Today

- **Finish up ceramics**
- **A bit on polymers**

- **Don't forget to evaluate the course**
  - **Minerva --- Mercury evaluation**
  - **Win an iPod!**
  - **Feedback will help improve the class**

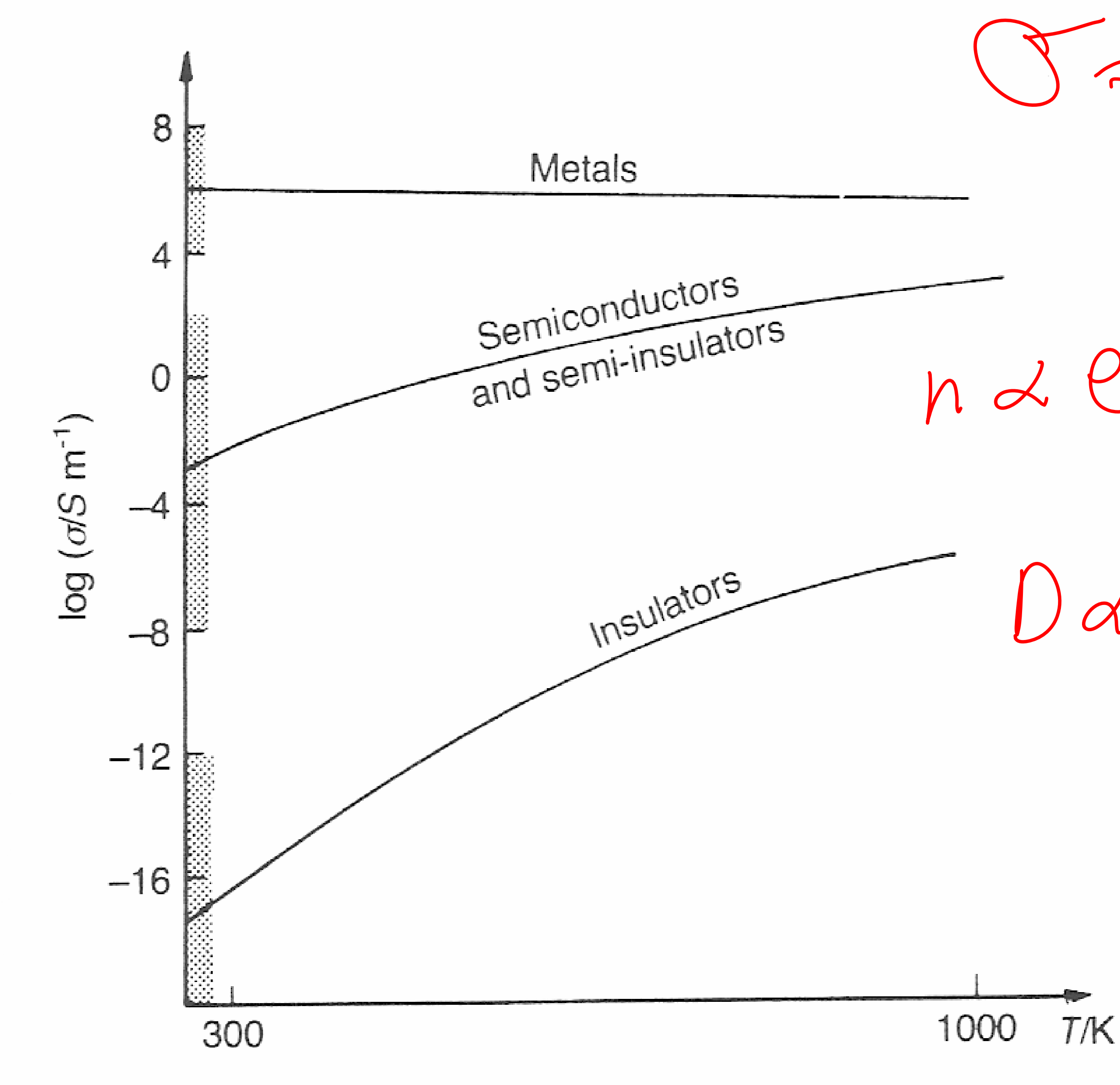
Ceramics in EE
“Electroceramics”

- **Electroceramics by A.J. Moulsen and J.M. Herbert**
- **http://www3.interscience.wiley.com/cgi-bin/booktoc/104557643**

Ceramics are everywhere…

- High temperature heating elements
- Gas sensors
- Microelectronics
- Fuel cells S.O.F.C.
- Batteries
- Dielectrics
- Thick and thin film resistors
- Specialized devices
  - Piezoelectrics ←
  - Pyroelectrics

Conductivity Behavior



$$\sigma = n|q|\nu$$

$$n \propto e^{-\frac{E_G}{k_b T}}$$

$$D \propto e^{-\frac{E_a}{k_b T}}$$

Conductivity Behavior

Table 2.3 Conductivity characteristics of the various classes of material

Material class	*Example*	*Conductivity level*	*dσ/dT*	*Carrier type*
Metals	Ag, Cu	High	Small, negative	Electrons
Semiconductors	Si, Ge	Intermediate	Large, positive	Electrons
Semi-insulators	ZrO_2	Intermediate	Large, positive	Ions or electrons
Insulators	Al_2O_3	Very low	Very large, positive	Ions or electrons; frequently 'mixed'

electrons and holes

$$C_T = C_{THERMAL} + C_{Defect} + C_{impurity}$$

Table 7.1 Some common electrical ceramics.

Ceramic		Crystalline phases	Glassy phase = SiO_2+	Made from
Porcelain	Triaxial	Quartz (SiO_2) Mullite $(Al_2O_3)_2(SiO_2)_3$	Al, K	45% clay e.g. kaolin (China clay) $Al_2(Si_2O_5)(OH)_4$ 35% flux e.g. feldspar $KAlSi_3O_8$ 20% filler e.g. quartz: flint or sand SiO_2
	Aluminous	Al_2O_3	Al, Mg	95% alumina Al_2O_3 5% talc (steatite) $Mg_3(Si_2O_5)_2(OH)_2$ (very similar to clay) or as for triaxial porcelain with flint replaced by alumina
Steatite		Enstatite $(MgO)(SiO_2)$ (mainly)	Mg	15% clay 83% talc 2% chalk ($CaCO_3$)
Cordierite		Cordierite $(MgO)_2(Al_2O_3)_2(SiO_2)_5$	Mg	80% clay 20% talc
Alumina		Alumina (Al_2O_3)	—	Bauxite $(Al_2O_3)(H_2O)_2$
Barium titanate		$BaTiO_3$ (= BaO-TiO_2)	—	Barium carbonate ($BaCO_3$) and rutile (TiO_2)

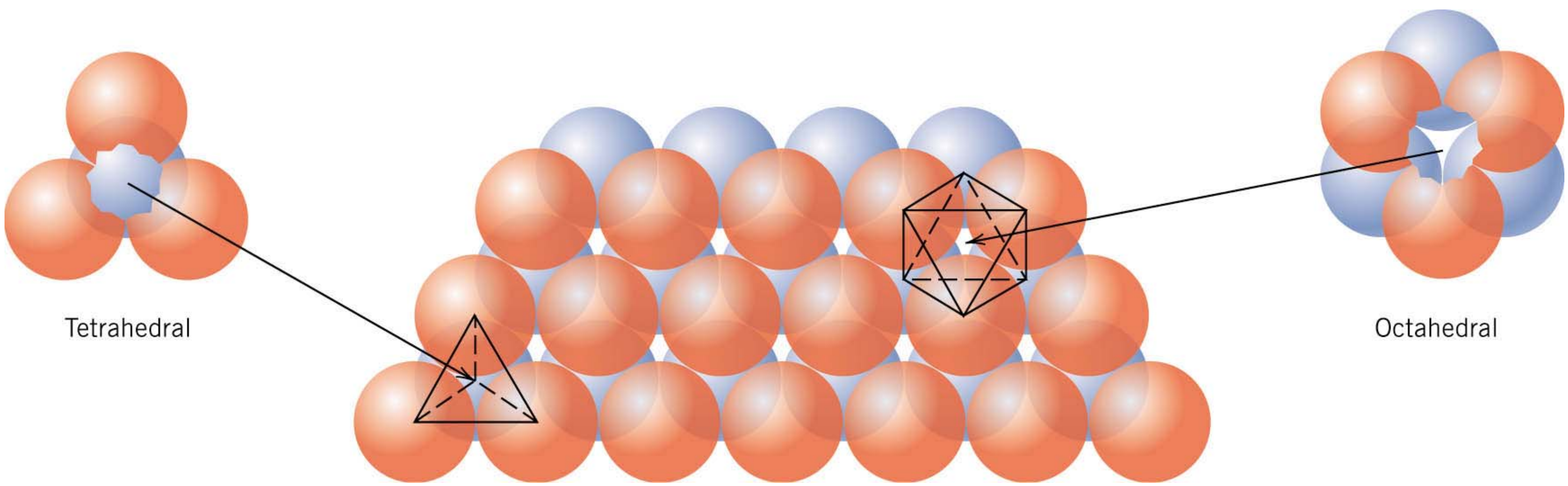
Ceramic Crystal Structures

Oxide structures

– oxygen anions much larger than metal cations

– "close packed" oxygen in a lattice (usually FCC)

– cations in the holes of the oxygen lattice

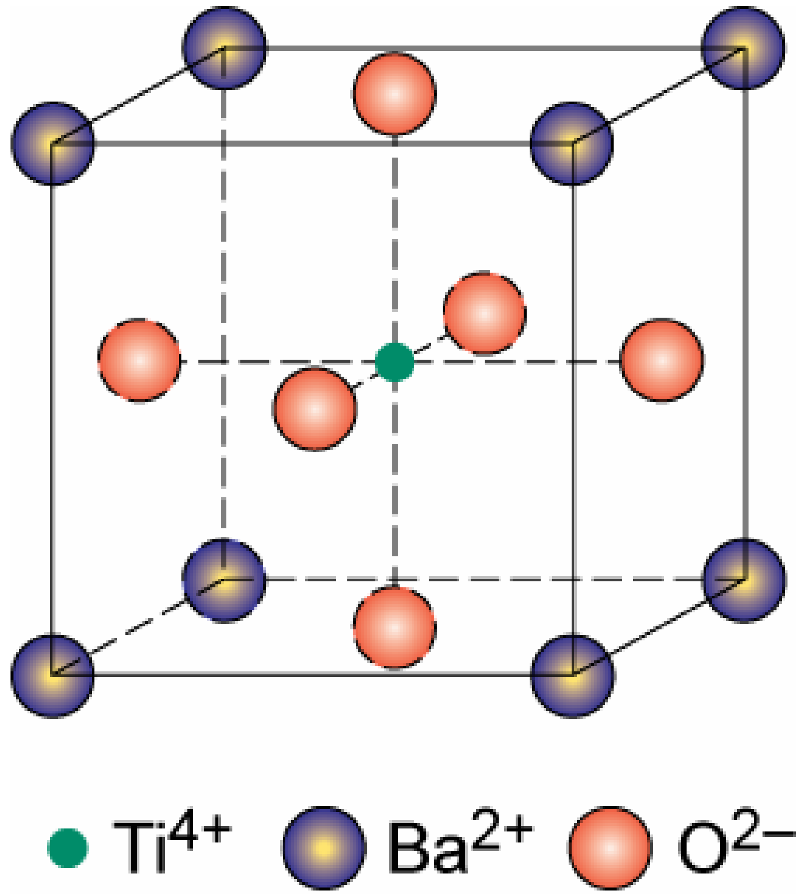


ABX$_3$ Crystal Structures

- Perovskite

Ex: complex oxide

$BaTiO_3$



Adapted from Fig. 12.6, *Callister 7e.*

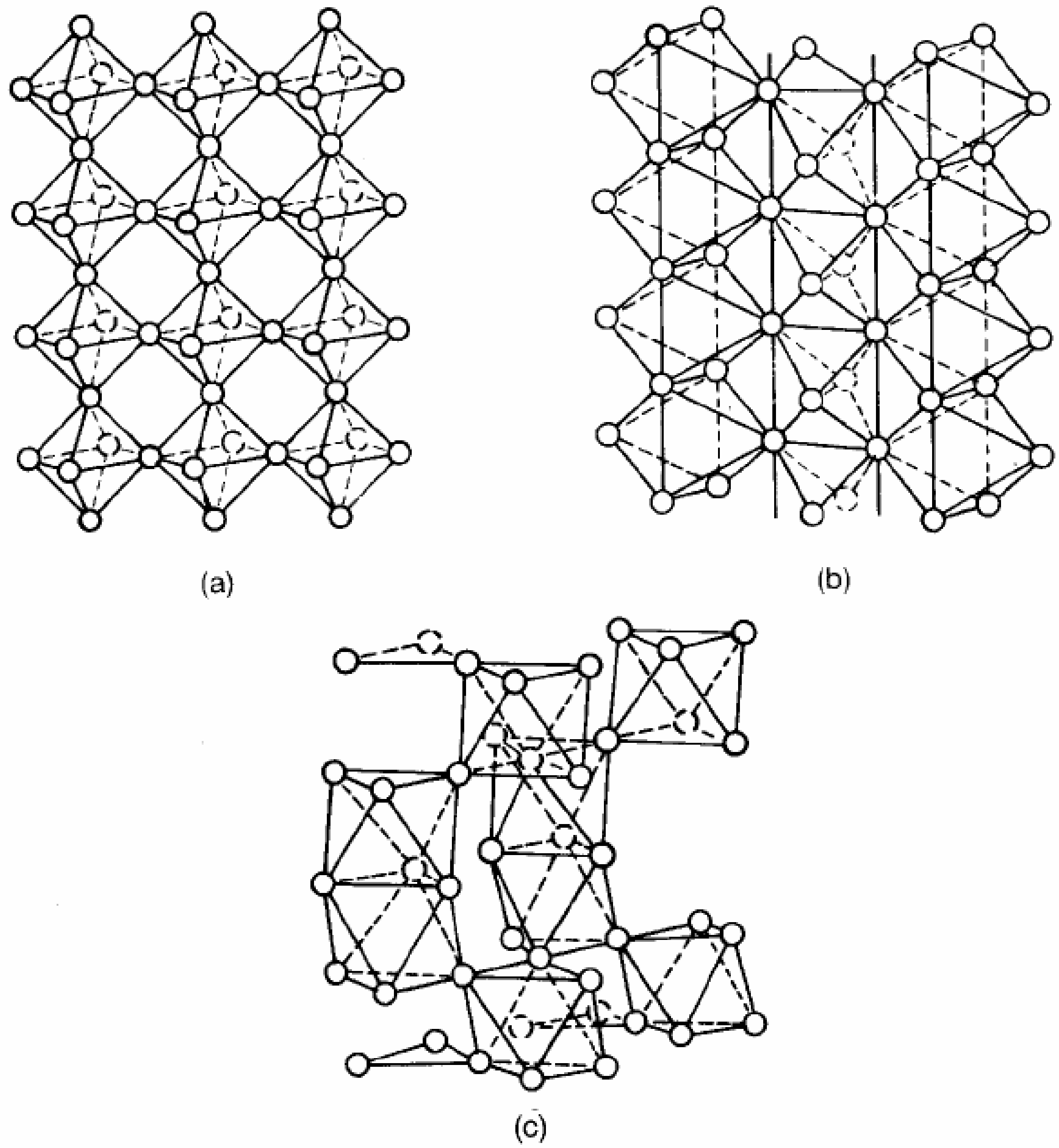
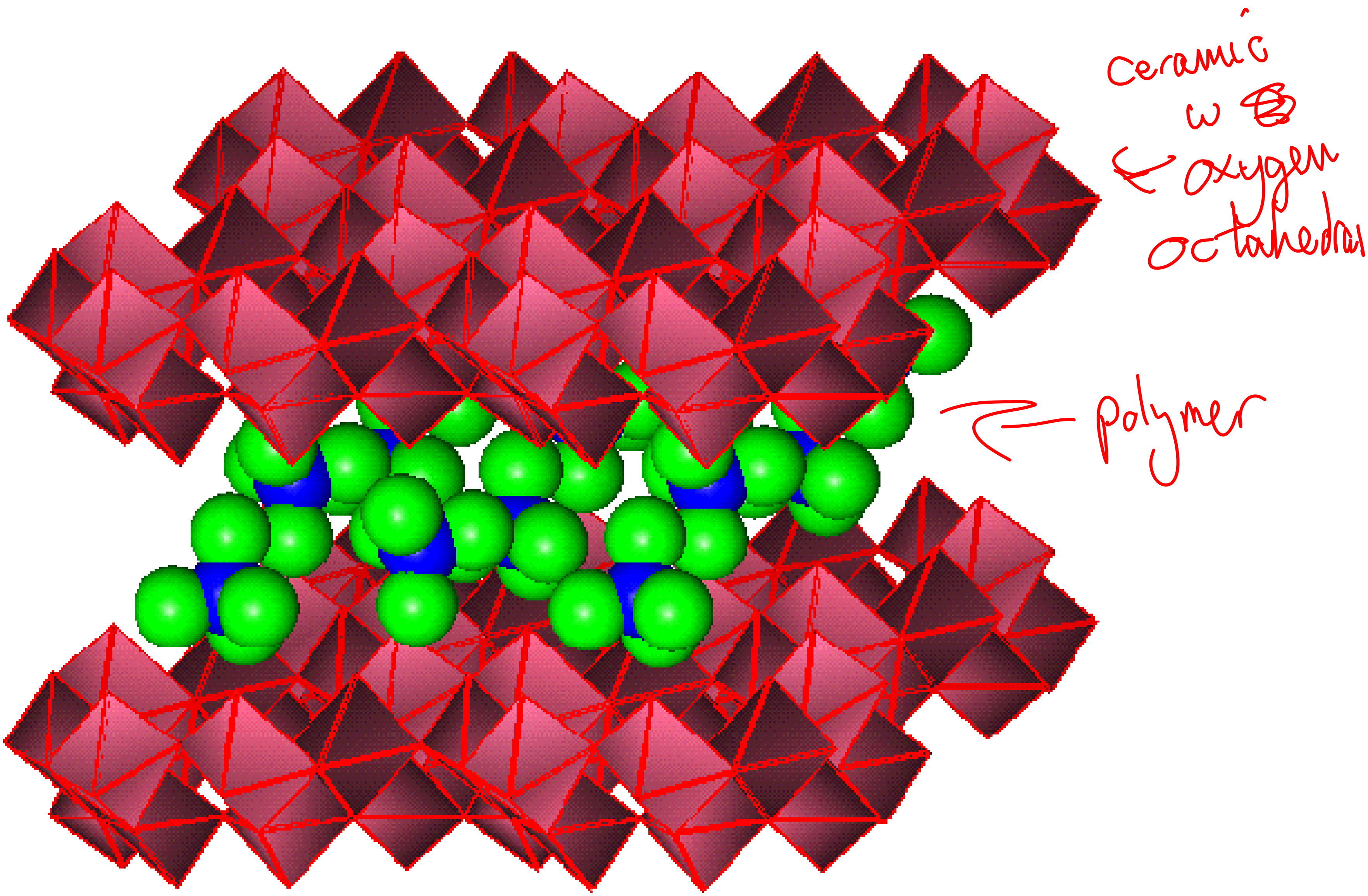
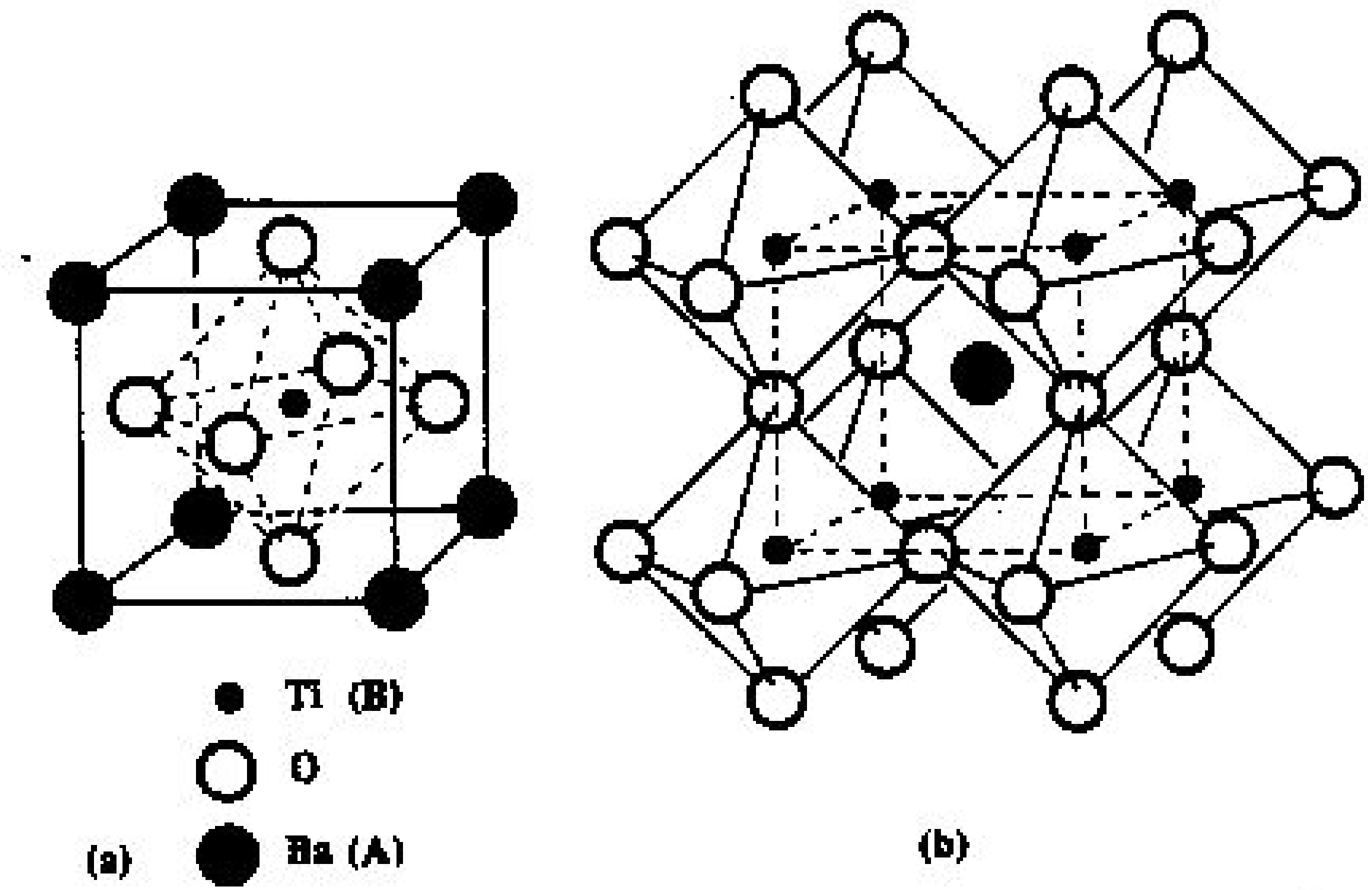


Fig. 2.2 MO_6 octahedra arrangements in (a) perovskite-type structures, (b) TiO_2 and (c) hexagonal $BaTiO_3$.


ceramic
w ⟵ oxygen
octahedral
polymer


Ti (B)
O
Ba (A)
(a)
(b)

Classifications

- **Ferroelectric – Ability of a crystal to exhibit a spontaneous polarization**
- **Pyroelectric – Temperature dependence of the spontaneous polarization.**
- **Piezoelectric – Ability of a crystal to expand and contract due to an applied voltage.**

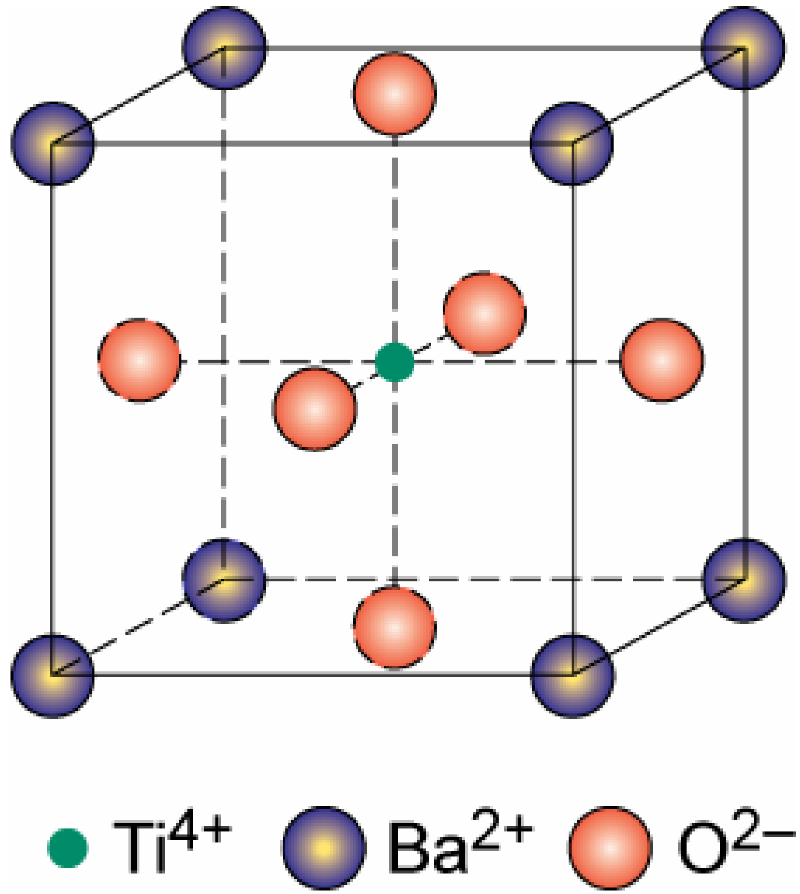
Crystal Structure	**Point Groups**	**Centro-Symmetric**	**Non-centrosymmetric**	
			Piezoelectric	**Pyroelectric**
Triclinic	$1, \bar{1}$	$\bar{1}$	1	1
Monoclinic	2, m, 2/m	2/m	2, m	2, m
Orthorhombic	222, mm2, mmm	mmm	222, mm2	mm2,
Tetragonal	$4, \bar{4}, 4/m, 422, 4mm, \bar{4}2m, (4/m)mm$	4/m, (4/m)mm	$4, \bar{4}, 422, 4mm, \bar{4}2m$	4, 4mm
Trigonal	$3, \bar{3}, 32, 3m, \bar{3}m$	$\bar{3}, \bar{3}m$	3, 32, 3m	3, 3m
Hexagonal	$6, \bar{6}, 6/m, 622, 6mm, \bar{6}m2, (6/m)mm$	6/m, (6/m)mm	$6, \bar{6}, 622, 6mm, \bar{6}m2$	6, 6mm
Cubic	$23, m\bar{3}, 432, \bar{4}3m, m\bar{3}m$	m3, m3m	$23, \bar{4}3m$	------

ABX_3 Crystal Structures

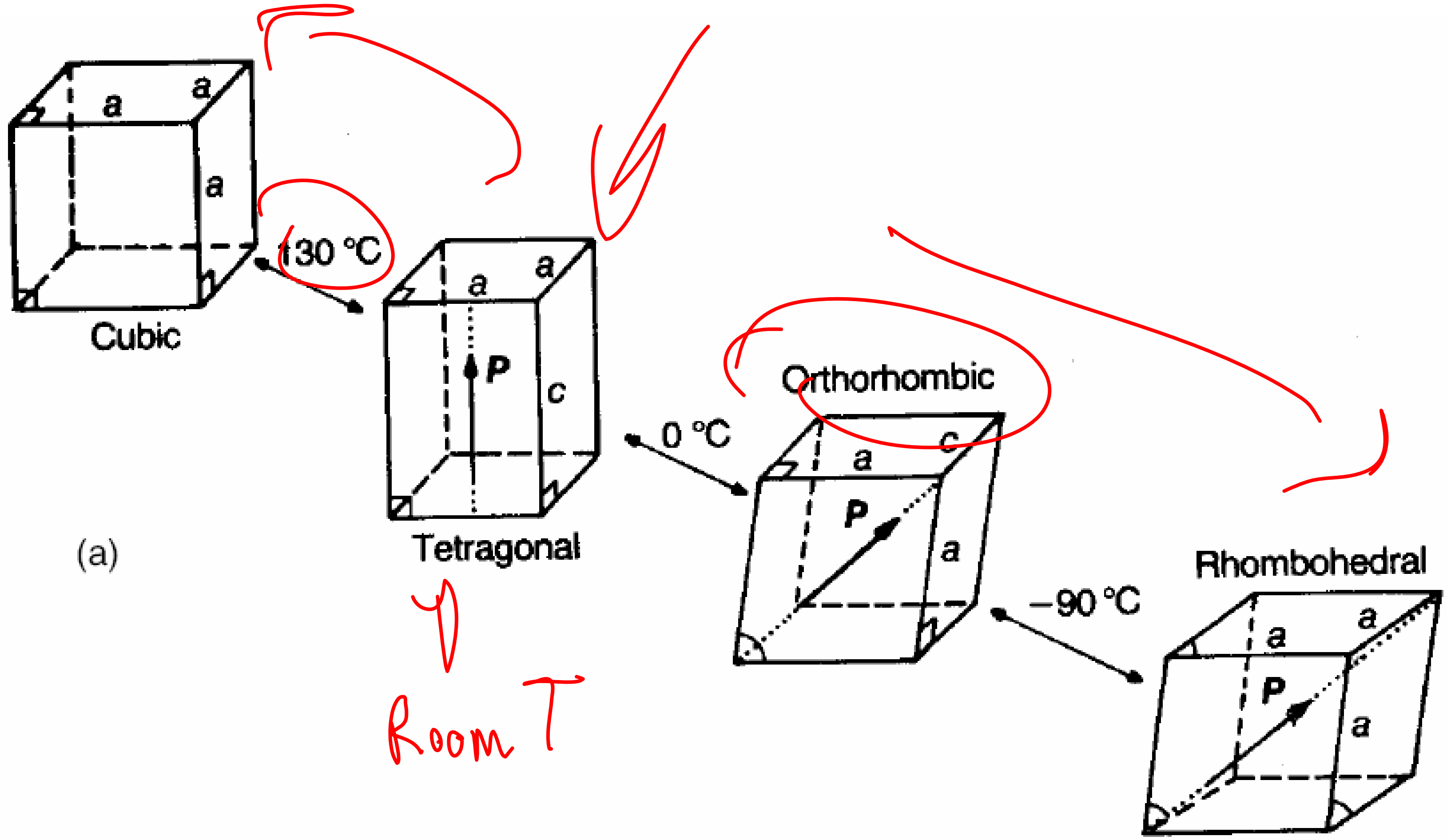
- Perovskite

Ex: complex oxide

$BaTiO_3$



Adapted from Fig. 12.6, *Callister 7e.*


a
a
a
Cubic
130 °C
a
a
P
c
Tetragonal
(a)
0 °C
Orthorhombic
a
c
P
a
−90 °C
Rhombohedral
a
a
P
a
Room T

pm → 10^{-12} m

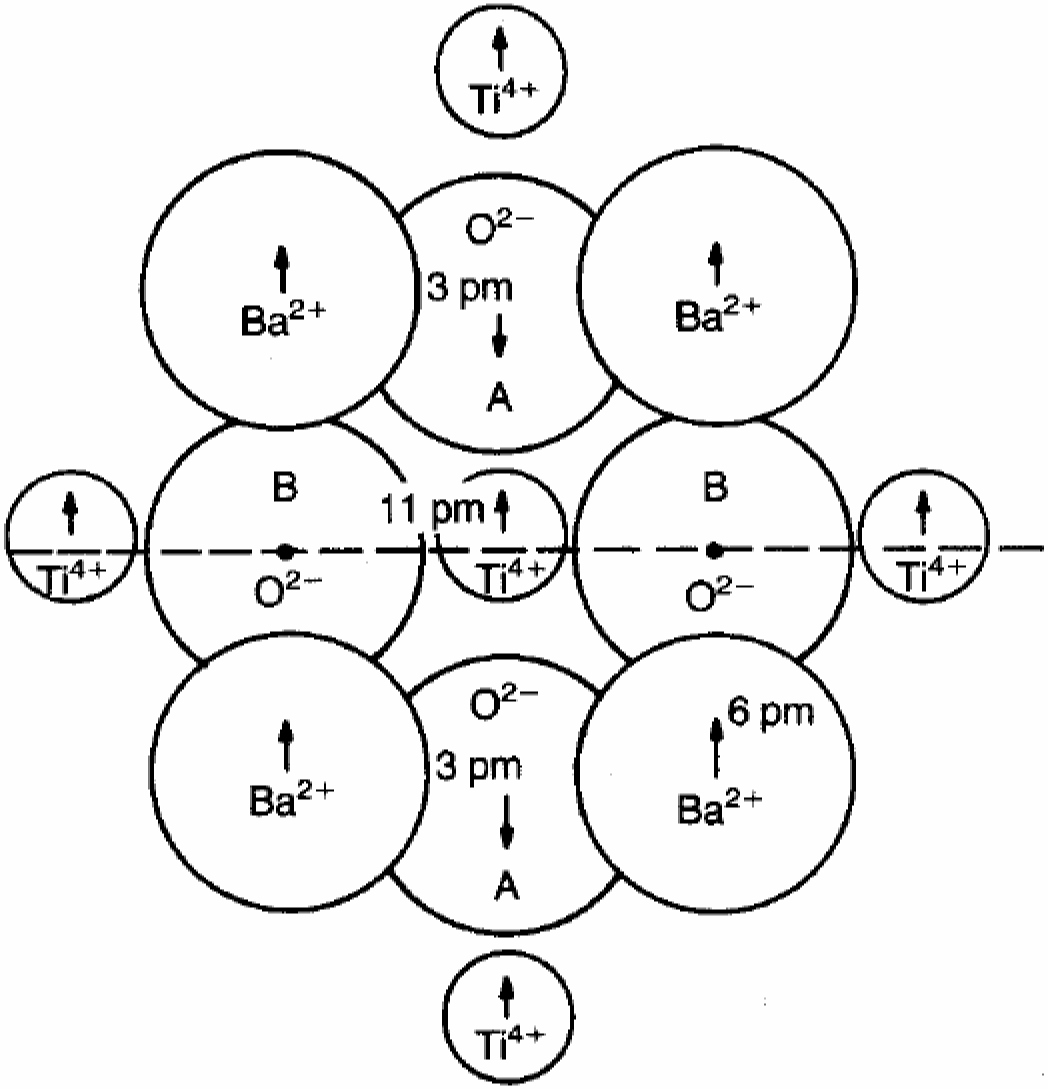


Fig. 2.41 Approximate ion displacements in the cubic–tetragonal distortion in $BaTiO_3$.

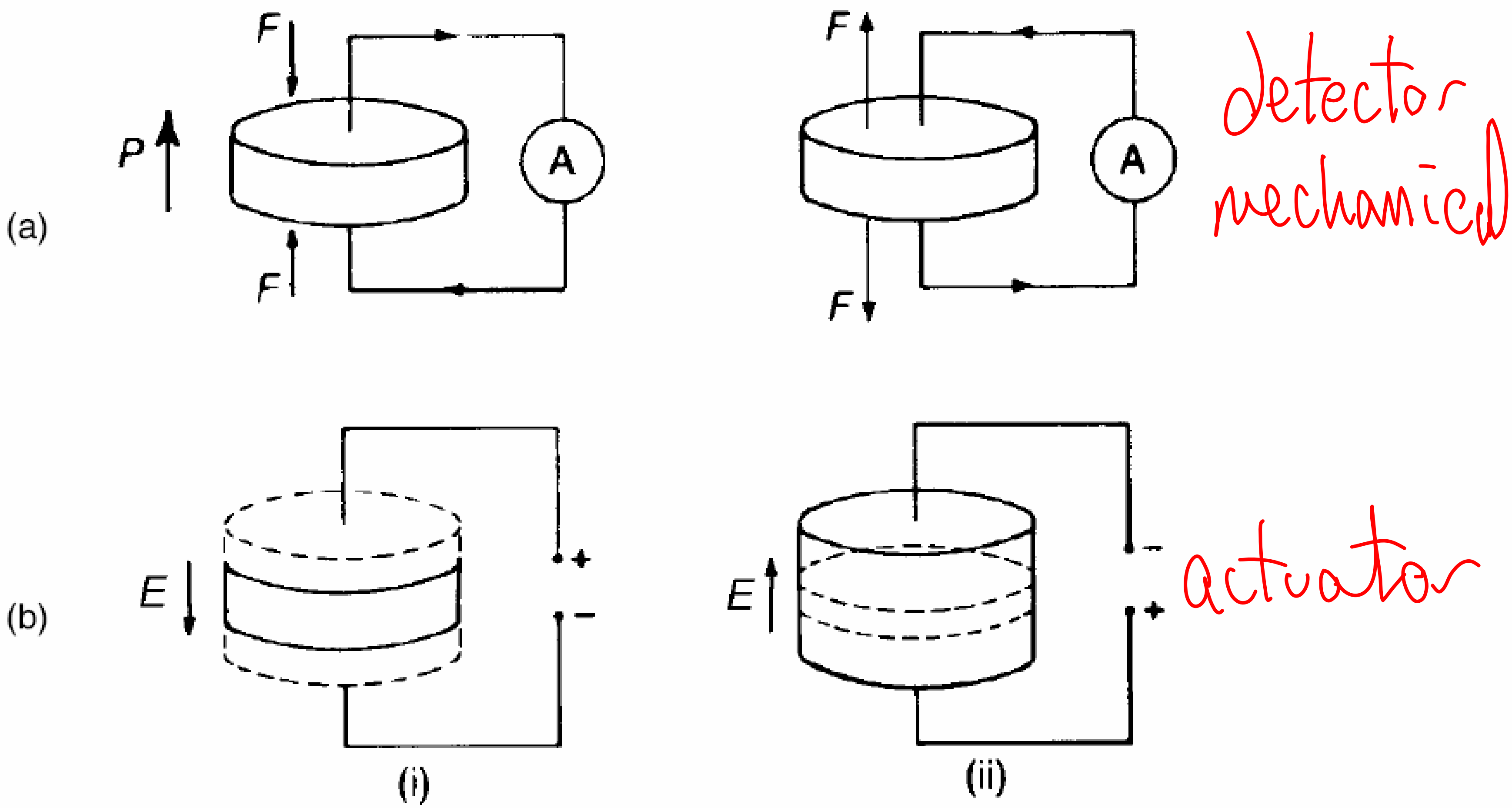


Fig. 6.1 (a) The direct and (b) the indirect piezoelectric effects: (i) contraction; (ii) expansion. The broken lines indicate the original dimensions.

1. the generation of voltages;
2. electromechanical actuation;
3. frequency control;
4. the generation and detection of acoustic and ultrasonic energy.

???

alarm clock

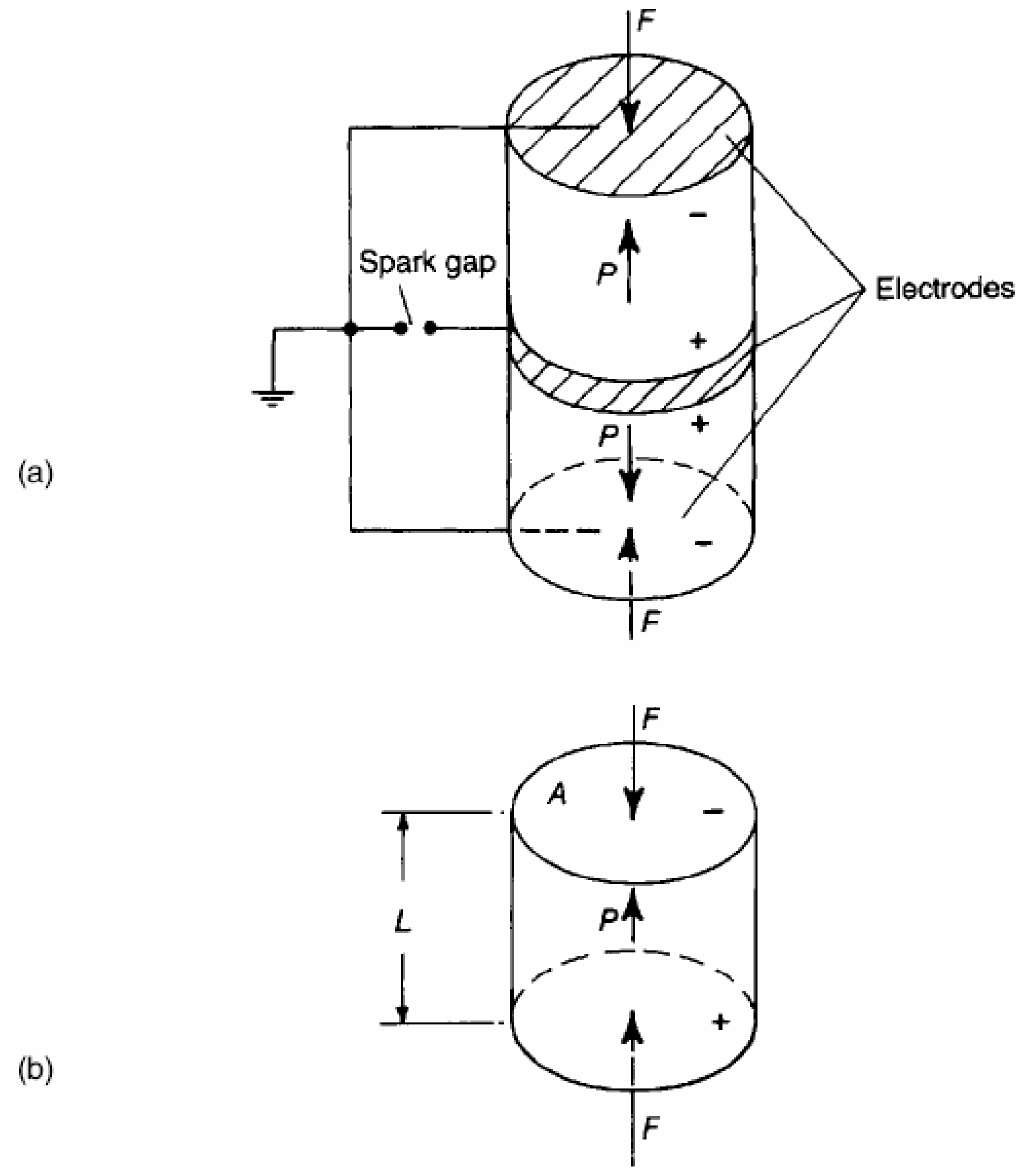
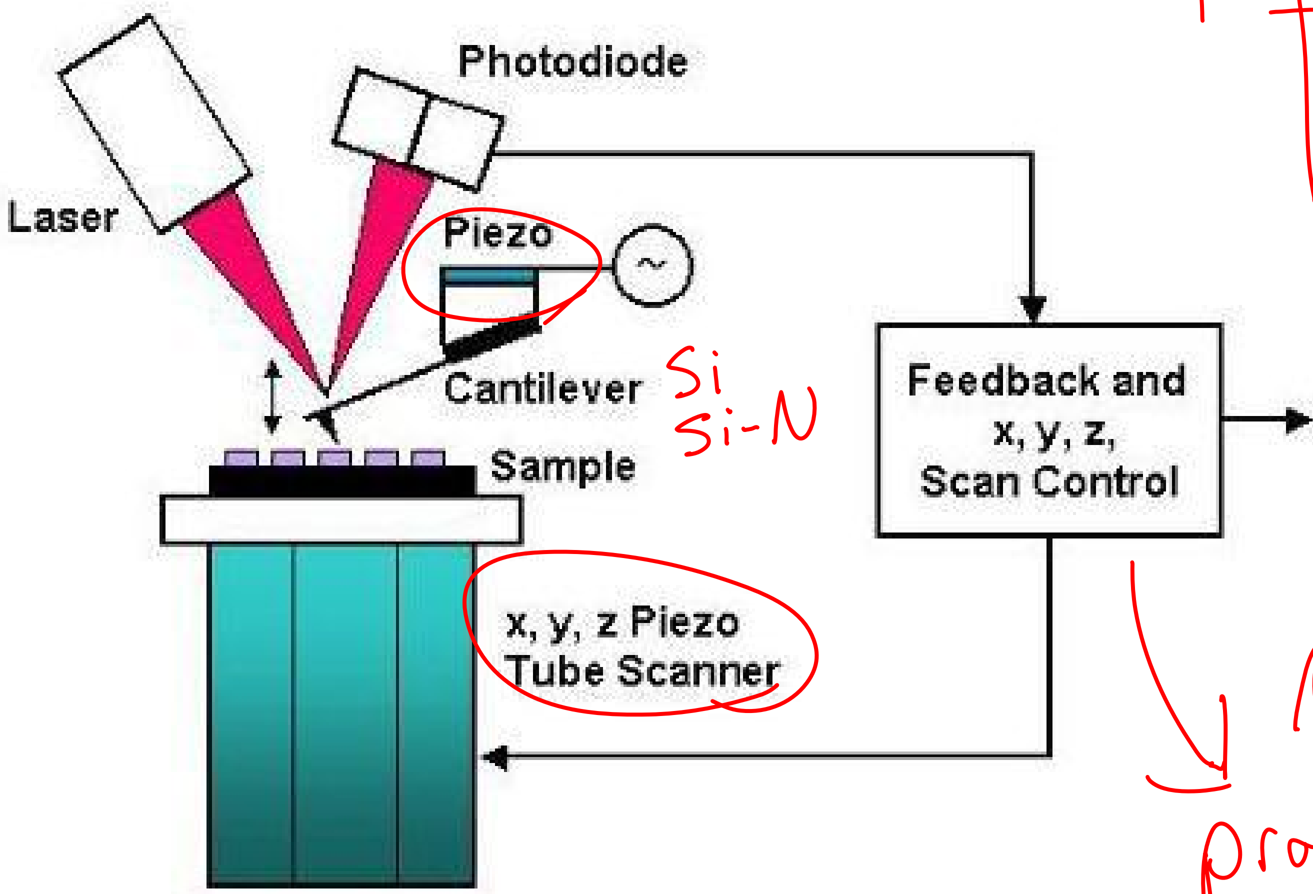
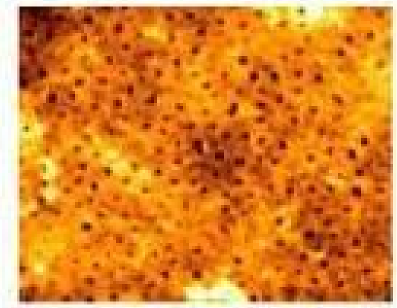


Fig. 6.21 (a) A piezoelectric spark generator. (b) A piezoceramic cylinder under axial compressive force.

Atomic Force Micoscope





P.I.D.

proportional
integral
differential

Polymers

- Polymers are made up of large numbers of similar repeat units linked to each other by covalent bonding.
- Repeat units – monomers.
- Polymerisation is the process that links all monomers to large macromolecules.

Mer Structures for a Variety of Polymers

Table 15.3 A Listing of Mer Structures for 10 of the More Common Polymeric Materials

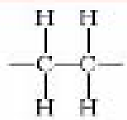
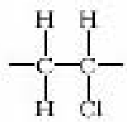
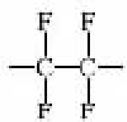
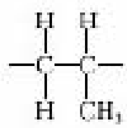
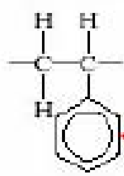
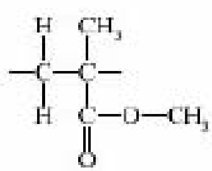
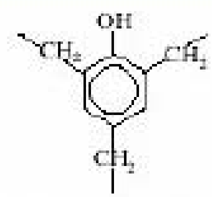
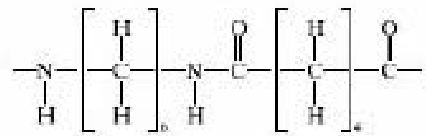
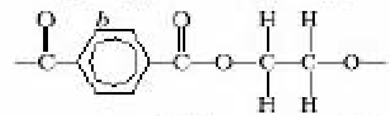
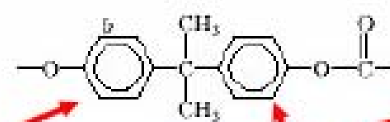
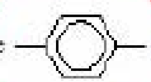
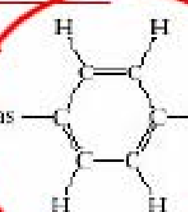
Polymer	*Repeating (Mer) Structure*
Polyethylene (PE)	
Polyvinyl chloride (PVC)	
Polytetrafluoroethylene (PTFE)	
Polypropylene (PP)	
Polystyrene (PS)	
Polymethyl methacrylate (PMMA)	

Table 15.3 *(Continued)*

Polymer	*Repeating (Mer) Structure*
Phenol-formaldehyde (Bakelite)	
Polyhexamethylene adipamide (nylon 6,6)	
Polyethylene terephthalate (PET, a polyester)	
Polycarbonate	

[a] The  symbol in the backbone chain denotes an aromatic ring as 

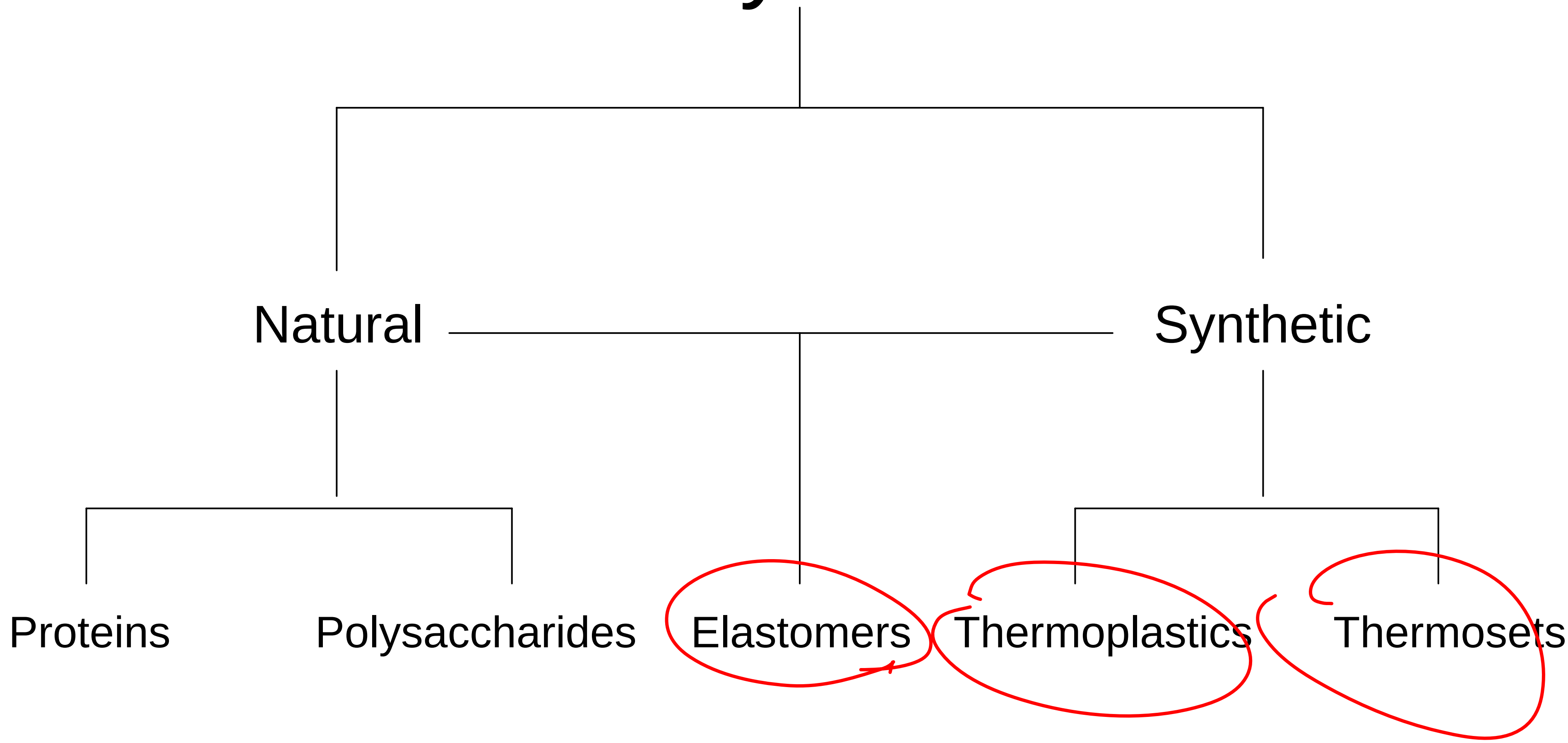
An Introduction to The Classification of Polymeric Materials

Plastic?

plastic = polymer +

- dye
- fire retardant
- filler
- etc.

Polymers



Natural
Synthetic
Proteins
Polysaccharides
Elastomers
Thermoplastics
Thermosets

Polymer Structures

- Linear Polymers mer units are end-to-end long chains,e.g.
  - polyethylene, polyvinyl chloride, polystyrene, nylon, polyfluoro carbons
- Branched Polymers synthesized with side branches
  - chain packing is less efficient thus lower density results
- Cross-linked: covalent bonding between chains such as in *vulcanized* rubber (elastomers)

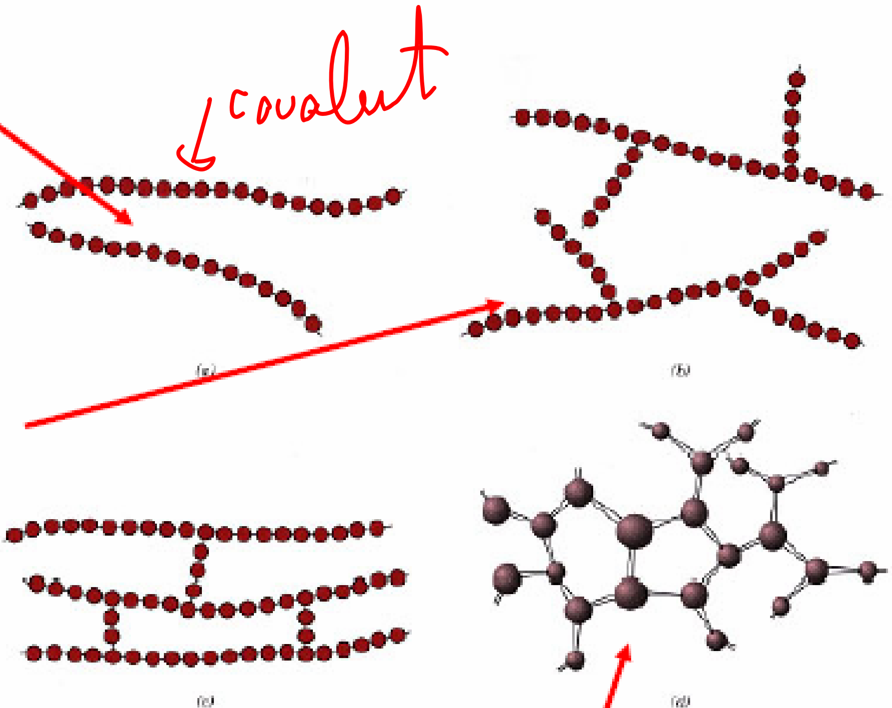


Figure 15.7 Schematic representations of (a) linear, (b) branched, (c) crosslinked, and (d) network (three-dimensional) molecular structures. Circles designate individual mer units.

- Network polymers:
- 3-dimensional linking of polymer chains, e.g. epoxies and bakelite

Classification of synthetic polymers

- Thermoplastics
- Thermosets
- Elastomers

Thermoplastic Polymers

bakelite

- *Thermoplastic* polymers soften and melt at high temperature
- fabrication is by simultaneous application of heat and pressure
- *linear* or *branch* type polymers are thermoplasts

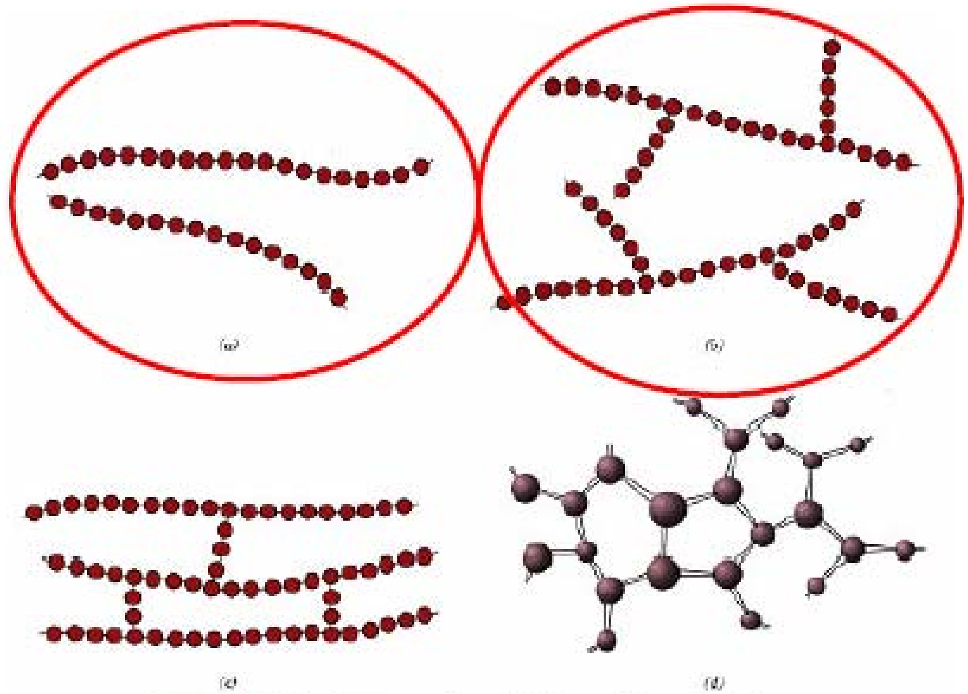


FIGURE 15.7 Schematic representations of (a) linear, (b) branched, (c) crosslinked, and (d) network (three-dimensional) molecular structures. Circles designate individual mer units.

Thermoplastics

General Structure

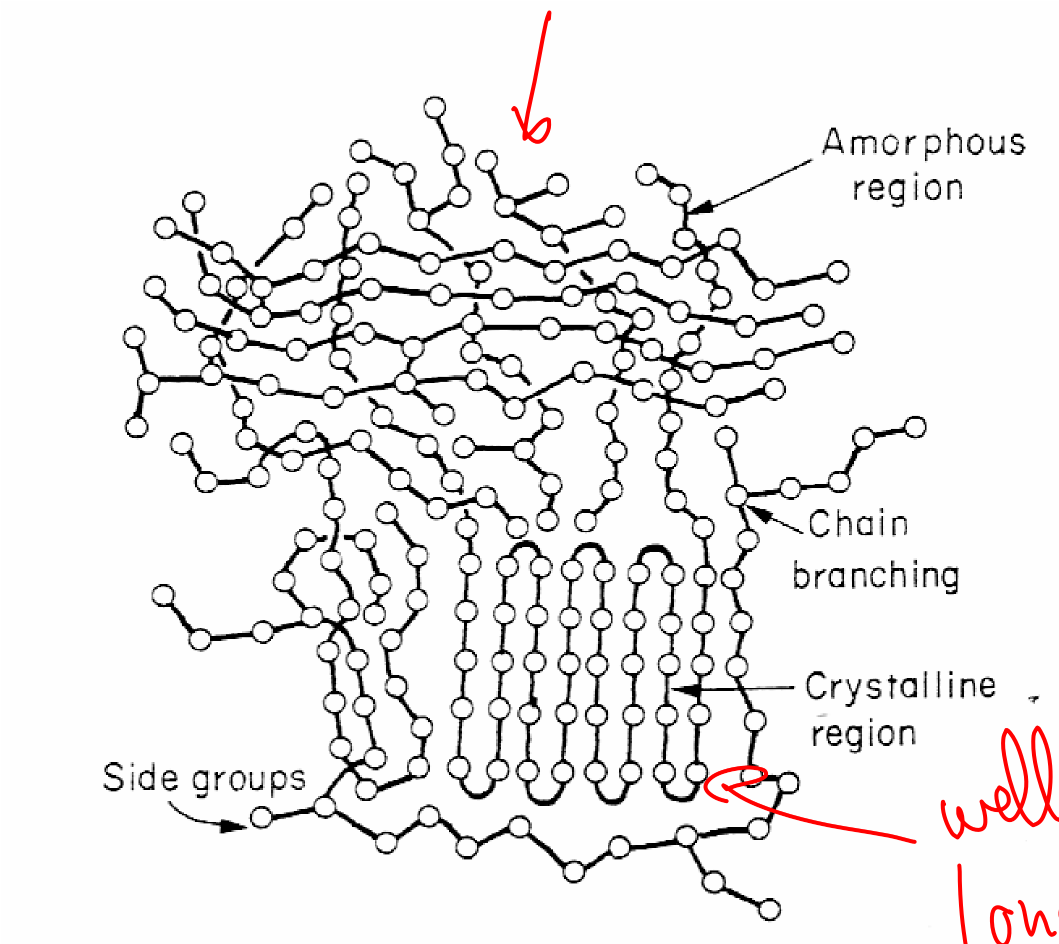
- Linear polymers with limited branching.
- Chemical chains are chemically separate from each other.
- No permanent links between chains, but are physically entangled.

Thermoplastics

General properties

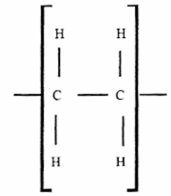
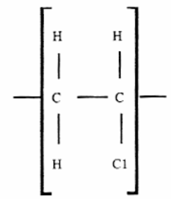
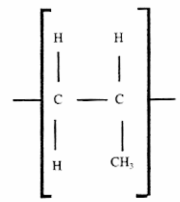
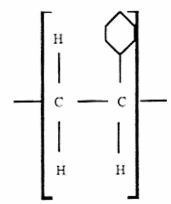
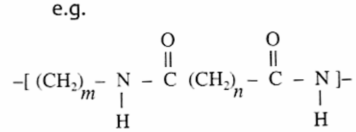
- Can be amorphous and semi-crystalline.
- Can be dissolved in solvents without destroying the chemical bonds.
- Can be heated and cooled to reshape. Chains can slide past each other under heat and pressure.
- E.g. Extrusion, injection and compression moulding.

short range order



well ordered
long range order

Table 8.1 Seven common thermoplastics used in electrical and electronic engineering.

Abbreviation	Full name	Repeating group
PE*	Polyethylene	
PVC	Poly(vinyl chloride)	
PP	Polypropylene	
PS	Polystyrene	
ABS	Acrylonitrile-butadiene-styrene copolymer	(mixture of polymers)
SAN	Styrene-acrylonitrile copolymer	
PA†	Nylon	e.g.  where m = 4, n = 6 ⇒ nylon 6,6

* LDPE, HDPE: Low Density PolyEthylene, High Density Polyethylene.
† PA6, PA66, PA610: Nylon 6, Nylon 66, Nylon 610.

Table 8.5 Typical applications for some common plastics used in electrical and electronic engineering.

Polymer	Typical applications
PE	High voltage and/or high frequency cable insulation
PVC	Domestic cable insulation
PP	Housings for simple household appliances, e.g. coffee makers
PS	Alternative to ABS; high frequency insulation; lamp shades, diffusers
ABS	High quality housings for: radio, TV, video recorders/players, washing machines, telephones, vacuum cleaners, hairdriers
SAN	(Transparent) windows in washing machines; battery casings
PA	Plugs and sockets; terminal strips; switch bases; electric tool housings; coin box telephones

FR4

Thermosetting Polymers

- *Thermosets* are permanently hard and do not soften upon subsequent heating
- during fabrication there is a reaction between two components which produces a 3-dimensional *network polymer*
- 10-50% of the chain mers are cross-linked
- heating to very high temperature causes severance of cross-links and polymer degradation, not melting

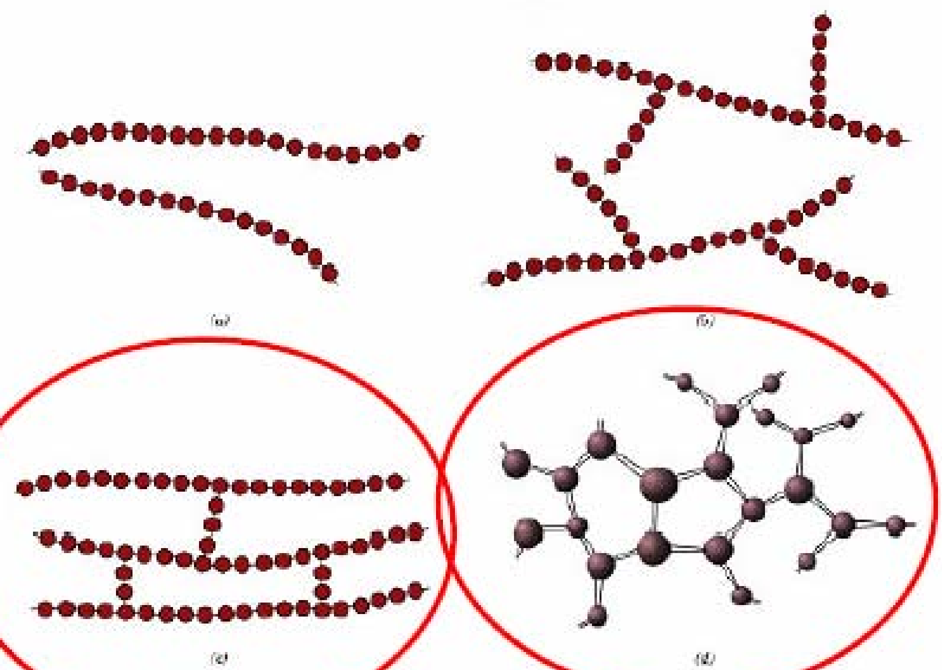


FIGURE 15.7 Schematic representations of (a) linear, (b) branched, (c) crosslinked, and (d) network (three-dimensional) molecular structures. Circles designate individual mer units.

Thermosets

General structure

- Also known as crosslinked or network polymers.
- Consist of network interconnected chains whose positions are fixed to neighbours.
- Permanently connected either directly or through short bridging chains.
- Up to 50% of chains are crosslinked

Thermosets

General Properties

- Good thermal and dimensional stability.
- Solvent resistant- does not dissolve, but can swell.
- Good stiffness, low strain to failure.
- Non-reversible polymers.
- Heat and pressure resistant. Crosslinks prevent large scale reorganisation of the chains.
- Polymerisation and shaping occurs at the same time. E.g. Casting.

Elastomers

General Structure

- Linear polymer chains that are lightly cross-linked.
- Large free volume. Atoms have large local freedom to vibrate, twist and rotate.
- Above their glass transition temperature.
- Synthetic elastomers modelled on Natural Rubber with polydienes with C=C in chain to permit vulcanisation.

Elastomers

General properties

- Amorphous.
- Soft and flexible.
- Chains do not entirely slide past each other due to chemical crosslinks.
- Capacity to undergo large rapidly recoverable deformation.
- They have high modulus and strength under high strain levels.

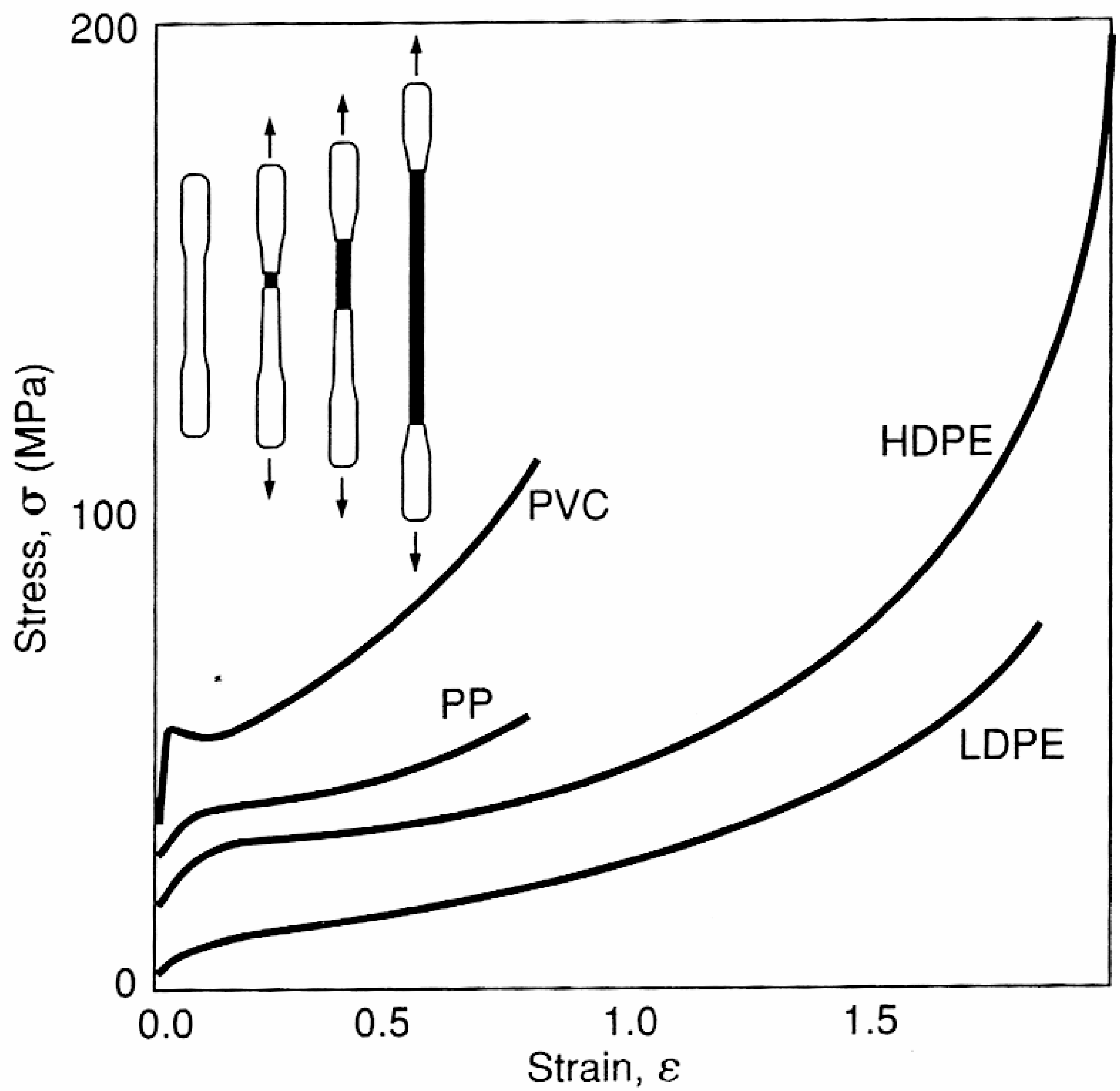


Fig. 8.9 Tensile test curves for a variety of polymers at room temperature. (From *Engineering materials science* by M. Ohring, courtesy of Academic Press, Inc.)

http://materials.npl.co.uk/NewIOP/Polymer.html