When atoms form a crystalline structure (metals, semiconductors, ...) the valence electrons loose their attraction to a local atom and form an band of ~equivalent charges- valence band. The conduction band lies within or above the valence band.
Energy Bands

- **Insulator**: Overlapping bands - little energy is needed for conduction.
- **Conductor**: Overlapping bands - little energy is needed for conduction.
- **Semiconductor**: Overlapping bands - little energy is needed for conduction.
Semiconductors and Dopants

Silicon atoms share valence electrons to form insulator-like bonds.

Phosphorus atom serves as n-type dopant

Boron atom serves as p-type dopant
Silicon Resistivity Versus Dopant Concentration

Electrical Resistivity (ohm-cm)

Dopant Concentration (atoms/cm$^3$)

- n-type
- p-type
Resistivity $\rho$

\[ j = n \cdot q \cdot v \ (A / m^2) \quad \text{current density} \]
\[ E = j \cdot \rho \quad \text{Ohm's Law} \]
\[ (j = I / A \quad R = \rho \cdot (L / A) \quad E = V / L) \]

- Electrons will collide on average $\tau$ seconds apart.

Drift velocity of electrons $v_d = a \cdot \tau = \frac{qE}{m} \cdot \tau$

\[ \rho = \frac{E}{j} = \frac{m}{ne^2} \frac{1}{\tau} = \frac{m}{ne^2} \left( \frac{1}{\tau_{\text{crystal}}} + \frac{1}{\tau_{\text{impurities}}} \right) \]

Metal

\[ \rho_m = \frac{m}{ne^2} \frac{1}{\tau} \]

Semiconductor

\[ \rho_{sc} = \rho_m \left( \frac{T}{T_0} \right)^{-3/2} e^{E_g / 2kT} \]

Diode or PN Junction

\[ I = I_0 \left[ e^{eV/kT} - 1 \right] \]

\[ \text{semiconductor wire} \]

\[ \text{Diode or PN Junction} \]

\[ E_g \]

\[ \text{Si} \]

\[ +V \quad p \quad n \quad -V \]
Diode Action

Diffusing electrons and holes create an electric field $E_o$ and potential step at the junction.

Anode

Cathode

Metal contact

Depletion Region $\Delta x$

p-type Si

n-type Si

Potential step

Barrier voltage

Potential step

0
In **forward bias** the applied E-field cancels internal electric field and charges begin flowing across the junction when $E_{\text{app}} > E_0$ or $V_{\text{app}} > \sim 0.6\text{V}$.
Reverse-Biased PN Junction Diode

In the **reverse bias** the external E-field increases the size of the depletion zone until all charge carries are near the contacts - **fully depleted**.
Diodes

\[ I = I_0 \left( \exp\left(\frac{eV}{kT}\right) - 1 \right) \]

- \( I \) is the current through the diode in Amps.
- \( I_0 \) is the diode’s ‘Saturation Current’ value.
- \( e \) is the electron charge, \( 1.602 \times 10^{-19} \) C.
- \( k \) is Boltzmann’s constant, \( 1.380 \times 10^{-23} \) J/K.
- \( T \) is the temperature in degrees Kelvin.
- \( V \) is the applied voltage in Volts.

**DIODE or PN JUNCTION**

\[ I = I_0 \left[ e^{(V-V_g)/kT} - 1 \right] = I_0 \left( V - V_g \right) / kT \]
Photoelectric Effect in a Metal

Photoelectric Effect
1) Record stopping voltage at three frequencies RGB.
2) Graph VS vs f and perform a linear fit.
3) Determine Planck's constant $h$ and the work function $W$ of the metal photocathode. Include errors.
4) Identify the metal.
5) What are sources of error in the experiment?

$$KE = hf - \phi$$

$$KE_{max} = eV_s = hf - W$$

$W \equiv \text{work function of the metal}$
Hall Effect in p-Germanium

- $n$ is the number of free charge carriers in the sample.
- In a semiconductor the free charge carriers $n$ are both electrons and holes.
- By measuring the Hall voltage $V_H$ vs $I$ at a known value of $B$ we can measure $n$ for the sample.
- Slope = $(1/nq) (B/t)$ where $R_H=1/nq$.
- Since $B = t \times I / R_H$ one can use the Hall effect to measure magnetic fields - Hall Probe!

\[
j = nq \bar{v}_d \quad \text{current density} = I / \text{area}
\]
\[
m \begin{pmatrix} \bar{v}_d \end{pmatrix} = q \begin{pmatrix} \bar{E} + \bar{v}_d \times \bar{B} \end{pmatrix} = 0 \quad \text{equilibrium}
\]
\[
E_z = -\bar{v}_d B_x \rightarrow V_y / w = \frac{I}{wt} \frac{1}{nq} B_x
\]
\[
V_H = \left( \frac{B_x}{nq t} \right) I \quad \text{Hall Voltage}
\]
\[
R_H = \frac{E_z}{j_y B_x} = \frac{1}{nq} \quad \text{Hall Coefficient}
\]
Transistor Action

- A transistor is constructed by opposing two diodes structures n-p-n or p-n-p.
- No collector current can flow through the collector-base junction (reverse diode).
- By increasing the base voltage \( +V_B \) to about +0.7V the potential barrier is lowered and a large collector current can cross to ground \( (\rho_{\text{transistor}} \rightarrow 0) \).
- By modulating the \( V_B \) one can form an amplifier \( A = I_C / I_B \). (Analogue electronics)
- If \( V_B \gg 1V \) then the transistor saturates to a digital pulse (Digital electronics).

\[
I_C = I_0 \left[ \exp \left( \frac{qV_B}{kT} \right) - 1 \right]
\]