

semiconductors

→ transistor
switches
diodes
photovoltaic cells
detectors
thermistors

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

semiconductors AB

Periodic Table of the Elements

The periodic table shows elements color-coded by groups: Alkali metals (red), Alkaline earth metals (orange), Transition metals (blue), Lanthanides (light blue), Actinides (green), Metalloids (yellow), Reactive nonmetals (purple), Noble gases (pink), and Unknown chemical properties (grey).

Legend for Hydrogen (H):

- Atomic Number: 1
- Symbol: H
- Name: Hydrogen
- Atomic Weight: 1.008
- Electrons per shell: 1

State of matter (color of name): GAS LIQUID SOLID UNKNOWN

Subcategory in the metal-metalloid-nonmetal trend (color of background):

- Alkali metals
- Alkaline earth metals
- Transition metals
- Lanthanides
- Actinides
- Metalloids
- Reactive nonmetals
- Noble gases
- Unknown chemical properties

III - V (three-five) semiconductor

GaAs: Gallium arsenide

InSb: Indium antimonide

II - VI (two-six) semiconductor

ZnS: Zinc sulfide

CdS: cadmium sulfide

III-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.

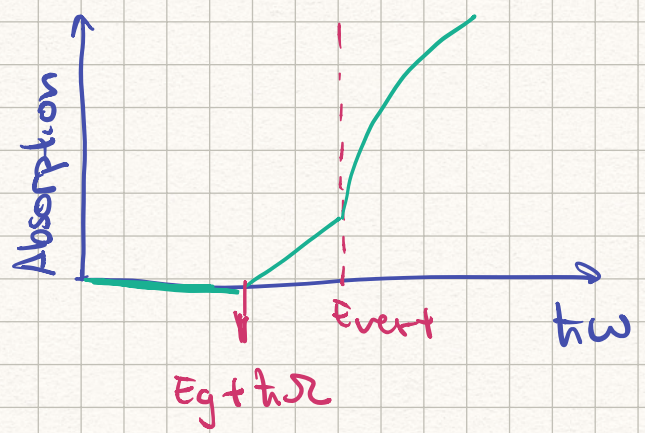
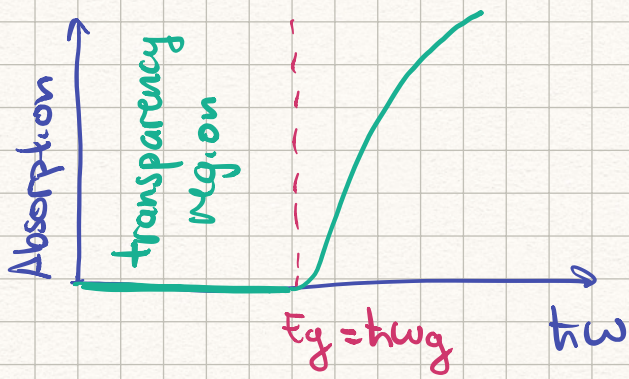
Conductivity is controlled by $E_g/k_B T$

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

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

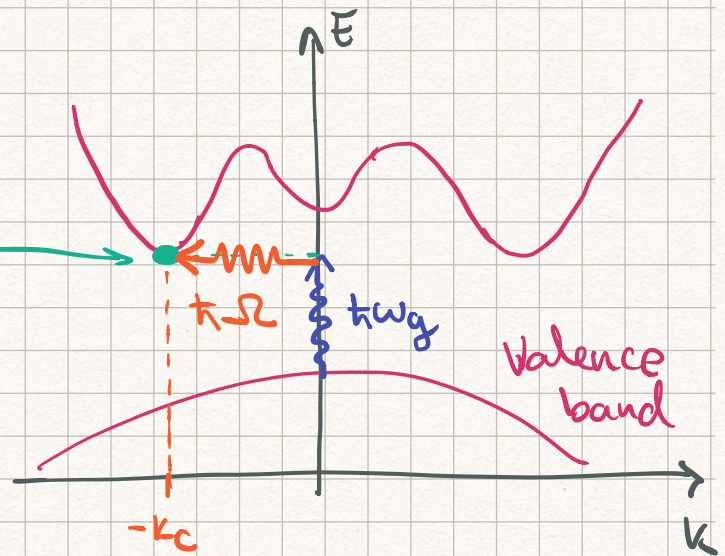
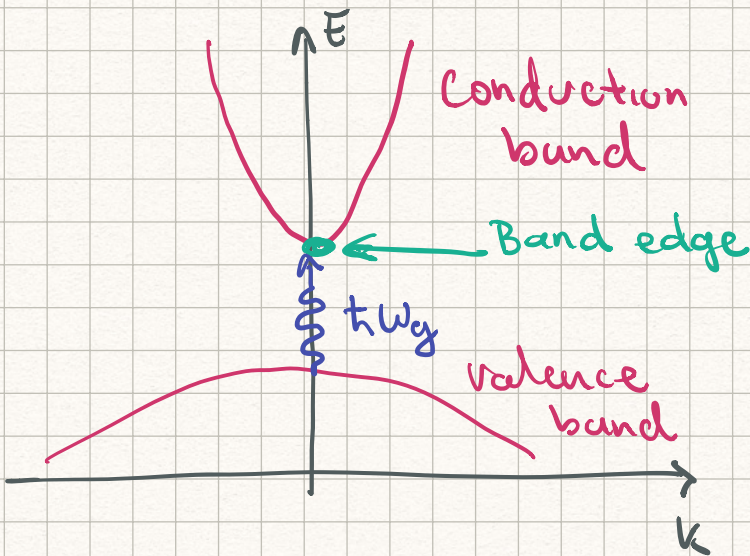
We investigate the band gap optically

→ light absorption



Direct absorption process

Indirect absorption process



1 free electron
1 hole

1 free electron
1 hole

1 phonon with energy $h\omega_p$

At $h\omega = E_{event}$:
1 free electron
1 hole
0 phonons

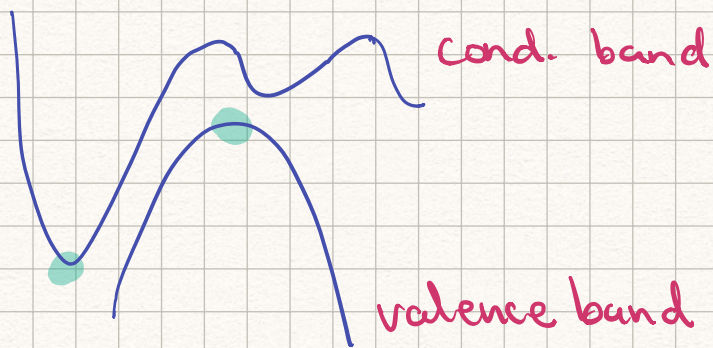
$$k(\text{photon}) = k_e + k(\text{phonon}) = 0$$

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

Direct gap: InSb

Indirect gap: Ge and Si

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



the band overlap
 $E_g < 0$

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

The WF near some k ψ_k

$$v_g = \frac{\partial \omega}{\partial k}$$

$$E = \hbar \omega$$

$$\frac{\partial \omega}{\partial k} = \frac{\partial}{\partial k} \left(\frac{E}{\hbar} \right)$$

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

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

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

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

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

$$\delta E = \frac{dE}{dk} \delta k = \hbar v_g \delta k$$

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

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

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

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

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

$$\frac{\partial \psi}{\partial t} = \frac{1}{\hbar} \vec{\nabla}_k \epsilon$$

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

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

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 $\psi_{\vec{k}}$ associated to the $\epsilon_{\vec{k}}$ and wavevector \vec{k}

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

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

$$\begin{aligned} \vec{\nabla} \psi_{\vec{k}} &= \sum_{\vec{G}} C_{\vec{k}+\vec{G}} \vec{\nabla} e^{i(\vec{k}+\vec{G}) \cdot \vec{r}} \\ &= \sum_{\vec{G}} i(\vec{k}+\vec{G}) C_{\vec{k}+\vec{G}} e^{i(\vec{k}+\vec{G}) \cdot \vec{r}} \end{aligned}$$

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

$$\begin{aligned} \langle p_x \rangle &= \hbar \sum_{\vec{G}'} \int d^3\vec{r} C_{\vec{k}+\vec{G}'}^* e^{-i(\vec{k}+\vec{G}') \cdot \vec{r}} \sum_{\vec{G}} (\vec{k}+\vec{G}) C_{\vec{k}+\vec{G}} e^{i(\vec{k}+\vec{G}) \cdot \vec{r}} \\ &= \hbar \sum_{\vec{G}'} \sum_{\vec{G}} (\vec{k}+\vec{G}) C_{\vec{k}+\vec{G}'}^* C_{\vec{k}+\vec{G}} \int d^3\vec{r} \underbrace{e^{i(\vec{G}-\vec{G}') \cdot \vec{r}}}_{\delta(\vec{G}-\vec{G}')} \end{aligned}$$

$$= \hbar \sum_{\vec{G}} (\vec{k} + \vec{G}) |\langle \vec{k} + \vec{G} | \rangle|^2$$

$$= \hbar \vec{k} \sum_{\vec{G}} |\langle \vec{k} + \vec{G} | \rangle|^2 + \hbar \sum_{\vec{G}} \vec{G} |\langle \vec{k} + \vec{G} | \rangle|^2$$

$$= \hbar \left(\vec{k} + \sum_{\vec{G}} \vec{G} |\langle \vec{k} + \vec{G} | \rangle|^2 \right)$$

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

\Rightarrow Force is applied for some time

$$\vec{J}: \text{impulse} \quad \vec{J} = \int \vec{F} dt = \Delta P_{\text{total}}$$

- If e^- do not interact with lattice

$$\vec{J} = \Delta \vec{P}_{\text{tot}} = \Delta \vec{P}_{e^-} = \hbar \Delta \vec{k}$$

- If e^- interacts with lattice

$$\vec{J} = \Delta \vec{P}_{\text{tot}} = \Delta \vec{P}_{e^-} + \Delta \vec{P}_{\text{lattice}} = \hbar \Delta \vec{k}$$

$$\Delta \vec{P}_{e^-} = \vec{v}_{\vec{k}} (\langle p_{e^-} \rangle \Delta \vec{k})$$

$$= \hbar \Delta \vec{k} + \sum_{\vec{G}} \hbar \vec{G} [\vec{v}_{\vec{k}} |\langle \vec{k} + \vec{G} | \rangle|^2 - \Delta \vec{k}]$$

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

- incident with $\hbar \vec{k}$
 - reflected with $\hbar (\vec{k} + \vec{G})$
- } lattice acquires $\vec{p} = -\hbar \vec{G}$

$$\Delta \vec{P}_{\text{lattice}} = -\hbar \sum_{\vec{G}} \vec{G} [\vec{v}_{\vec{k}} |\langle \vec{k} + \vec{G} | \rangle|^2 - \Delta \vec{k}]$$

a fraction $\vec{v}_{\vec{k}} |\langle \vec{k} + \vec{G} | \rangle|^2 - \Delta \vec{k}$ of each component is

reflected

$$\Delta \vec{p}_i + \Delta \vec{p}_{\text{lat}} = \hbar \Delta \vec{k} = \vec{J}$$

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