Solid State

Dragg’s law \( n \lambda = 2d \sin \theta \)

Ideal crystal = infinite repetition of identical structural unit in space (basis)

Basis = a group of atoms attached to every lattice point

Bravais lattice = every lattice site is equivalent and specified in terms of primitive lattice vectors

\[ B(n_1, n_2, n_3) = n_1a_1 + n_2a_2 + n_3a_3 \]

\( n_1, n_2, n_3 \) are integers

The unit cell defined by primitive vectors has one atom and can be used to fill all space.

Bravais lattice + basis = crystal structure

Cohesive energy = energy of free atoms - energy of atoms in crystal

- van der Waals - molecular bonding
  - filled electron shells
  - non-zero dipole moment may form, e.g., charge dist.
    \( \rightarrow \) E-field \( \rightarrow \) induced dipole mom. \( \rightarrow \) attractive force

- ionic - electrostatic interaction of oppositely charged ions
  - electron transfer

- covalent - electrons forming the bond are partly localized in the region between the two atoms formed by the bond.

- metallic - lowering KE of valence electrons compared to the free atom.
Bloch Theorem: The eigenstates of a 1D lattice can be chosen to have the form...

\[ \Psi(x) = \psi(x) e^{i\mathbf{K} \cdot \mathbf{r}} \]

with \( \psi(x+a) = \psi(x) \)

periodicity of the lattice

periodicity of the lattice is manifested in the energy bands

Whenever the Bragg condition is satisfied an energy gap appears because propagation is suppressed - only standing waves are allowed.

Band structure of a solid consists of continuous bands of energy levels separated by energy gaps.

\begin{figure}
  \centering
  \includegraphics[width=\textwidth]{bands.png}
  \caption{Band structure of a solid}
  \end{figure}

Note: most elemental solids are derived from partially filled atomic energy levels \( \Rightarrow \) metals

metal \quad \text{insulator/ semiconductor (can conduct heat by lattice vibrations)}

effective mass - the curvature of the energy dispersion is different from that of the free-electron parabola

\( \Rightarrow \) the acceleration of an electron in a constant external force is not the same as a free electron in a vacuum

- electron behaves as though it has effective mass, \( m^* \)

semiconductor is an insulator at \( T=0 \) with electrical properties that can be controlled by doping.

donor - \( e^- \) into conduction band

acceptor - \( h^+ \) into valence band
\[ \mu = \left( \frac{2m}{\hbar} \right)_{5,3} \]

\[ N = \int_{E_c}^{\infty} \rho_c(E) \delta(E) \, dE = \int_{E_c}^{\infty} \frac{\rho_c(E) \, dE}{e^{E - E_c} / kT + 1} \quad \frac{1}{e^{E - E_c} / kT + 1} = e^{(E - E_c) / kT} \]

\[ r = \int_{E_c}^{E_V} \rho_c(E) \, dE = \int_{E_c}^{E_V} \frac{\rho_c(E) \, dE}{e^{(E - E_c) / kT} + 1} \quad \frac{1}{e^{(E - E_c) / kT} + 1} = e^{(E - E_c) / kT} \]

\[ s^2 \rho^2 \rightarrow s^2 \rho \quad \text{tetrahedral} \]

Promotion costs energy but results in strong, directional covalent bonds.

High T | energy to remove an electron from this strong covalent bond leaves a hole in the conduction band.

This explains why semiconductors have low carrier densities.

\[ n_e = N_c e^{-\frac{(E - E_c)}{kT}} \]

\[ n_h = N_v e^{-\frac{(E - E_c)}{kT}} \]

\[ n \mu = \text{electrons can hop between wells} \]

Discrete levels \( \rightarrow \) energy bands.

1D crystal acting as a diffraction grating for electrons.

\[ k_{\alpha} = n \pi \]

\[ \text{Grating condition:} \]

\[ \text{Varying } \phi = \frac{2\pi}{\lambda} \]

\[ \text{Complex prop. solution} \rightarrow 2 \text{ standing waves} \]

\[ \begin{align*}
\text{max. comp} & \quad \text{higher energy} \\
\text{min. comp} & \quad \text{lower energy}
\end{align*} \]

\[ \text{free electron dispersion except with } m^* \]
log(n) vs \( \frac{1000}{T} \)

- Intrinsic: Excite \( v \)-electrons into the C-band
- Saturation: All donors are ionized (constant at dopant concentration)
- Operational range
- Squeeze out: Donors are beginning to be ionized (increasing \( n \))

- Transition region

- Balance:
  - Diffusion current: Response to concentration step of electrons-holes at the interface
  - Drift current: Response to field created by diffusing carriers leaving behind ionized dopants

- Reverse bias
- Forward bias

Reinforce the built-in: Applied field opposes built-in field, which reduces the potential

Greater barrier at the junction due to intrinsic carriers

Diffusion current due to extrinsic carriers dominant