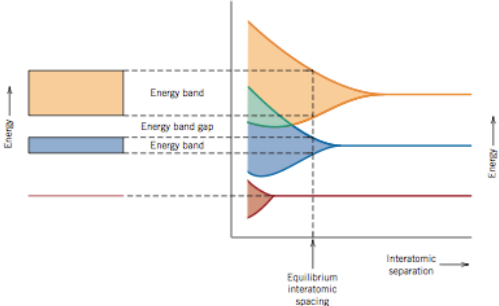
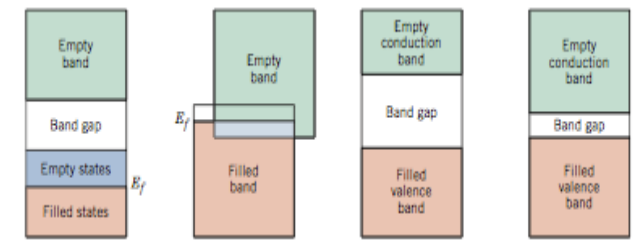


OHM'S LAW $V = IR$	CONDUCTIVITIES Metals – $10^7 (\Omega \cdot \text{m})^{-1}$ Semi-conductors – $10^{-6} \text{ to } 10^4 (\Omega \cdot \text{m})^{-1}$ Insulators – $10^{-10} \text{ to } 10^{-20} (\Omega \cdot \text{m})^{-1}$	CURRENT result of motion of charged particles responding to forces from externally applied electric field [+ moves with current direction, - moves opposite]
ELECTRICAL RESISTIVITY $\rho = \frac{RA}{\ell} = \frac{VA}{I\ell}$ units = $(\Omega \cdot \text{m})$	ELECTRIC CONDUCTION: flow of electron causing a current (within most solids) IONIC CONDUCTION: possible current produced from net motion of charged ions (diffusion of ions)	
ELECTRICAL CONDUCTIVITY ease with which a material generates an electric current $\sigma = \frac{1}{\rho}$ units = $(\Omega \cdot \text{m})^{-1}$	BAND STRUCTURE = how electrons fill orbitals in an atom - electrons acted upon by the electrons & nuclei of adjacent atoms when in close proximity - may split into series of closely spaced electronic states (electron energy bands) - extent of splitting depends on separation - energy band gaps = the gaps between adjacent bands - total # states in each band = total states from N atoms (s band = N states, p band = 3N states)	
FERMI ENERGY (E_f) energy of last filled state at 0K. CONDUCTOR if bands partially full/overlap INSULATOR/ SEMICONDUCTOR if valence bond full & conduction band empty		
FREE ELECTRON participates in conduction process HOLE (semiconductor/insulators) electrons with energy LESS than E_f and still participate in conduction	CONDUCTION IN METALS - electron excited to empty state above the Fermi energy (free electron) • requires little energy because there are vacant states adjacent to highest-filled state at Fermi energy (provided by electric field) - very high conductivity – many electrons excited into empty state above E_f	
ELECTRON MOBILITY - free electrons accelerate opposite field direction - acceleration is counteracted by friction • friction from scattering e^- from lattice impurities • impurity atoms, vacancies, thermal vibrations, dislocations, interstitial atoms - scattering— e^- loses kinetic energy, motion changes direction, resistance to passage of current - net motion opposite field - drift velocity (V_d) = average e^- velocity opposite field $V_d = \mu_e E$ electron mobility (m^2/Vs) x electric field	RESISTIVITY depends on TEMPERATURE as T increases, # of impurities increases, BUT μ_e decreases (dominates) $\rho_t = \rho_o + aT$ a is the material constant $\frac{1}{\sigma} = \rho = \rho_o + aT$ for $T > -200^\circ\text{C}$	
RESISTIVITY depends on COLDWORKING Strengthening pure alloys (soft) by adding solutes/particles – not much effect on conductivity	RESISTIVITY depends on # OF IMPURITIES as T increases, # of impurities increases, BUT μ_e decreases (dominates) $\rho_i = A c_i (1 - c_i)$ A is the constant concentration is in terms of atomic fraction (%at / 100) Matthieson's Rule: $\rho_{total} = \rho_t + \rho_i + \rho_d$ (temp + impurities + deformation)	
CONDUCTION IN SEMICONDUCTORS & INSULATORS - electron must be thermally promoted across band gap into empty states at bottom of conduction band to become a free electron - band gap energy (E_g) ~ 1eV ... from non-electric source - $E_g > 3\text{eV}$ = insurmountable gap = insulating material - E_g increase = larger band gap & decreased electrical conductivity - Semiconductors have a narrow band gap - Insulators have a relatively wide band gap	INTRINSIC SEMICONDUCTIVITY - narrow band gap (less than 2eV) - At $T = 0\text{K}$, conductivity = 0 - At $T > 0\text{K}$ heat helps e^- jump over band gap (e^- -hole pair) - Hole is created for every e^- excited to conduction band INTRINSIC CONDUCTION - Free electrons ($n = \# e^- / \text{m}^3$) - Holes ($p = \# \text{ holes} / \text{m}^3$) - $\sigma = n e \mu_e + p e \mu_h$ - since # holes = # free e^- for intrinsic semi-conductors $\sigma = n e (\mu_e + \mu_h)$ - electrons and holes move in response to electric field - $e/\text{atom} = e/\text{volume} \times \text{volume}/\text{atom}$	
N-TYPE EXTRINSIC SEMICONDUCTION - e^- loosely bound—weak attraction promotes conduction band - e^- binding energy = E required to excite e^- to state within conduction band (E_D) - each excitation donates an e^- to the conduction band (donor) - no corresponding hole created in valence band - Fermi level shifted up in band gap - $E_D \ll E_g, n \gg p$ – many donor e^- promoted at room T $\sigma = n e \mu_e$	P-TYPE EXTRINSIC SEMICONDUCTION - Dopant atoms (each with a valence bond deficient in an e^-) - Hole for electron... new level above valence (acceptor state) - Hole left in valence bond when e^- fills acceptor state - $p \gg n$... $\sigma = n e \mu_e$ - Fermi level positioned within	

CARRIER CONCENTRATION – TEMPERATURE DEPENDENCE (semiconductors)

- Increased thermal energy allows e^- to move to conduction band
 - Intrinsic carrier concentration increases
- Intrinsic excitations insignificant vs. extrinsic donor excitations until very high temperatures

INTRINSIC SEMICONDUCTORS

$$n = n_o e^{-\frac{E_g}{2kT}}$$

N-TYPE EXTRINSIC SEMICONDUCTORS

$$n = n_{D_o} e^{-\frac{E_D}{kT}}$$

P-TYPE EXTRINSIC SEMICONDUCTORS

$$p = n_{A_o} e^{-\frac{E_A}{kT}}$$

COEFFICIENT OF THERMAL EXPANSION

- Materials expand/contract when heated and cooled

$$\frac{\Delta \ell}{\ell} = \alpha_\ell \Delta T \quad \text{OR} \quad \frac{\ell_f - \ell_o}{\ell_o} = \alpha_\ell (T_f - T_o) \quad (^\circ\text{C}^{-1})$$
- **Thermal expansion** = extent a material expands upon heating
- **Volume changes with T:** $\frac{\Delta V}{V_o} = \alpha_V \Delta T$
- For materials with isotropic thermal expansion, $\alpha_V = 3\alpha_\ell$
- Thermal expansion—increase in avg. distance between atoms
- Thermal expansion due to asymmetric curvature of potential energy trough NOT the increased vibrational amplitudes with T
 - A symmetric potential energy curve = NO NET CHANGE in interatomic separation (NO THERMAL EXPANSION)
- **Thermal stress** = stresses induced in body due to T changes

$$\sigma = E\alpha_\ell (T_o - T_f)$$

THERMAL CONDUCTIVITY (steady-state heat flow)

- Heat transported from high T to low T regions
- **Thermal conductivity** = ability to transport heat
- **Heat flux (q)** = rate heat energy transfer through given surface

$$q \left(\frac{W}{m^2} \right) = -k \frac{dT}{dx} \quad \frac{dT}{dx} \text{ is T gradient through conducting medium}$$

k is thermal conductivity $-\left(\frac{W}{mK} \right)$
- Heat is conducted by lattice vibration waves (phonons) and free electrons (usually just one predominates)
 - Metals = free electrons
 - Ceramic = phonons (vibrational)
 - Polymers = vibrational/rotational

STRESS-STRAIN BEHAVIOUR

- Hooke's law – relation: stress & strain for elastic deformation

Tension $\sigma = E\epsilon$ (E is Young's elastic Modulus)

Shear $\tau = G\gamma$ (G is Shear Modulus)
- **Modulus of Elasticity (Young's), E** = proportionality constant
 - Ration stress : strain in elastic region (measures stiffness)
 - Deformation completely elastic
- **Elastic Deformation** = when stress & strain are proportional
 - Slope of line = E, independent of time
 - Nonpermanent (return original shape when load released)
- High Modulus of Elasticity (E) = stiff material
- Varies by 10^6 – depends little on alloying/T in crystalline solid
- Apply tension (pull solid) – atoms forced apart ($r > r_o$)
 - Net attractive force (reaction force apposed applied force)
- If force vs. interatomic spacing in approx. straight line
 - If slope = S then... $F = -s(r - r_o)$
 - To describe elastic behavior: $\sigma = E\epsilon$
 - σ is stress $\left(\frac{F}{\text{unit A}} \right)$, E is modulus of elasticity, ϵ is strain
- response correlated by stress (normalized force) & strain

CARRIER DENSITY—CONDUCTIVITY

- Steeper T-dependence for intrinsic region ($E_g \gg E_A$)
- Small saturation region
- Nearly constant conductivity near room temperature
- Conductivity SOMETIMES DECREASE with T in extrinsic regions
 - # of carriers in extrinsic region is constant
 - mobility decreases with temperature due to increased scattering from thermal fluctuations

HEAT CAPACITY

- Solids increase in temperature when heater (absorb energy)
- **Heat capacity** = ability to absorb heat from surroundings
- **(C)** energy to raise 1 mole of solid by 1 degree

$$C = \frac{dQ}{dt} \left(\frac{J}{\text{mol} \cdot K} \right)$$
- **Specific heat capacity** = energy per unit mass per degree

$$c = \left(\frac{J}{kg \cdot K} \right) \dots \text{energy content of material}$$
 - Can be measured at constant volume (C_V) or pressure (C_P)
- Atoms constantly vibrate at high frequency and small amplitude
 - Elastic/sound waves—short wavelength, high frequency, propagate at speed of sound
 - Quantized energy—**phonon** = single quantum of vibrational energy
 - Elastic waves responsible for thermal scattering
- Increasing K.E. of e^- (only for free e^- about E_f)
- Heat Capacity depends on TEMPERATURE
 - θ_D = **Debye temperature** (usually less than room T)
 - At low T ($< \theta_D$) $C_V = AT^3$ (T-dependent)
 - At high T ($> \theta_D$) $C_V = 3R \dots 25 \frac{J}{\text{mol} \cdot K}$ (T-independent)

MECHANICAL PROPERTIES OF METALS

- Solid moves if: a net force acts OR if forces & moments balance atoms are pushed close (compression) or apart (tension)
- External compressive force – forces atoms closer ($r < r_o$)
 - Net repulsive force (solid exerts reaction force)
- Apply tension (pull solid) – atoms forced apart ($r > r_o$)
 - Net attractive force (reaction force apposed applied force)
- If force vs. interatomic spacing in approx. straight line
 - If slope = S then... $F = -s(r - r_o)$
 - To describe elastic behavior: $\sigma = E\epsilon$
 - σ is stress $\left(\frac{F}{\text{unit A}} \right)$, E is modulus of elasticity, ϵ is strain
- response correlated by stress (normalized force) & strain (normalized destruction)
- loads can be applied through...compression, tension, or shear
- **stress** (MPa): $\sigma = \frac{F}{A_o} = \frac{\text{instantaneous load applied}}{\text{cross-sectional A (before deformation)}} \left[1 \text{MPa} = 10^6 \frac{N}{m^2} \right]$
- **strain**: $\epsilon = \frac{\ell_t - \ell_o}{\ell_o} = \frac{\Delta \text{gauge length (direction of applied force)}}{\text{original gauge length}} \quad \text{NO UNITS}$
- **shear stress**: $\tau = \frac{F}{A_o} = \frac{\text{instantaneous shear load}}{\text{original cross-sectional area}}$
- **shear strain** (γ): tangent of shear angle from applied shear load