

Semiconductors

→ Transistor
switches
diodes
photovoltaic cells
detectors
thermistors

→ Silicon (Si)

→ Germanium (Ge)

→ Gallium Arsenide (GaAs)

Semiconductors AB

Periodic Table of the Elements

1 IA	2 IIA																	18 VIIA			
H Hydrogen 1.008 1	Be Beryllium 9.012 2																	He Helium 4.0026 2			
Li Lithium 7.016 3	Mg Magnesium 24.309 12																				
Na Sodium 22.9976128 11																					
K Potassium 39.0983 19	Ca Calcium 40.078 20	Sc Scandium 44.959808 21	Ti Titanium 47.867 22	V Vanadium 50.9415 23	Cr Chromium 51.981 24	Mn Manganese 54.938644 25	Fe Iron 55.845 26	Co Cobalt 58.933 27	Ni Nickel 58.693 28	Al Aluminum 26.982 11	B Boron 10.81 13	C Carbon 12.01 6	N Nitrogen 14.01 15	O Oxygen 16.00 8	F Fluorine 18.99 17	Ne Neon 20.180 10					
Rb Rubidium 61.941 37	Sr Strontium 87.620 38	Y Yttrium 88.906 39	Zr Zirconium 91.224 40	Nb Niobium 92.906 41	Mo Tungsten 192.23 42	Tc Technetium 98.906 43	Ru Ruthenium 101.12 44	Rh Rhodium 102.906 45	Pd Palladium 106.42 46	Ag Silver 107.87 47	Ga Gallium 69.723 31	As Arsenic 74.922 33	Se Selenium 78.971 34	Br Bromine 79.904 35	Kr Krypton 83.788 36						
Cs Cesium 122.954996 55	Ba Barium 137.327 56	57-71 Lanthanides		Hf Hafnium 178.49 72	Ta Tantalum 183.44 73	W Tungsten 183.84 74	Re Rhenium 186.21 75	Os Osmium 190.23 76	Ir Iridium 192.22 77	Pt Platinum 195.08 78	Au Gold 196.97 79	Gn Germanium 72.639 30	Ge Germanium 74.922 32	As Antimony 74.922 33	Sb Antimony 121.80 51	Te Tellurium 127.60 52	I Iodine 126.90 53	Xe Xenon 131.327 54			
Fr Francium (223) 87	Ra Radium (226) 88	89-103 Actinides		Rf Rutherfordium (267) 104	Db Dubnium (268) 105	Sg Seaborgium (269) 106	Bh Bohrium (270) 107	Hs Hassium (277) 108	Mt Meitnerium (278) 109	Ds Darmstadtium (281) 110	Rg Roentgenium (282) 111	Cn Copernicium (285) 112	Nh Nihonium (286) 113	Fl Flerovium (289) 114	Mc Moscovium (290) 115	Po Polonium (291) 116	At Astatine (210) 117	Rn Radon (222) 118	Og Oganesson (294) 119		
La Lanthanum (138.91) 57	Ce Cerium (140.12) 58	Pr Praseodymium (141.91) 59	Nd Neodymium (144.24) 60	Pm Promethium (145) 61	Sm Samarium (150.34) 62	Eu Europium (151.96) 63	Gd Gadolinium (157.25) 64	Tb Terbium (158.93) 65	Dy Dysprosium (162.50) 66	Ho Holmium (164.93) 67	Er Erbium (167.26) 68	Tm Thulium (168.93) 69	Yb Ytterbium (174.97) 70	Lu Lutetium (176.97) 71							
Ac Actinium (227) 89	Th Thorium (232.04) 90	Pa Protactinium (231.04) 91	U Uranium (238.03) 92	Np Neptunium (237.04) 93	Pu Plutonium (244) 94	Am Americium (243) 95	Cm Curium (247) 96	Bk Berkelium (247) 97	Cf Californium (250) 98	Einsteinium (252) 99	Fm Fermium (257) 100	Md Mendelevium (258) 101	No Neptunium (259) 102	Lr Livermorium (264) 103							

III-V (three-five) semiconductor

GaAs : Gallium arsenide

InSb : Indium antimonide

II-VI (two-six) semiconductor

ZnS : Zinc sulfide

CdS : Cadmium sulfide

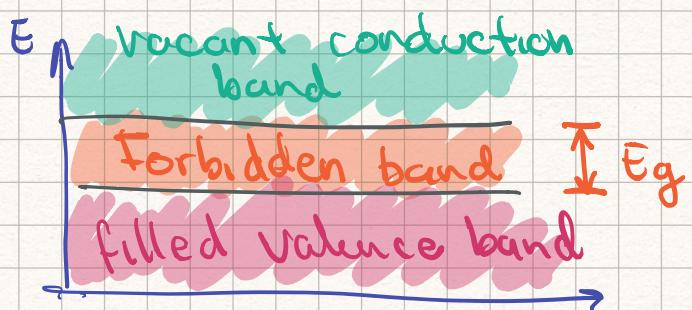
II-IV (four-four) semiconductor

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.

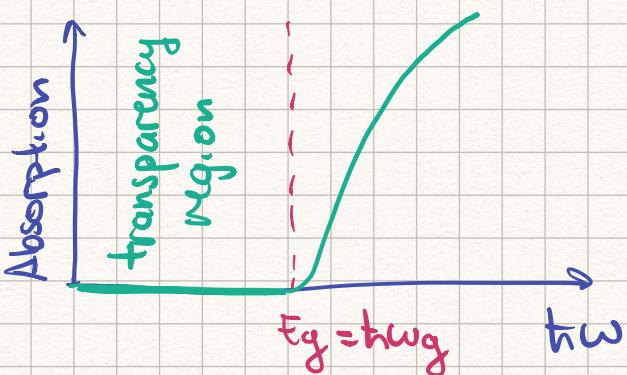
Conductivity is controlled by $E_g / k_B T$

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

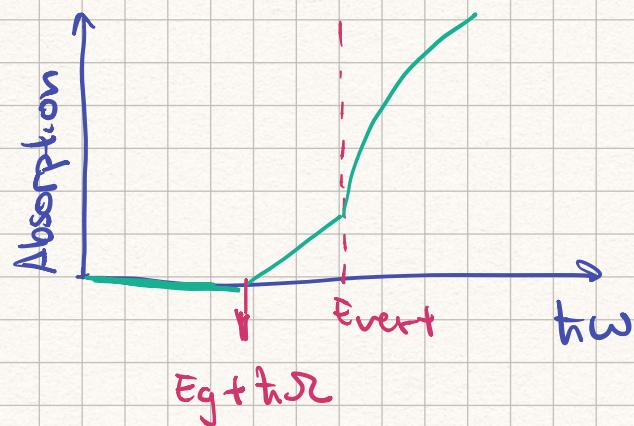
$E_g / k_B T \ll 1$: high carrier concentration

We investigate the band gap optically

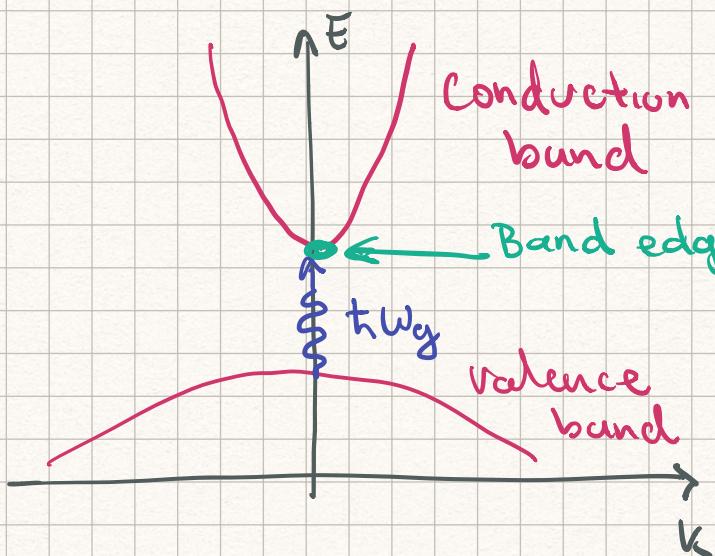
\rightarrow light absorption



Direct absorption process

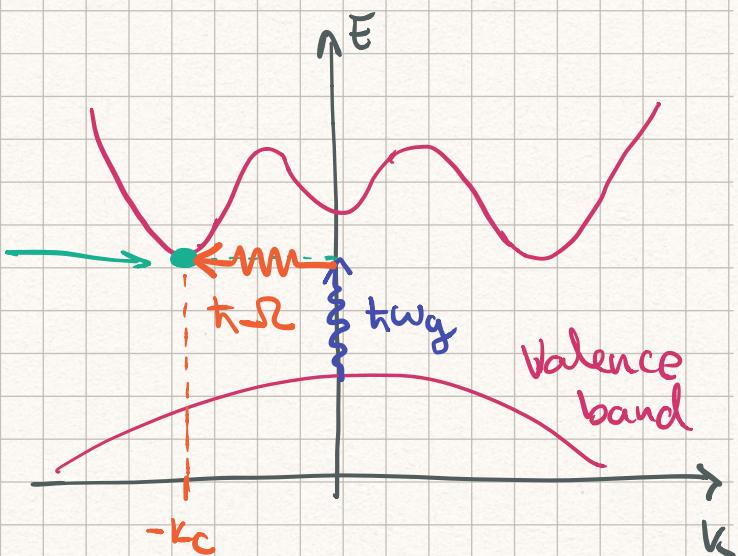


Indirect absorption process



1 free electron

1 hole



1 free electron

1 hole

1 phonon with energy $\hbar\omega_{\text{R}}$

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

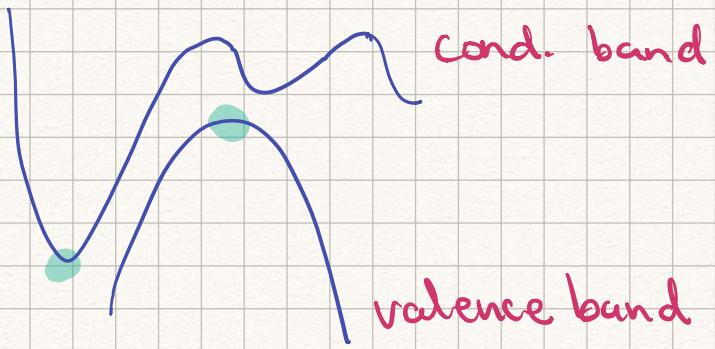
$$K(\text{photon}) = K_e + K(\text{phonon}) = 0$$

$$K(\text{phonon}) = -K_e$$

Direct gap: InSb

Indirect gap: Ge and Si

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



the band overlap

Eg 20

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

The wt near some \mathbf{k} $\nabla_{\mathbf{k}}$

$$\nabla g = \frac{\partial \omega}{\partial \mathbf{k}}$$

$$\epsilon = \hbar \omega$$

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

$$= \frac{1}{\hbar} \frac{\partial \epsilon}{\partial \mathbf{k}}$$

$$\text{In 3D: } \vec{\nabla}_g = \frac{1}{\hbar} \vec{\nabla}_{\mathbf{k}} \epsilon$$

$$\vec{\nabla}_{\mathbf{k}} = (\partial_{k_x}, \partial_{k_y}, \partial_{k_z})$$

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

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

$$\delta E = \frac{d\epsilon}{d\mathbf{k}} \delta \mathbf{k} = \hbar \nabla_g \delta \mathbf{k}$$

$$\hbar \nabla_g \delta \mathbf{k} = -eE \nabla_g \delta t$$

$$\hbar \delta \mathbf{k} = -eE \delta t$$

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

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

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

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

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

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

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 $w \neq \omega_k$ associated to the E_k and wavevector k

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

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

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

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

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

$$\begin{aligned}
 &= \hbar \sum_{\vec{k}} (\vec{k} + \vec{G}) |\psi_{\vec{k} + \vec{G}}|^2 \\
 &= \hbar \vec{k} \sum_{\vec{G}} |\psi_{\vec{k} + \vec{G}}|^2 + \hbar \sum_{\vec{G}} \vec{G} |\psi_{\vec{k} + \vec{G}}|^2 \\
 &= \hbar \left(\vec{k} + \sum_{\vec{G}} \vec{G} |\psi_{\vec{k} + \vec{G}}|^2 \right)
 \end{aligned}$$

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

⇒ 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

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

- If e^- interacts with lattice

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

$$\Delta \vec{P}_{\text{el}} = \vec{v}_k (\langle p_{\text{el}} \rangle \Delta \vec{k})$$

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

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 $\vec{p} = -\hbar \vec{G}$

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

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

reflected

$$\Delta \vec{P}_{\text{el}} + \Delta \vec{P}_{\text{lat}} = h \Delta \vec{k} = \vec{f}$$

$$h \frac{d\vec{k}}{dt} = \frac{d}{dt} \int \vec{f} dt \Rightarrow \boxed{h \frac{d\vec{k}}{dt} = \vec{f}}$$