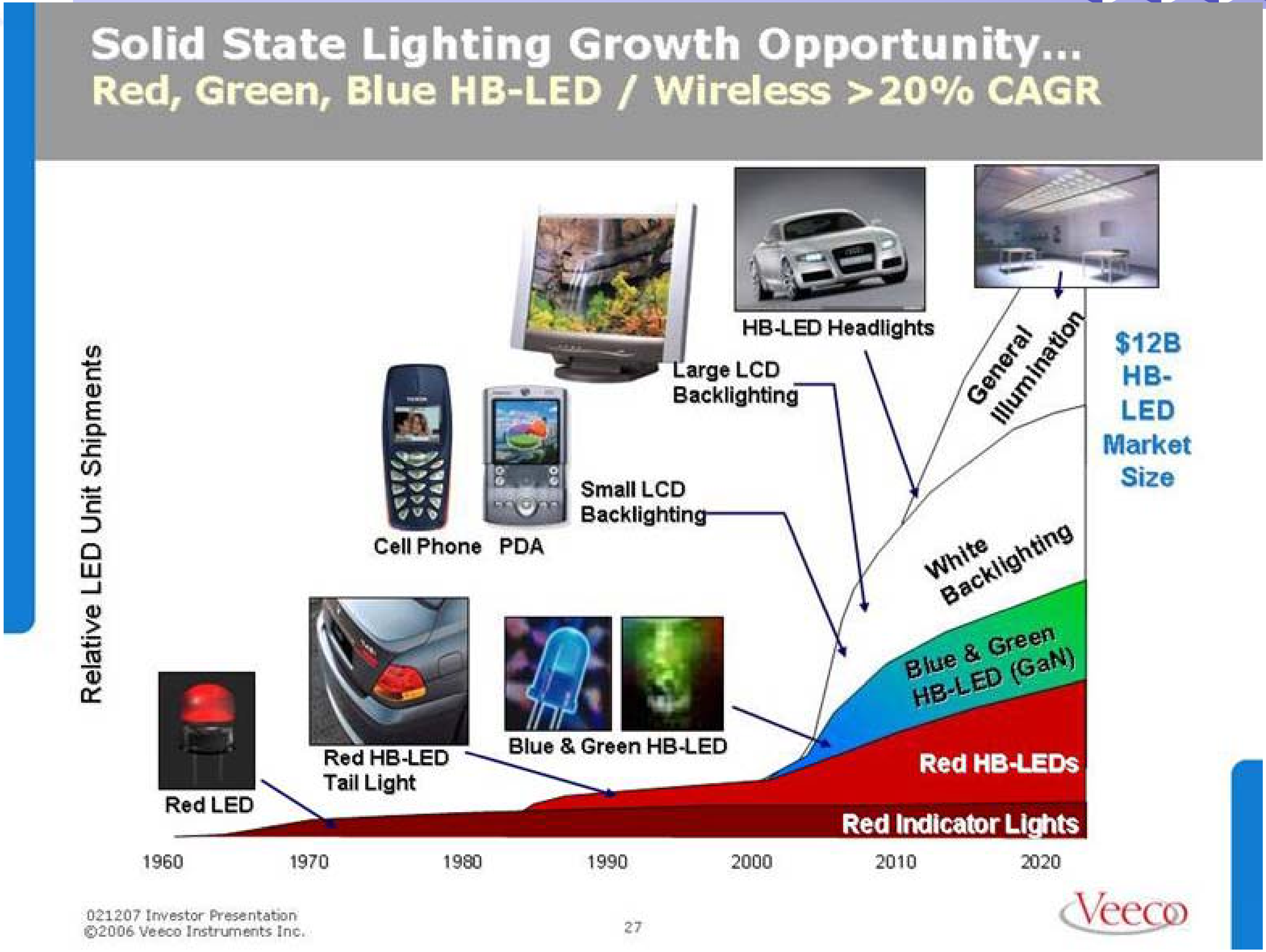
Introduction to Materials Science & Engineering

Chapter 19. THERMAL PROPERTIES

- How does a material respond to heat?
- What do we care and measure?
  - √ Heat capacity
  - √ Thermal-expansion coefficient
  - √ Thermal conductivity
  - √ Thermal shock resistance
- How do ceramics, metals, and polymers behave?

Solid State Lighting



Solar Cell

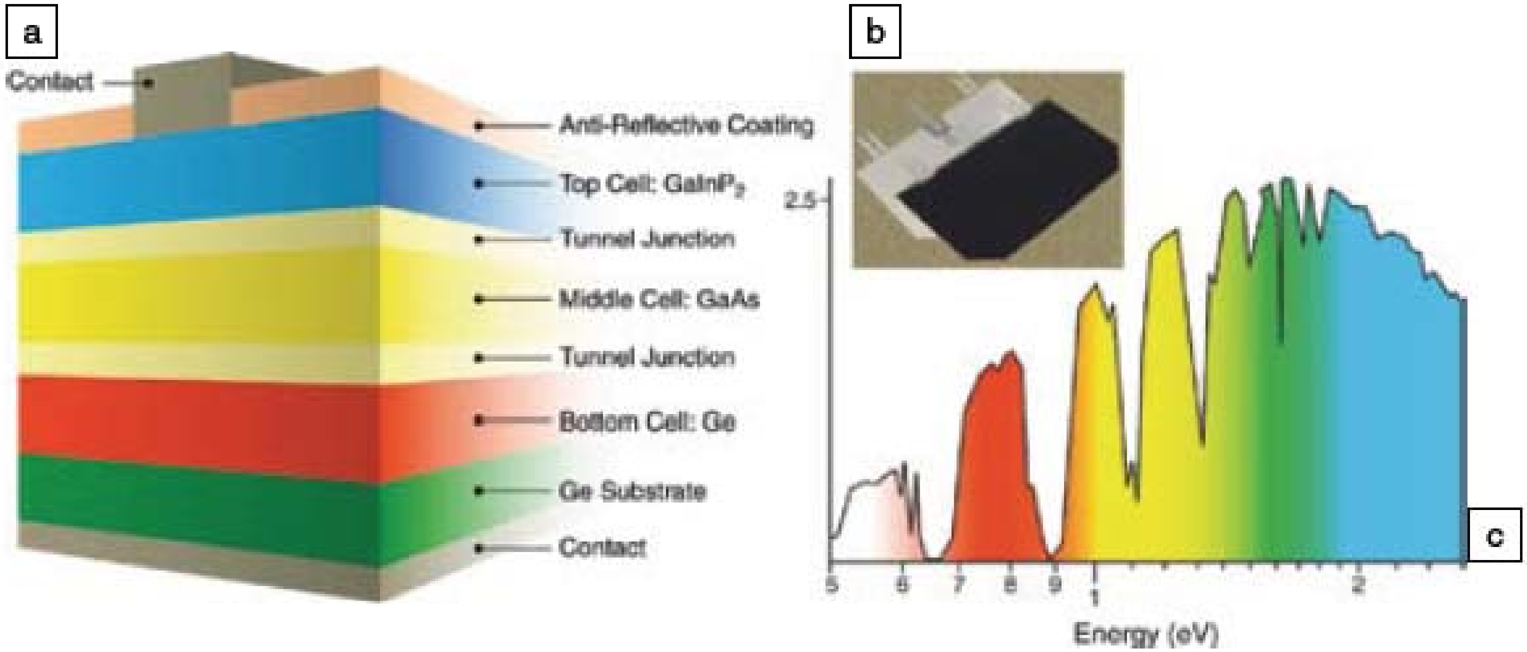


Figure 8. (a) Schematic of a possible configuration for a three- (triple-) junction device and (b) picture of a GaInP/GaAs/GaInAs cell with a demonstrated 31.3% efficiency. (c) Solar spectrum illustrating the basic approach for spectrum splitting by a multijunction cell. A four-junction device with bandgaps of 1.8 eV, 1.4 eV, 1.0 eV, and 0.7 eV would have a theoretical efficiency of >52%.

Fuel Cell

Laptop

Samsung SDI

Cellular Phone

LG Chem.

Power Sources for the Next Generation

LEV

Hyundai Motor

PMP

Samsung SDI

Contents

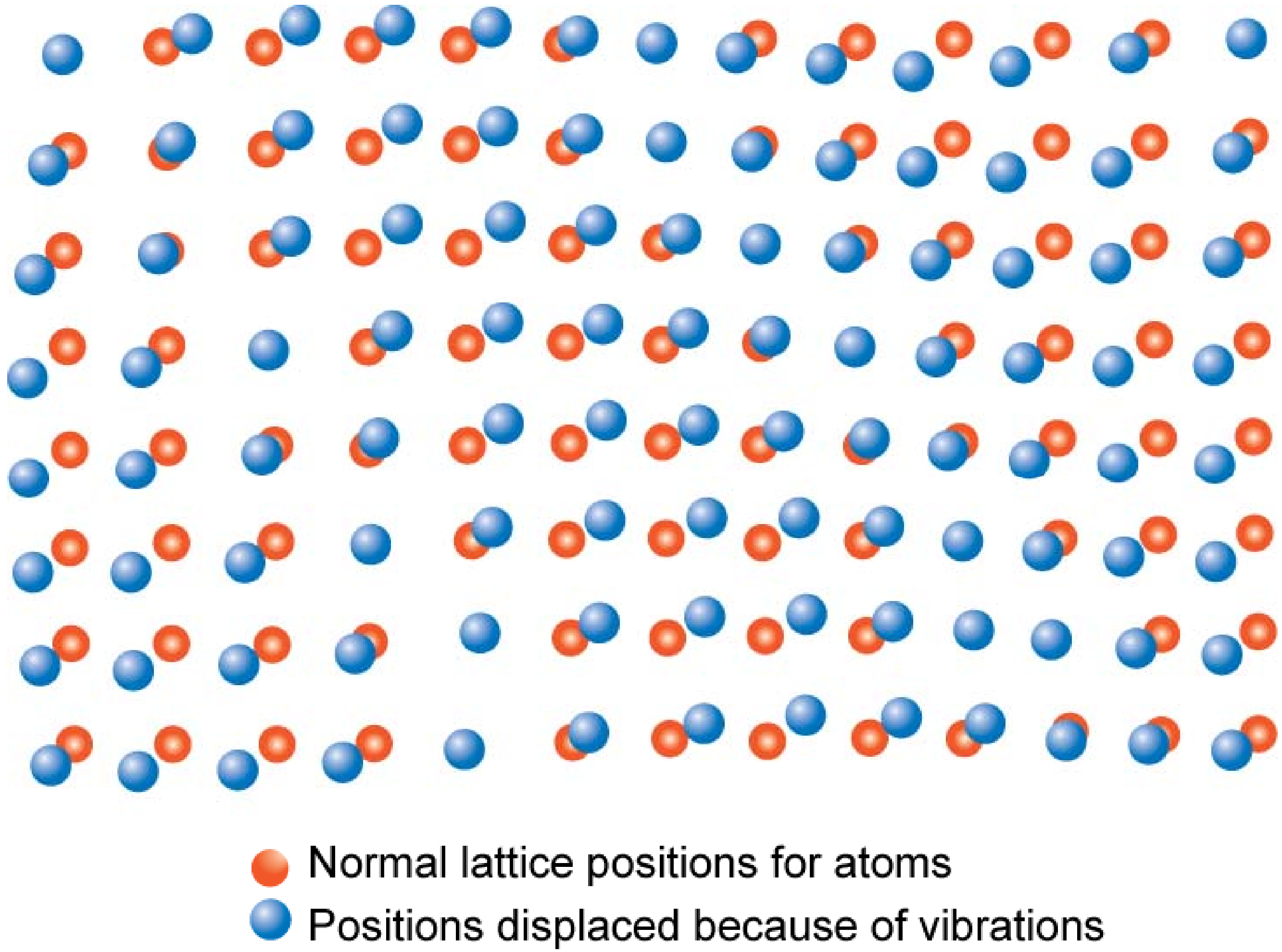
- Phonon - A packet of elastic waves. It is characterized by its energy, wavelength, or frequency, which transfers energy through a material.
- Specific heat (= Heat capacity) - The energy required to raise the temperature of a material by one degree.
- Thermal expansion coefficient - Describes the amount by which each unit length of a material changes when the temperature of the material changes by one degree.
- Thermal conductivity - A nanostructure-sensitive rate at which heat is transferred through a material **(by electron and/or phonon)**.
- Thermal stress - Stresses introduced into a material due to differences in the amount of expansion or contraction that occur because of a temperature change.

Contents

Energy Storage

How is the energy stored?

Phonons = Vibrational Modes = Thermal Waves



(Fig. 19-1)

Phonon

- **Atoms in solids are constantly vibrating at very high frequencies with relatively small amplitudes:**

  → **traveling lattice waves, elastic waves.**

- **In most solids, thermal energy = vibrational energy of the atoms.**
- **Phonon – single quantum of vibrational energy (waves).**
- **Phonon is one of the major causes of electron scattering during the electric conduction.**
- **Phonon + electron participate in the transport of energy during thermal conduction.**

Heat Capacity = Specific Heat

- General: The ability of a material to absorb heat.
- Quantitative: The amount of energy required to increase the temperature of the material by one degree.

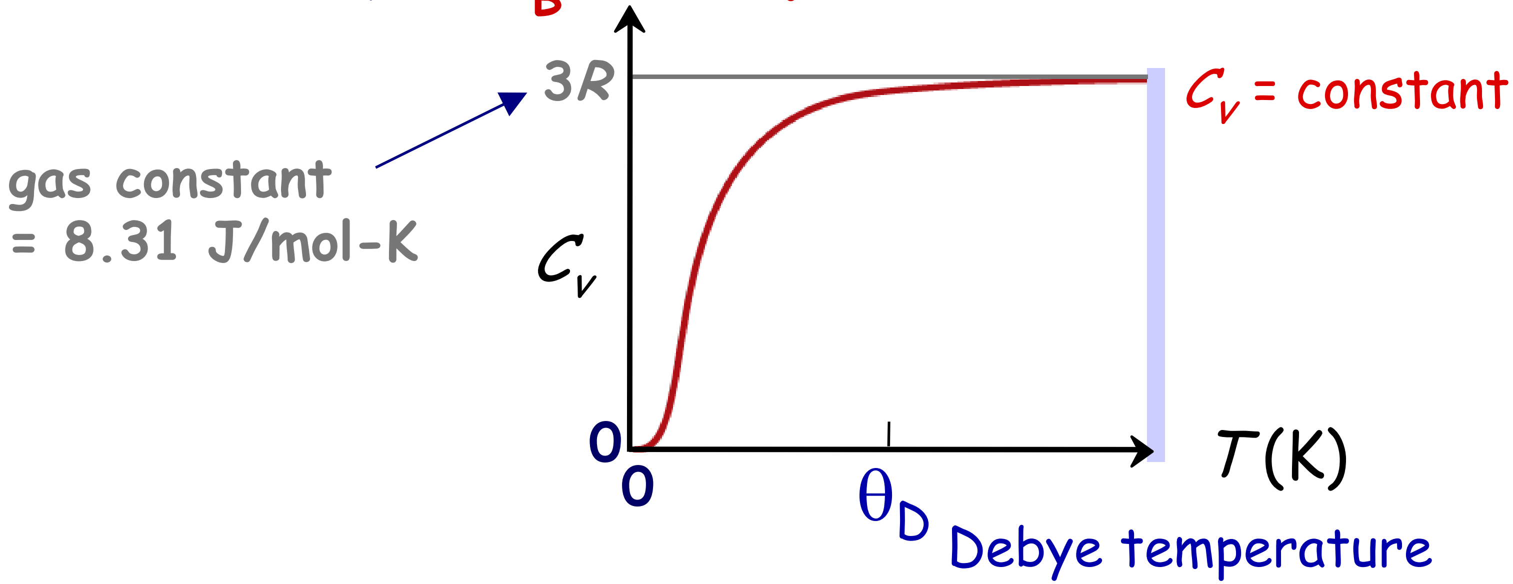
heat capacity (J/mol-K) → $$C = \frac{dQ}{dT}$$ ← **energy input (J/mol)** (dQ), **temperature change (K)** (dT)

- Two ways to measure heat capacity:
  - √ C_p : Heat capacity at constant pressure
  - √ C_v : Heat capacity at constant volume
- Specific heat - the energy required to raise the temperature of a material by one degree.

Heat Capacity vs. T

- Heat capacity
  - √ increases with temperature
  - √ reaches a value of **~3k_B / atom**

(Fig. 19-2)



- Atomic view:
  - √ Energy is stored as atomic vibrations.
  - √ As *T* goes up, so does the average energy of atomic vibration

Heat Capacity: Comparison

(Table 19-1)

increasing C_p

material	c_p (J/kg-K) at room T
• **Polymers**	
Polypropylene	1925
Polyethylene	1850
Polystyrene	1170
Teflon	1050
• **Ceramics**	
Magnesia (MgO)	940
Alumina (Al_2O_3)	775
Glass	840
• **Metals**	
Aluminum	900
Steel	486
Tungsten	138
Gold	128

c_p: (J/kg-K)

C_p: (J/mol-K)

- Why is c_p significantly larger for polymers?

$\sim 3k_B$ / atom

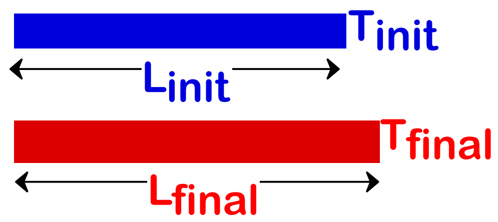
- 2009-11-25

Contents

Thermal Expansion

- Materials change size when heated

$$\frac{L_{final} - L_{initial}}{L_{initial}} = \alpha(T_{final} - T_{initial})$$

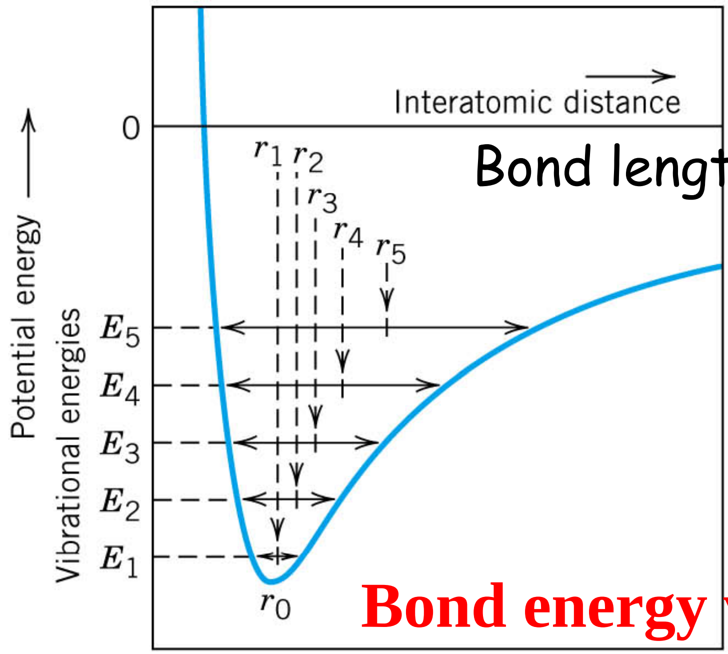


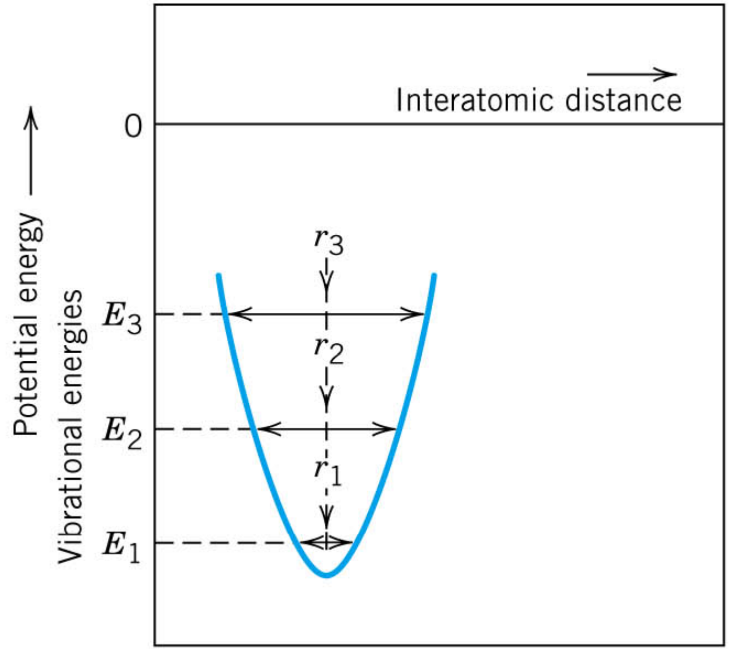
linear coefficient of thermal expansion (1/K or 1/°C)

- Atomic view: Mean bond length increases with *T*

(Fig. 19-3)

Bond energy

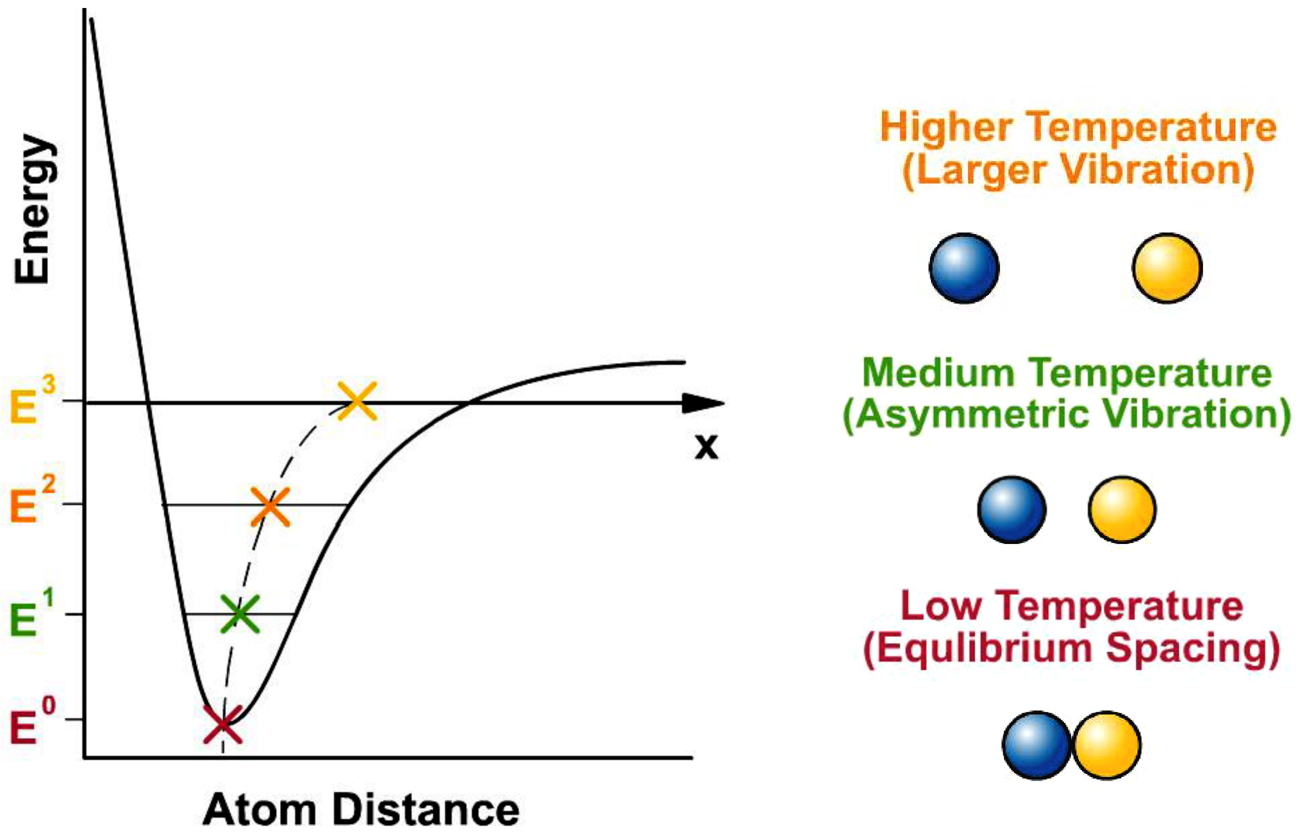




Bond energy vs. bond curve is "asymmetric."

Properties from Bonding: α

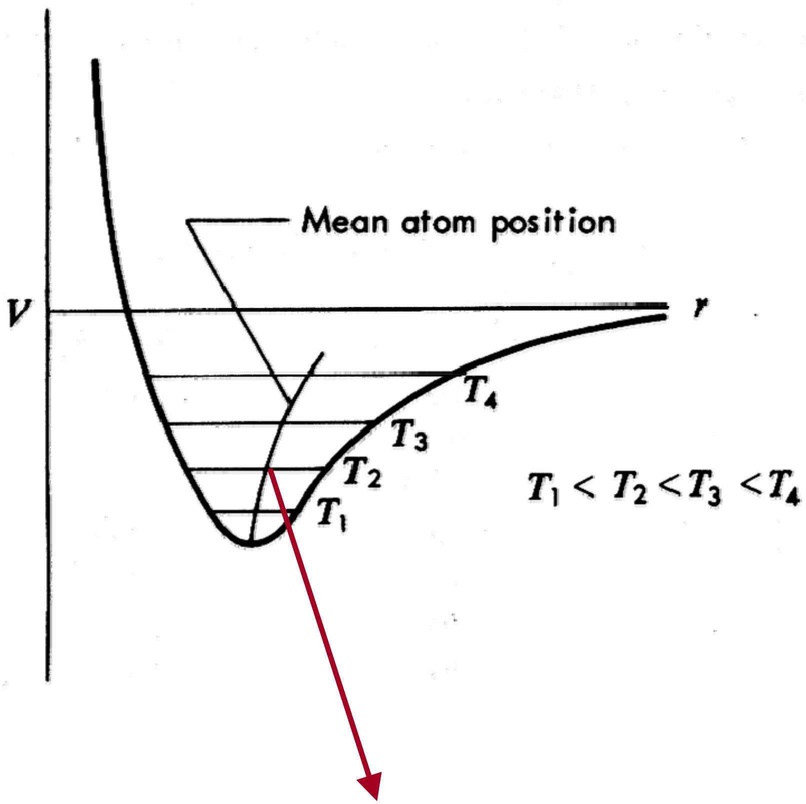
- Thermal expansion ← asymmetric nature of the energy well
- Broad well (generally more asymmetric) → larger expansion

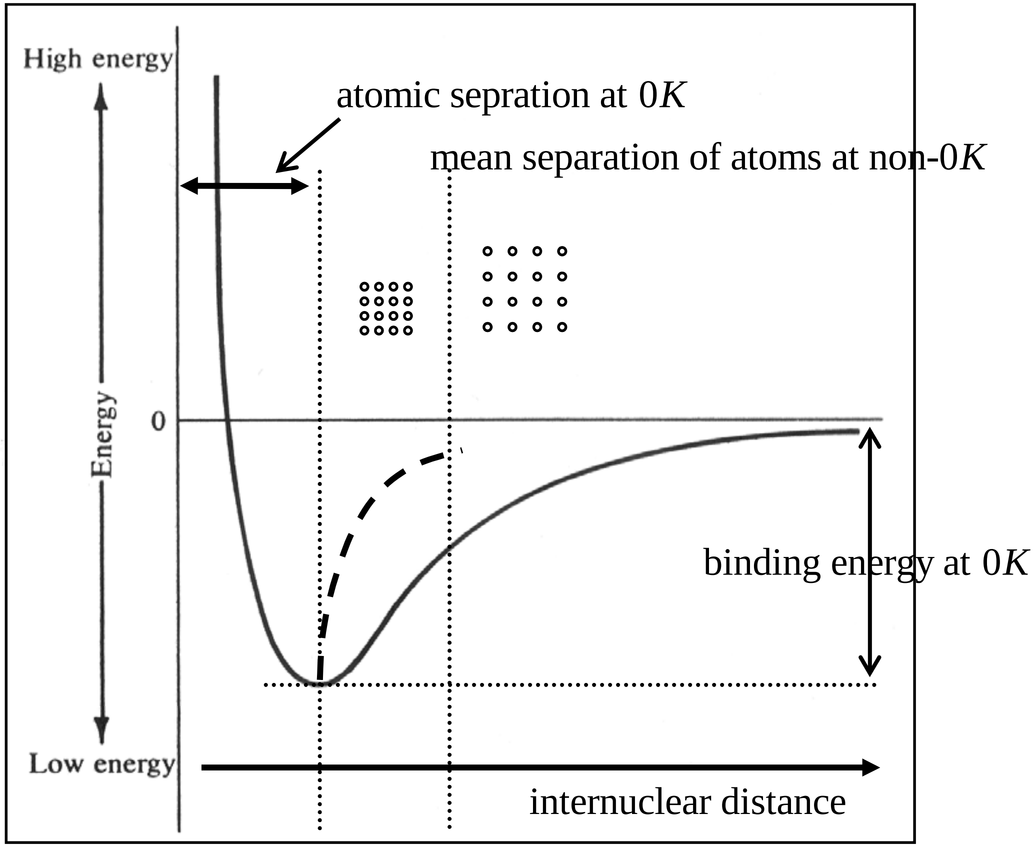


Properties from Bonding: α

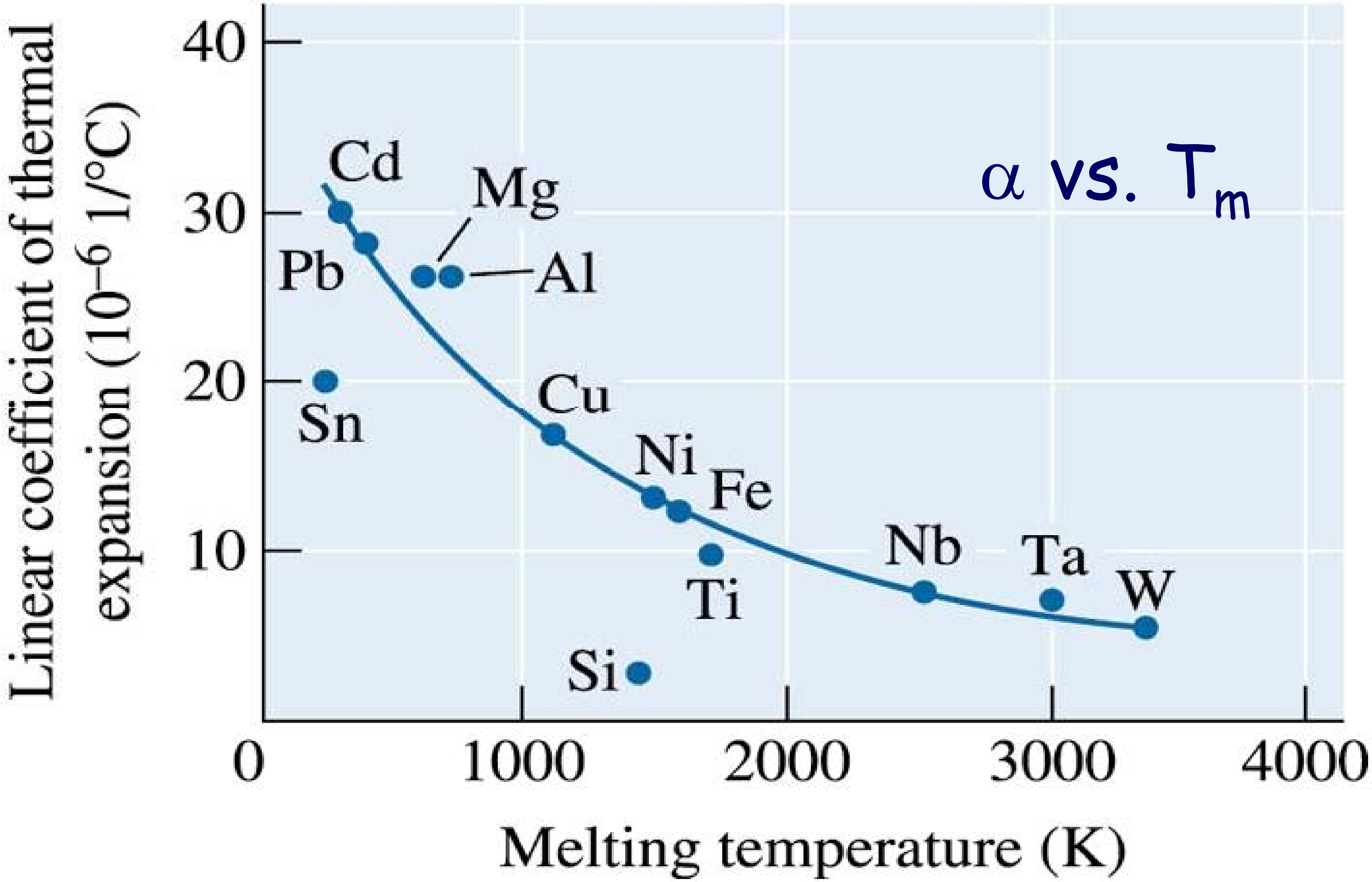
Temperature supplies thermal energy into solids

→ thermal vibration (phonon)





<u>Asymmetry and vacancy concentration</u> are related to the thermal expansion coefficient of materials.



$\alpha \sim 10^{-5}/K$

Contents

Thermal Conductivity

- General: The ability of a material to transfer heat
- Quantitative:

$$q = -k\frac{dT}{dx}$$

heat flux (J/m^2-s) → q

temperature gradient → $\frac{dT}{dx}$

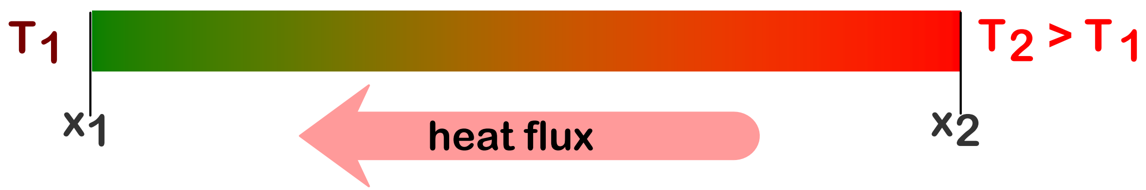
thermal conductivity (J/m-K-s) → k

Fourier's Law

Sec. 19-4

unit wrong

(Eq. 19-5)

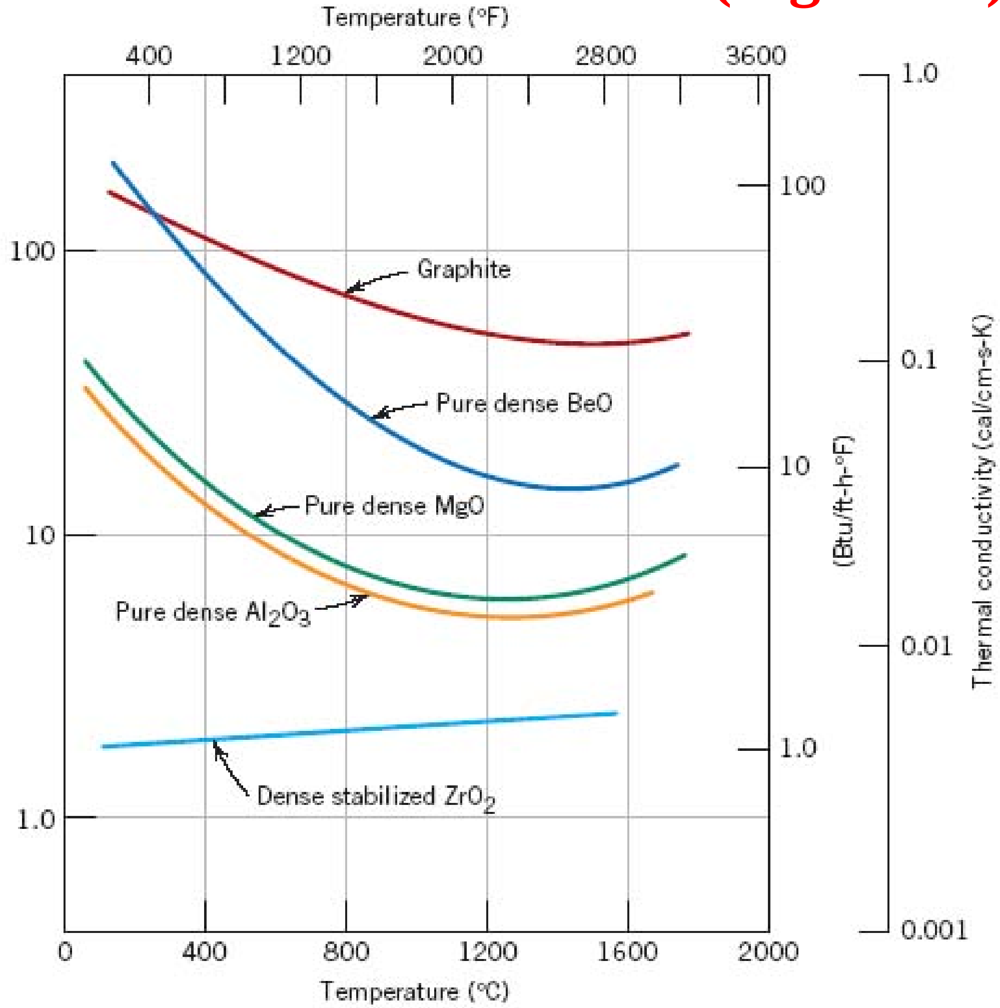


- Lattice vibrations (<u>phonons</u>) in hotter region carry energy (vibrations) to cooler regions.
- Free or conducting <u>electrons</u> can participate in the electronic thermal conduction.

Thermal Conductivity - Ceramics

- Does not have large amount of free electrons:
  - → Mostly phonon contribution.
  - → Lattice imperfections scatter phonons.
- Scattering of phonon increases with temperature:
  - → *k* decreases.
- *k* increases with *T* at higher *T*
  - ← radiant heat transfer (by infrared photons).

Thermal conductivity vs. *T* for several ceramics **(Fig. 19-5)**



Which has the lowest thermal conductivity?

→ vacuum

Porosity in ceramic materials may have a dramatic influence on thermal conductivity:

Increasing the pore volume will generally result in a reduction of the thermal conductivity.

Insulating properties of polymers are good, but may be further enhanced by the introduction of small pores, which are ordinarily introduced by foaming during polymerization → foamed polystyrene (Styrofoam)

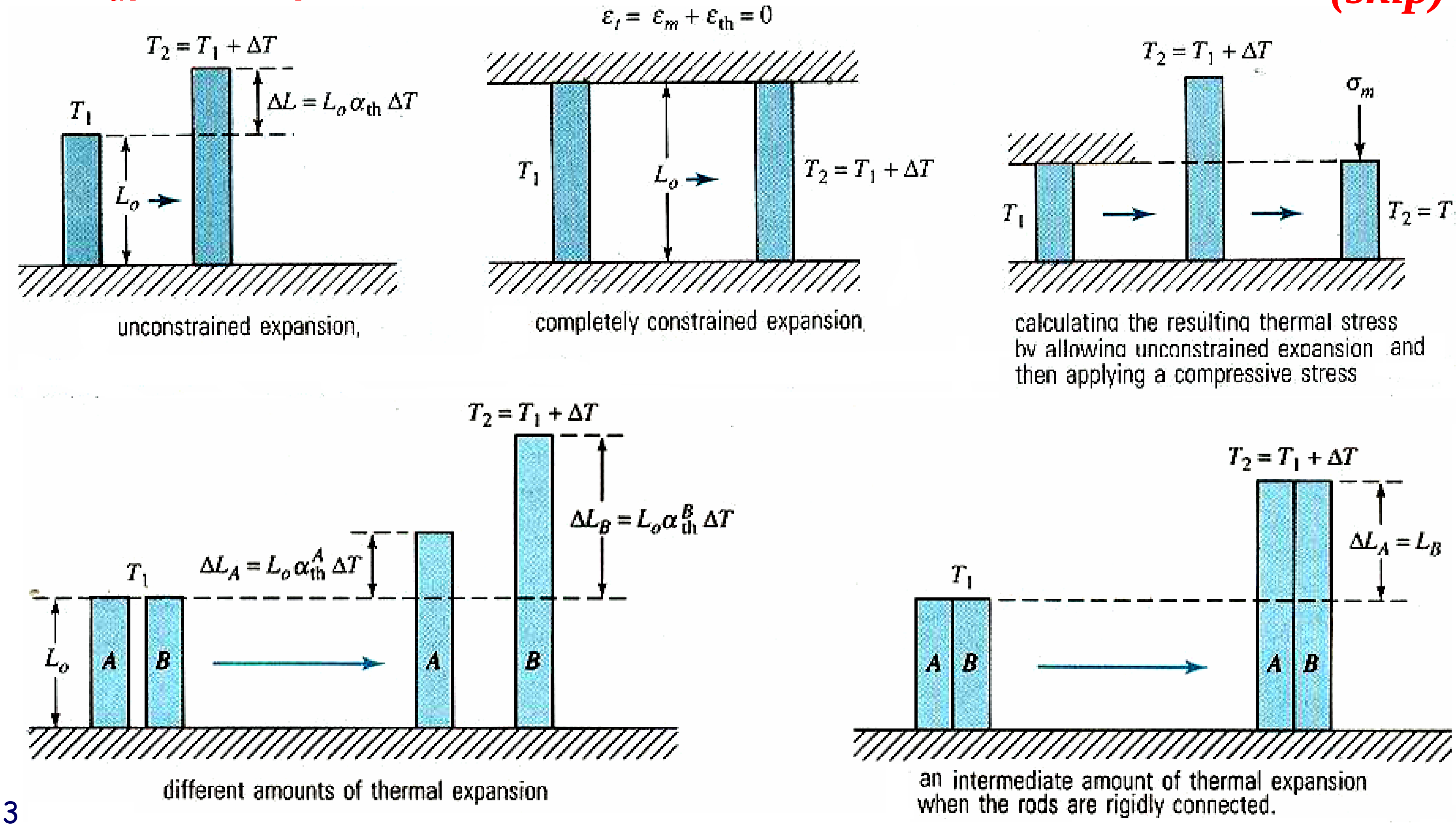
Contents

Thermal Stress

- Due to thermal expansion/contraction for electronics

$$\sigma_{th} = E\alpha_l \Delta T$$

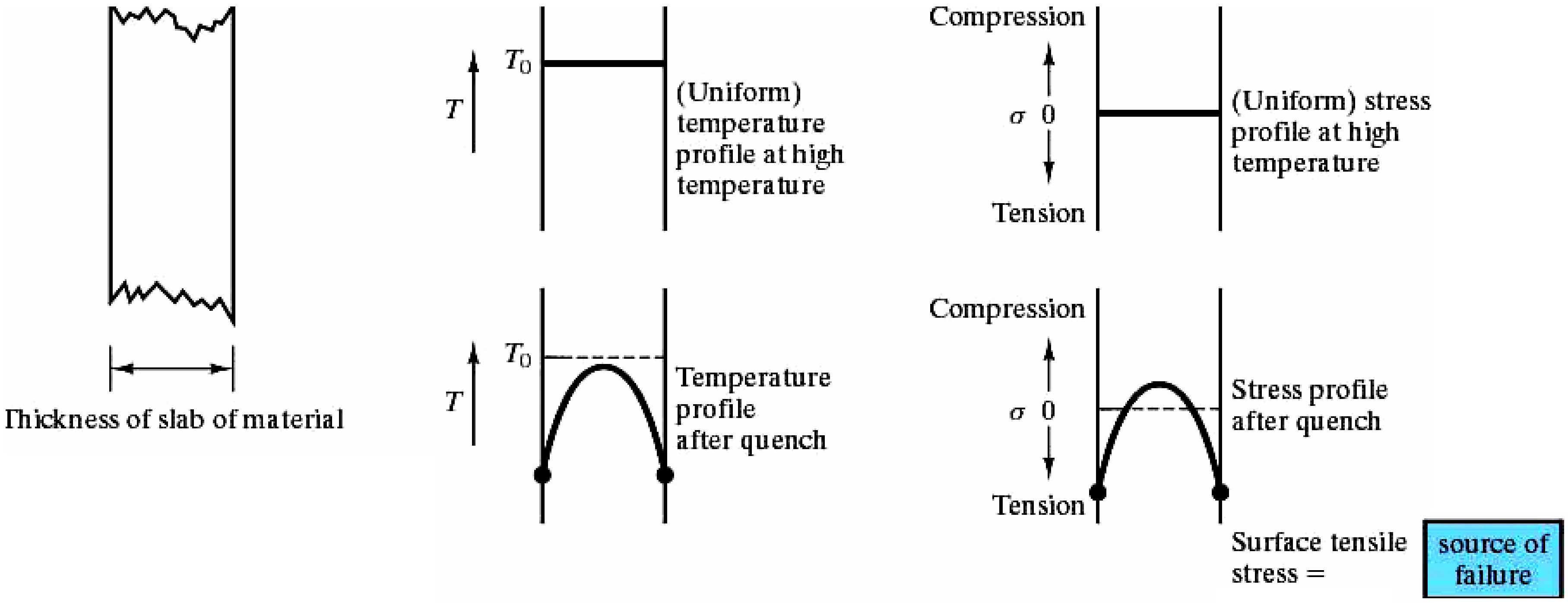
(skip)



Thermal Stress

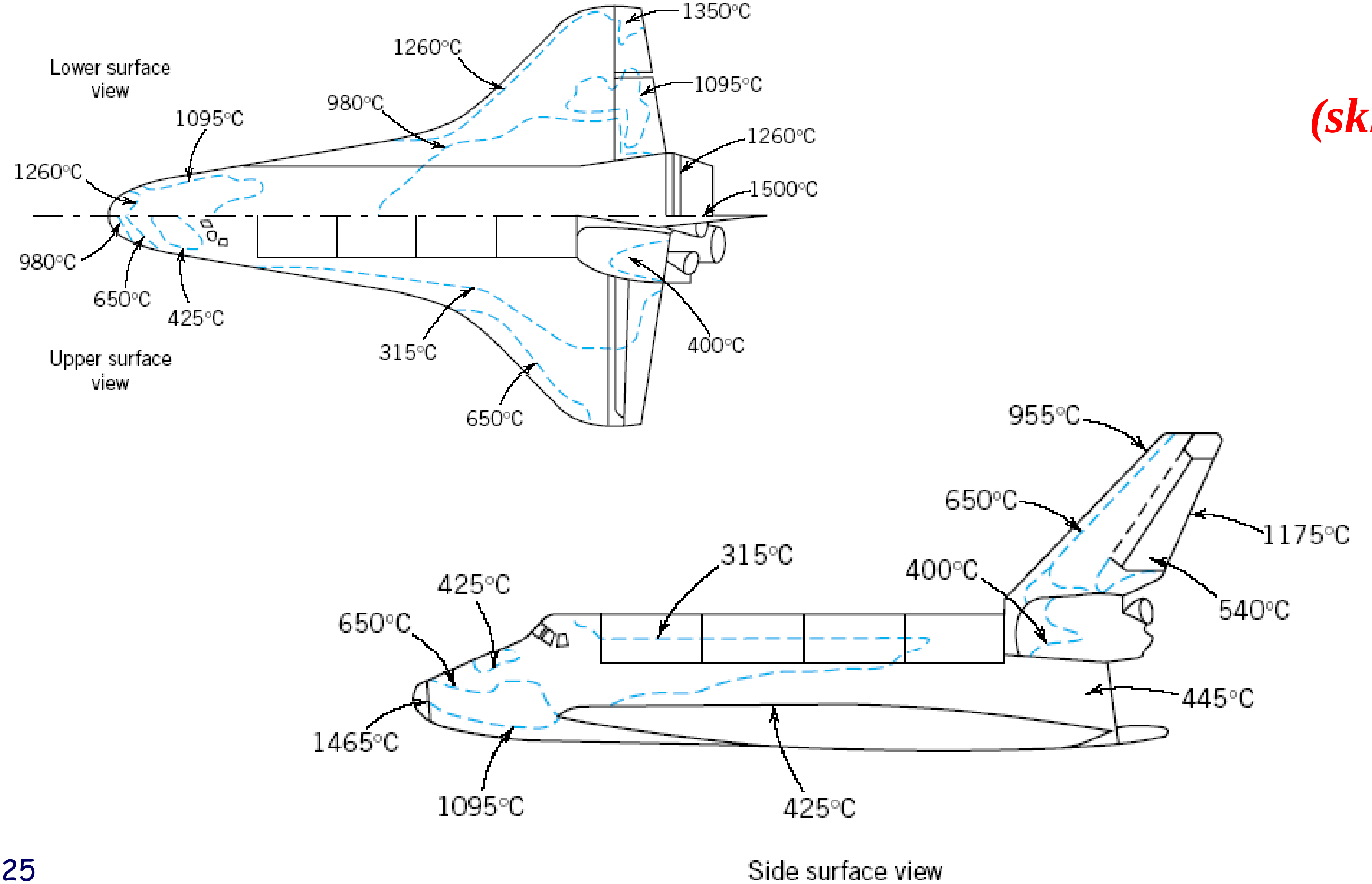
➢ Due to a temperature gradient

(skip)

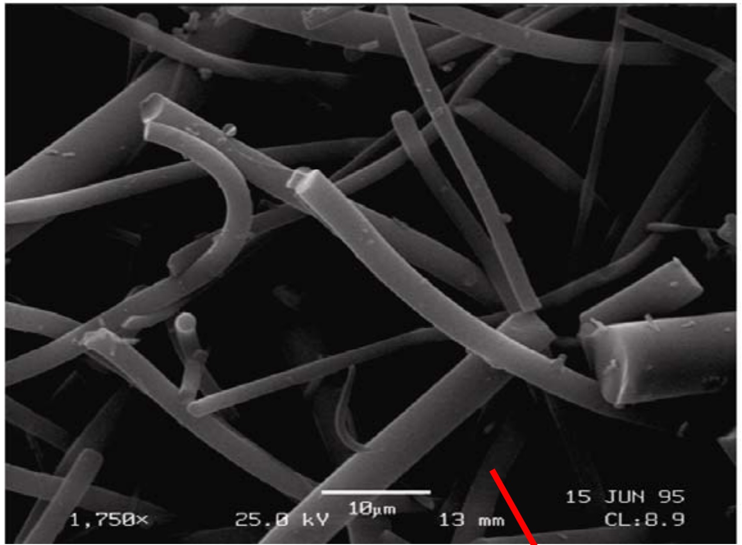


Thermal Protection System of Space Shuttle Orbiter

(skip)

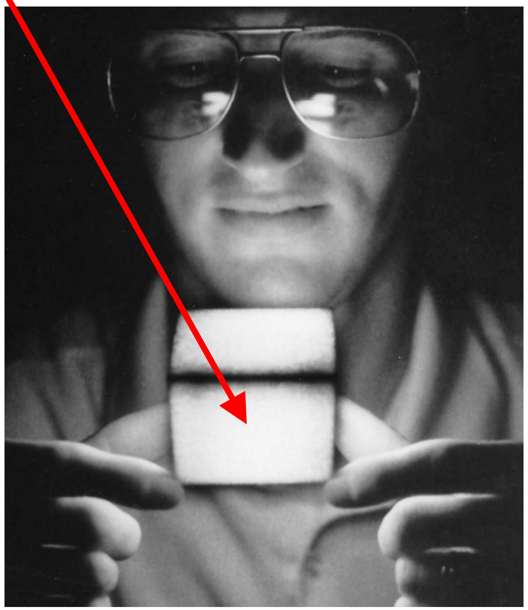


Thermal Protection System of Space Shuttle Orbiter



Sintered silica fiber in a space shuttle orbital ceramic tile

(skip)

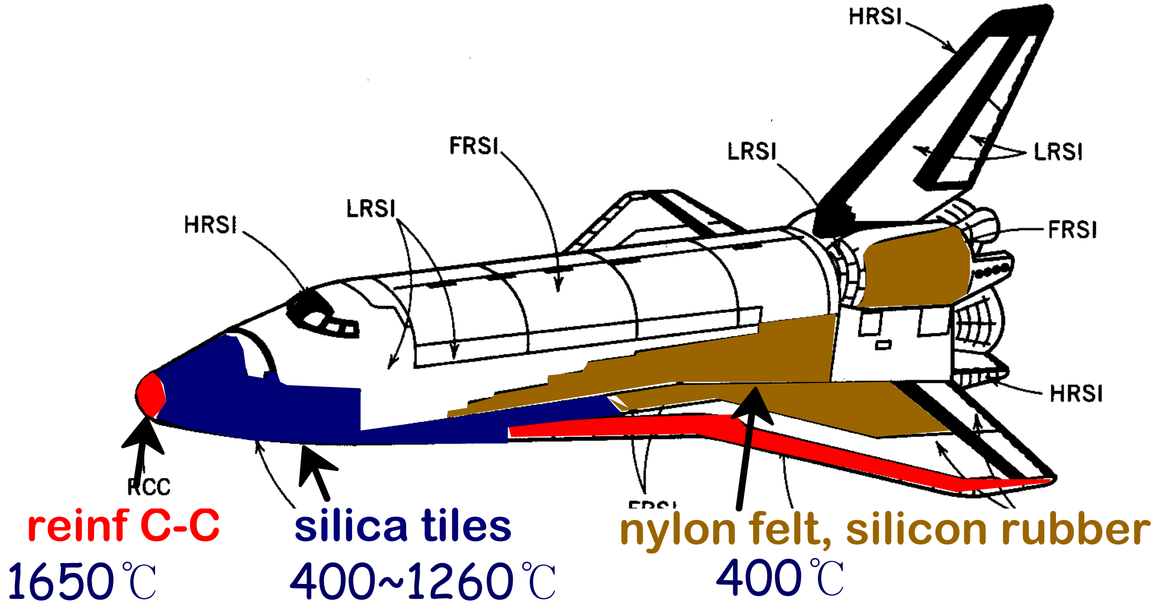


This photograph shows a white-hot cube of a silica fiber insulation material, which, only seconds after having been removed from a hot furnace, can be held by its edges with the bare hands. Initially, the heat transfer from the surface is relatively rapid; however, the thermal conductivity of this material is so small that heat conduction from the interior [maximum temperature approximately 1250°C (2300°F)] is extremely slow.

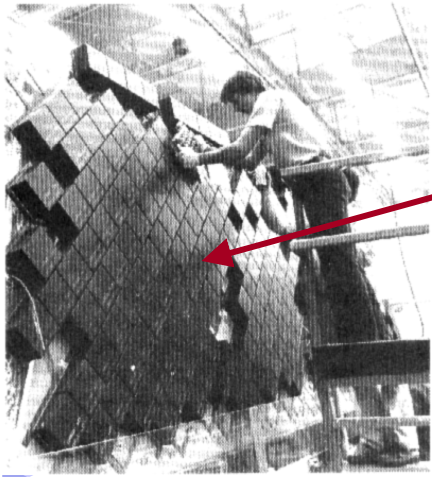
This material was developed especially for the tiles that cover the Space Shuttle Orbiters and protect and insulate them during their fiery reentry into the atmosphere (Section 19.6W). Other attractive features of this *high-temperature reusable surface insulation* (*HRSI*) include low density and a low coefficient of thermal expansion. (Photograph courtesy of Lockheed Missiles & Space Company, Inc.)

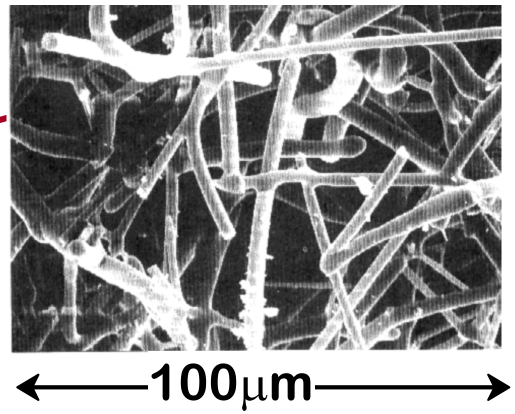
Thermal Protection System of Space Shuttle Orbiter

(skip)



➤ Silica tiles (400-1260℃): 24,300 pieces, cover ~70% of outer surface





~90% porosity!
Si fibers bonded to one another during heat treatment

Summary

- Heat capacity (Specific heat):
  - √ Energy required to increase a mole (or mass) by a unit *T*.
- Thermal expansion coefficient:
  - √ The stress-free strain induced by heating by a unit temperature.
- Thermal conductivity:
  - √ The ability of a material to transfer heat.
  - √ Metals in general have the largest values. [diamond]

Problems from Chap. 19

Prob. 19-3 Prob. 19-10 Prob. 19-17

Prob. 19-18 Prob. 19-19

http://bp.snu.ac.kr