsilon}{\hbar}\right)$$

$$= \frac{1}{\hbar}\frac{\partial \varepsilon}{\partial k}$$

In 3D: $\vec{v}_g = \frac{1}{\hbar}\vec{\nabla}_k \varepsilon$

$$\vec{\nabla}_k = (\partial_{k_x}, \partial_{k_y}, \partial_{k_z})$$

The work done on the e^- by an $\vec{E}$-field on a time δt

$$\delta\varepsilon = -eE v_g \delta t$$

$$\delta\varepsilon = \frac{d\varepsilon}{dk}\delta k = \hbar v_g \delta k$$

$$\hbar v_g \delta k = -eE v_g \delta t$$

$$\hbar \delta k = -eE \delta t$$

$$\hbar\frac{\delta k}{\delta t} = -eE \Rightarrow \hbar\frac{dk}{dt} = -eE = F$$

$$\boxed{\vec{F} = \hbar\frac{d\vec{k}}{dt}}$$

with a magnetic field $\hbar\frac{d\vec{k}}{dt} = -e\vec{v}_g \times \vec{B}$

$$\vec{v}_g = \frac{1}{\hbar}\vec{\nabla}_k \varepsilon$$

$$\hbar \frac{d\vec{k}}{dt} = -\frac{e}{\hbar}\vec{\nabla}_k \varepsilon \times \vec{B}$$

$$\boxed{\frac{d\vec{k}}{dt} = -\frac{e}{\hbar^2}\vec{\nabla}_k \varepsilon \times \vec{B}}$$

coordinates of $\vec{k}$ - space

In a magnetic field an e^- moves in $\vec{k}$-space in a direction normal to the direction of the gradient of the energy $\Rightarrow$ the e^- moves on a surface of constant energy.

Consider WF ψ_k associated to the ε_k and wavevector k

$$\psi_{\vec{k}} = \sum_{\vec{G}}' C_{\vec{k}+\vec{G}}\, e^{i(\vec{k}+\vec{G})\cdot\vec{r}}$$

$$\langle p_{el}\rangle = \int d^3\vec{r}\, \psi_{\vec{k}}^* \hat{p}\, \psi_{\vec{k}} = \int d^3\vec{r}\, \psi_{\vec{k}}^* (-i\hbar\vec{\nabla})\psi_{\vec{k}}$$

$$\vec{\nabla}\psi_{\vec{k}} = \sum_{\vec{G}}' C_{\vec{k}+\vec{G}}\, \vec{\nabla} e^{i(\vec{k}+\vec{G})\cdot\vec{r}}$$

$$= \sum_{\vec{G}}' i(\vec{k}+\vec{G})\, C_{\vec{k}+\vec{G}}\, e^{i(\vec{k}+\vec{G})\cdot\vec{r}}$$

$$\psi_{\vec{k}}^* = \sum_{\vec{G}'}' C^*_{\vec{k}+\vec{G}'}\, e^{-i(\vec{k}+\vec{G}')\cdot\vec{r}}$$

$$\langle p_{el}\rangle = \hbar\sum_{\vec{G}'}'\int d^3\vec{r}\, C^*_{\vec{k}+\vec{G}'}\, e^{-i(\vec{k}+\vec{G}')\cdot\vec{r}} \sum_{\vec{G}} (\vec{k}+\vec{G})\, C_{\vec{k}+\vec{G}}\, e^{i(\vec{k}+\vec{G})\cdot\vec{r}}$$

$$= \hbar\sum_{G'}'\sum_{G} (\vec{k}+\vec{G})\, C^*_{\vec{k}+\vec{G}'} C_{\vec{k}+\vec{G}} \underbrace{\int d^3r\, e^{i(\vec{G}-\vec{G}')\cdot\vec{r}}}_{\delta(\vec{G}-\vec{G}')}$$

$$= \hbar \sum_{\vec{G}}' (\vec{k}+\vec{G}) \, |C_{\vec{k}+\vec{G}}|^2$$

$$= \hbar \vec{k} \sum_{\vec{G}} |C_{\vec{k}+\vec{G}}|^2 + \hbar \sum_{\vec{G}}' \vec{G} \, |C_{\vec{k}+\vec{G}}|$$

$$= \hbar \left(\vec{k} + \sum_{\vec{G}}' \vec{G} \, |C_{\vec{k}+\vec{G}}| \right)$$

Force changing the electron from $\vec{k} \rightarrow \vec{k}+\Delta\vec{k}$

$\Rightarrow$ Force is appled for some time

$\vec{J}$: impulse $\qquad \vec{J} = \int \vec{F} \, dt = \Delta P_{total}$

- If e^- do not interact with lattice

$$\vec{J} = \Delta\vec{P}_{tot} = \Delta\vec{P}_{el} = \hbar\Delta\vec{k}$$

- If e^- interacts with lattice

$$\vec{J} = \Delta\vec{P}_{tot} = \Delta\vec{P}_{el} + \Delta\vec{P}_{lattice} = \hbar\Delta\vec{k}$$

$$\Delta\vec{P}_{el} = \vec{\nabla}_{k} \cdot \left(\langle p_{el} \rangle \, \Delta\vec{k} \right)$$

$$= \hbar\Delta\vec{k} + \sum_{\vec{G}}' \hbar\vec{G} \left[\vec{\nabla}_k |C_{\vec{k}+\vec{G}}|^2 \cdot \Delta\vec{k} \right]$$

An e^- reflected by the lattice transfers some momentum to the lattice

- incident with $\hbar\vec{k}$
- reflected with $\hbar(\vec{k}+\vec{G})$

$\Big\}$ lattice acquires $\vec{p} = -\hbar\vec{G}$

$$\Delta\vec{P}_{latt} = -\hbar \sum_{\vec{G}}' \vec{G} \left[\vec{\nabla}_k |C_{\vec{k}+\vec{G}}|^2 \cdot \Delta\vec{k} \right]$$

a fraction $\vec{\nabla}_k |C_{\vec{k}+\vec{G}}|^2 \cdot \Delta k$ of each component is reflected

$$\Delta\vec{p}_{el} + \Delta\vec{P}_{lat} = \hbar\Delta\vec{k} = \vec{J}$$

$$\hbar\frac{d\vec{k}}{dt} = \frac{d}{dt}\int\vec{F}\,dt \Rightarrow \boxed{\hbar\frac{d\vec{k}}{dt} = \vec{F}}$$