M. Sc. Bionics Engineering

Università di Pisa — Sant'Anna Scuola Universitaria Superiore Pisa — IMT Scuola Alti Studi Lucca

Advanced Materials for Bionics

Lecture 6: CERAMICS

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AY 2024-25

L6 - 14.10.2024

QUESTIONS

- How do the crystal structures of ceramic materials differ from those for metals?
- How are defects, impurities accommodated in the ceramic lattice?
- What are glasses?
- Why some ceramics exhibit piezoelectricity? What are uses of piezoceramics?
- What are bioceramics?
- Why is silicon carbide becoming important in electronics and biomedicine?

L6.1

STRUCTURE AND PROPERTIES OF CERAMICS

Atomic Bonding in Ceramics

- two or more elements involved: generally more complex struct than metals
- Bonding:
  - -- Can be ionic and/or covalent in character
  - -- % ionic character increases with difference in electronegativity of atoms
- Degree of ionic character: large or small

CaF_2: large

SiC: small

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
H 2.1																	He –
Li 1.0	Be 1.5											B 2.0	C 2.5	N 3.0	O 3.5	F 4.0	Ne –
Na 0.9	Mg 1.2											Al 1.5	Si 1.8	P 2.1	S 2.5	Cl 3.0	Ar –
K 0.8	Ca 1.0	Sc 1.3	Ti 1.5	V 1.6	Cr 1.6	Mn 1.5	Fe 1.8	Co 1.8	Ni 1.8	Cu 1.9	Zn 1.6	Ga 1.6	Ge 1.8	As 2.0	Se 2.4	Br 2.8	Kr –
Rb 0.8	Sr 1.0	Y 1.2	Zr 1.4	Nb 1.6	Mo 1.8	Tc 1.9	Ru 2.2	Rh 2.2	Pd 2.2	Ag 1.9	Cd 1.7	In 1.7	Sn 1.8	Sb 1.9	Te 2.1	I 2.5	Xe –
Cs 0.7	Ba 0.9	La–Lu 1.1–1.2	Hf 1.3	Ta 1.5	W 1.7	Re 1.9	Os 2.2	Ir 2.2	Pt 2.2	Au 2.4	Hg 1.9	Tl 1.8	Pb 1.8	Bi 1.9	Po 2.0	At 2.2	Rn –
Fr 0.7	Ra 0.9	Ac–No 1.1–1.7															

Bond Hybridization

Bond Hybridization is possible when there is significant covalent bonding

- hybrid electron orbitals form

example: SiC

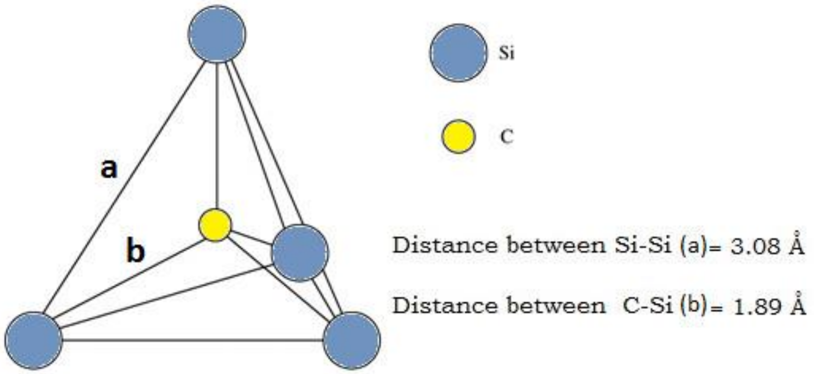
$X_{Si} = 1.8$ and $X_C = 2.5$

$$\%\text{ ionic character} = 100\,\{1-\exp[-0.25(X_{Si} - X_C)^2]\} = 11.5\%$$

~ 89% covalent bonding

Both Si and C prefer *sp*³ hybridization

Si atoms occupy tetrahedral sites



Ionic Character

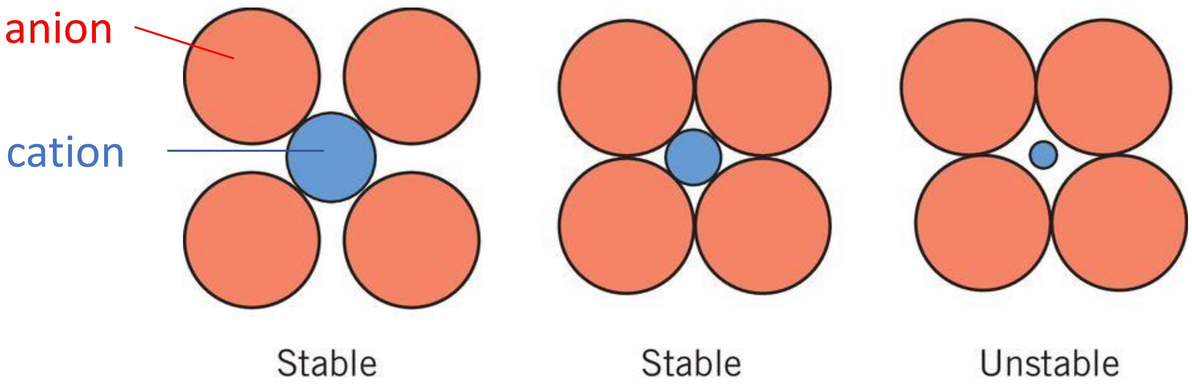
% Ionic Character of interatomic bonds for several ceramic materials

Material	Percent Ionic Character
CaF_2	89
MgO	73
$NaCl$	67
Al_2O_3	63
SiO_2	51
Si_3N_4	30
ZnS	18
SiC	12

Factors Determining Crystal Structure

1. Maintenance of Charge Neutrality :
   - net charge should be zero

2. Relative sizes of ions – Formation of stable structures:
   - maximize the # of oppositely charged ion neighbors.



r_c: ionic radius cation
r_a: ionic radius anion

important:

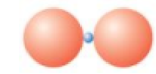
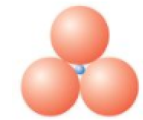
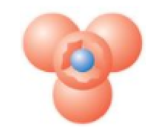
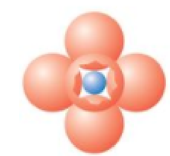
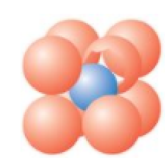
r_c / r_a

IONIC RADII AND COORDINATION NUMBERS

r_c: ionic radius cation

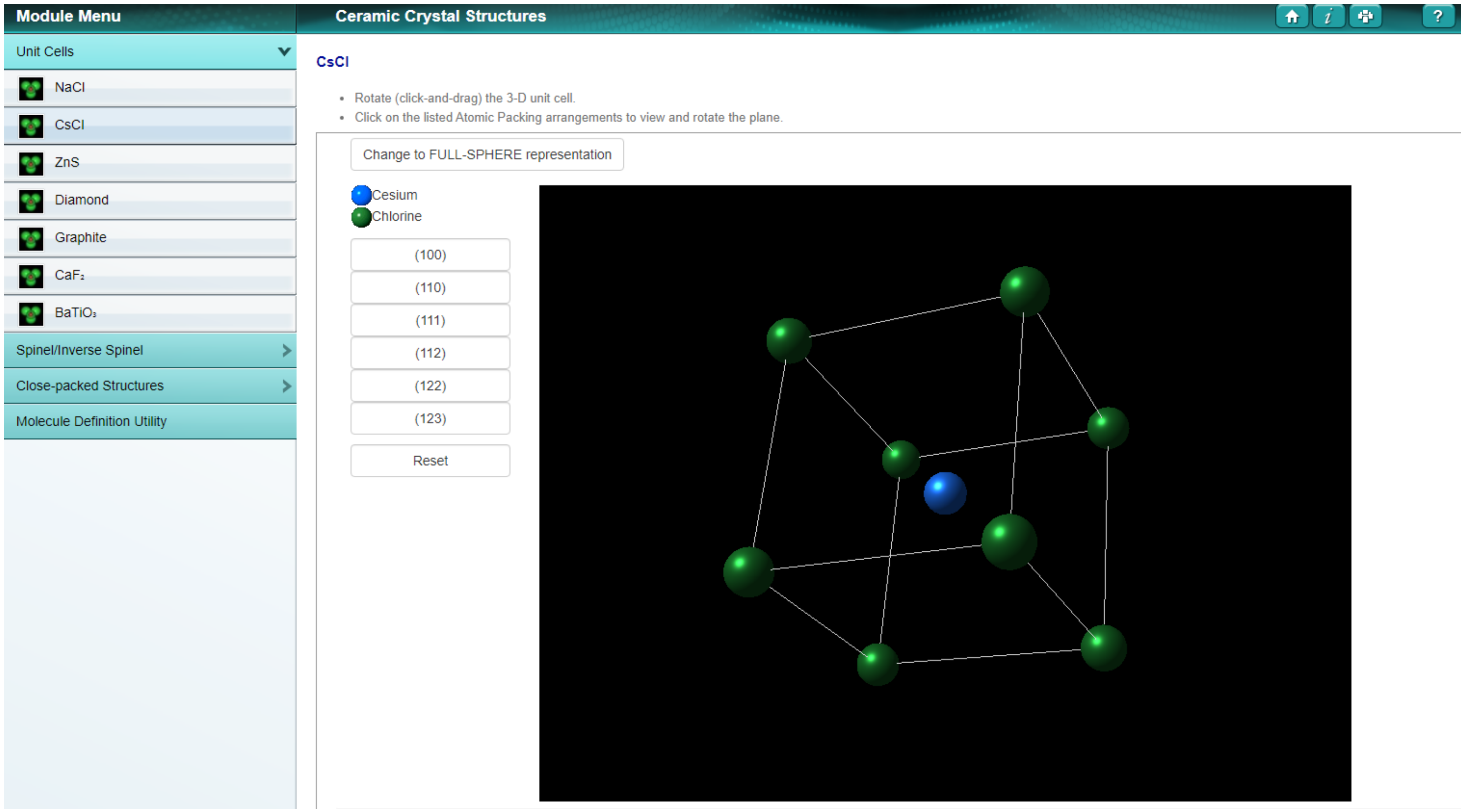
r_a: ionic radius anion

Cation	Ionic Radius (nm)	Anion	Ionic Radius (nm)
Al^{3+}	0.053	Br^-	0.196
Ba^{2+}	0.136	Cl^-	0.181
Ca^{2+}	0.100	F^-	0.133
Cs^+	0.170	I^-	0.220
Fe^{2+}	0.077	O^{2-}	0.140
Fe^{3+}	0.069	S^{2-}	0.184
K^+	0.138		
Mg^{2+}	0.072		
Mn^{2+}	0.067		
Na^+	0.102		
Ni^{2+}	0.069		
Si^{4+}	0.040		
Ti^{4+}	0.061		

Coordination n.	r_c / r_a	*Geometry*
2	< 0.155	
3	0.155 – 0.255	
4	0.255 – 0.414	
6	0.414 – 0.732	
8	0.732 – 1.0	

most common in ceramics

CRYSTAL STRUCTURES OF CERAMICS

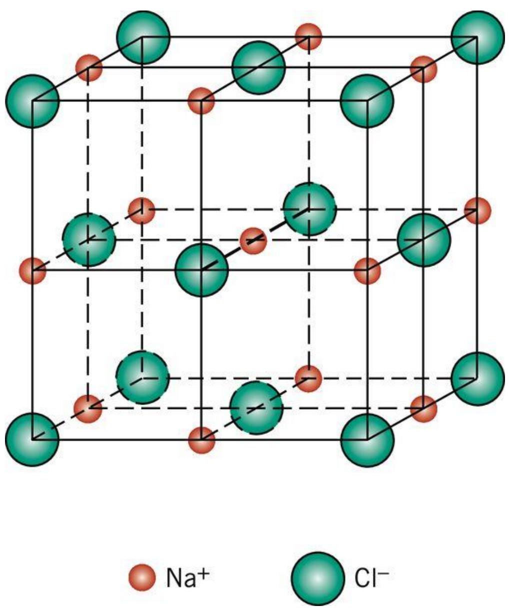


[Wiley - VMSE (drbuc2jl8158i.cloudfront.net)](https://drbuc2jl8158i.cloudfront.net)

AX STRUCTURES

- A: cation, X: anion same charge

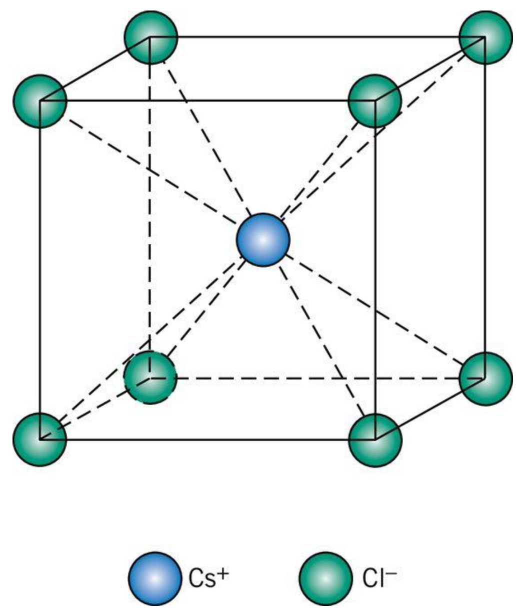
NaCl type



CN: 6 - fcc, 2 atoms basis

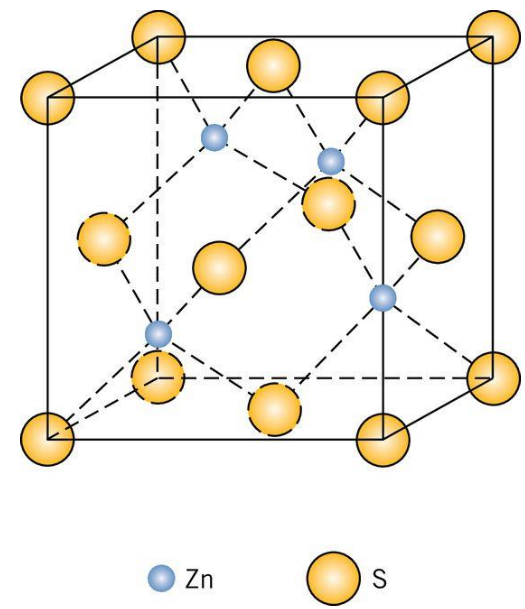
NaCl, MgO, MnS, LiF, FeO

CsCl type



CN: 8 - sc, 2 atoms basis

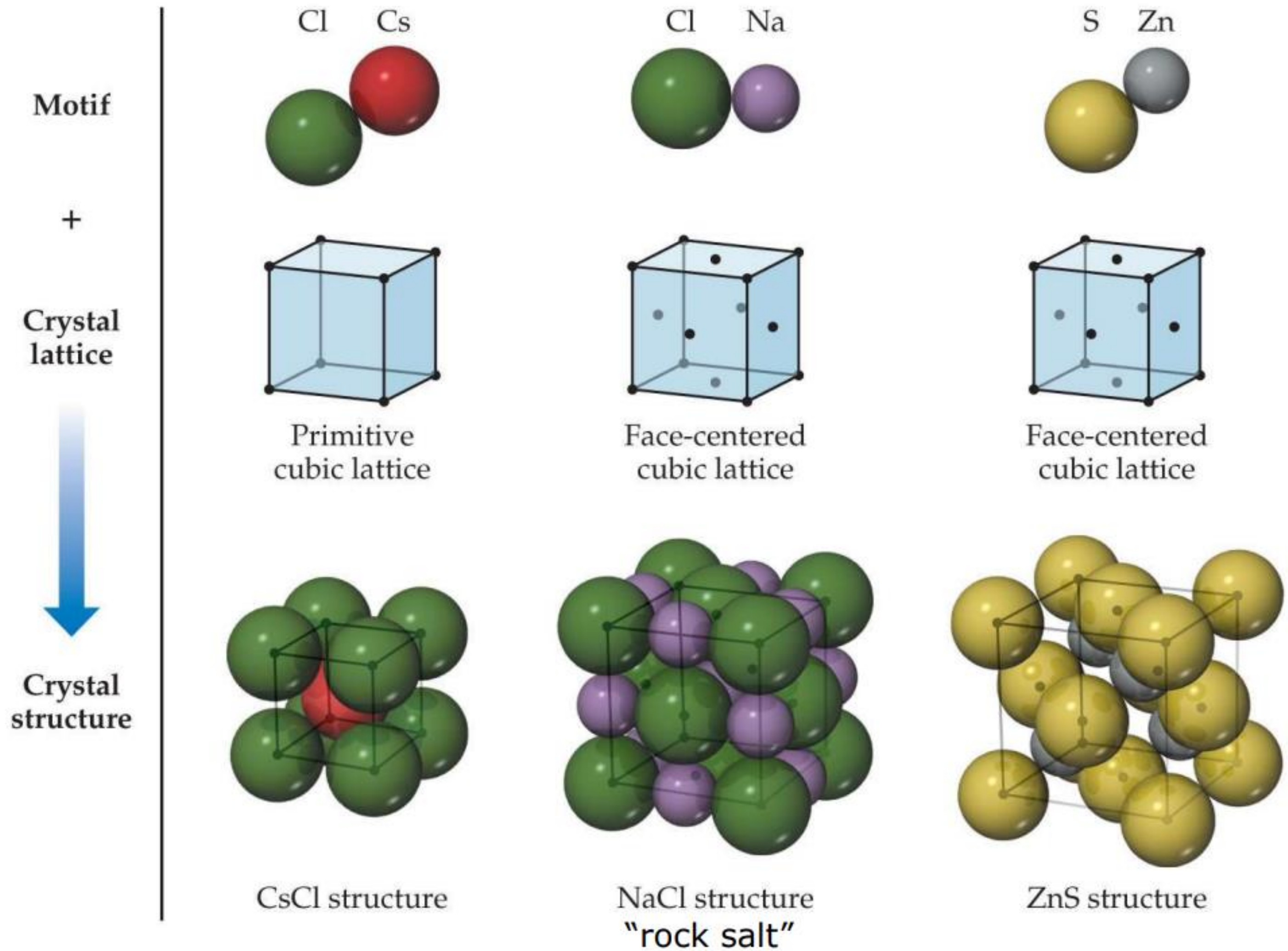
Blend (ZnS) type



CN: 4 - fcc, 2 atoms basis

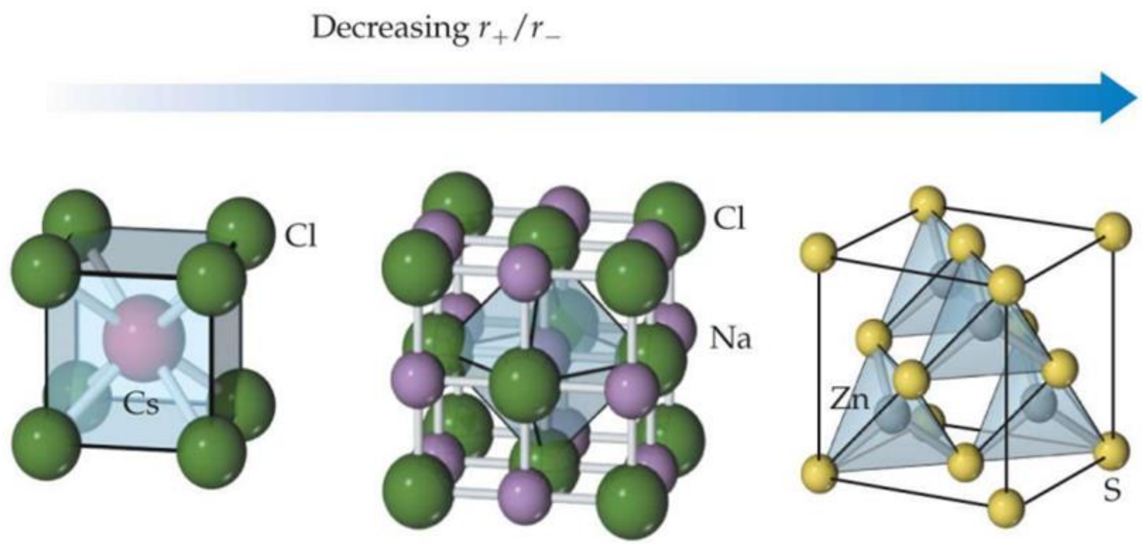
ZnS, ZnTe, SiC

AX STRUCTURES – MOTIF+LATTICE



Source: https://www.unf.edu/~michael.lufaso/chem204

AX STRUCTURES – IONIC RADII &CN

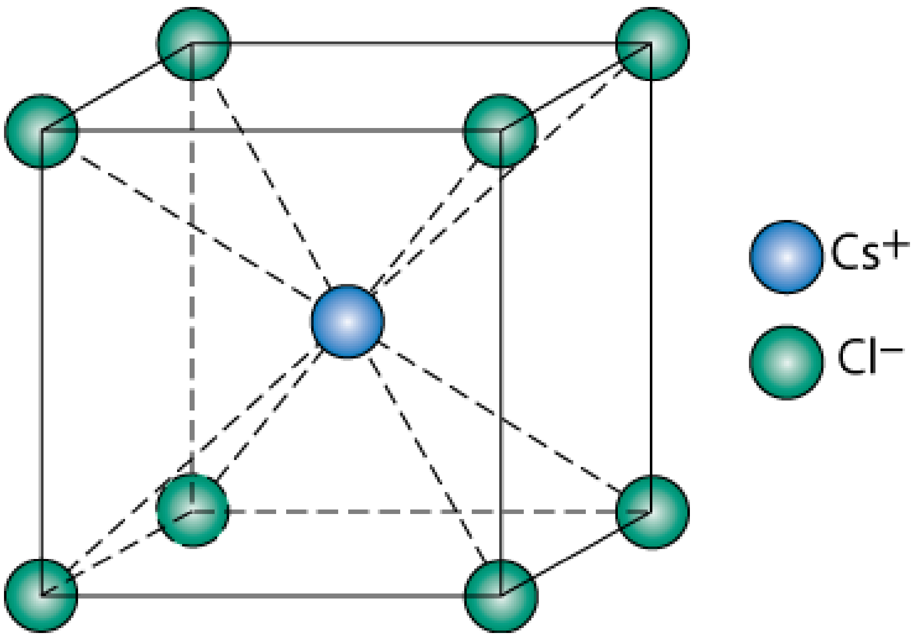


	CsCl	NaCl	ZnS
Cation radius, r_+ (Å)	1.74	1.02	0.74
Anion radius, r_- (Å)	1.81	1.81	1.84
r_+/r_-	0.96	0.56	0.40
Cation coordination number	8	6	4
Anion coordination number	8	6	4

Source: https://www.unf.edu/~michael.lufaso/chem204

CsCl STRUCTURES

Cesium Chloride structure:



Cs^+ $r_{Cs+} = 0.174$ nm

Cl^- $r_{Cl-} = 0.181$ nm

$r_c/r_a = 0.961 \approx \mathbf{1}$

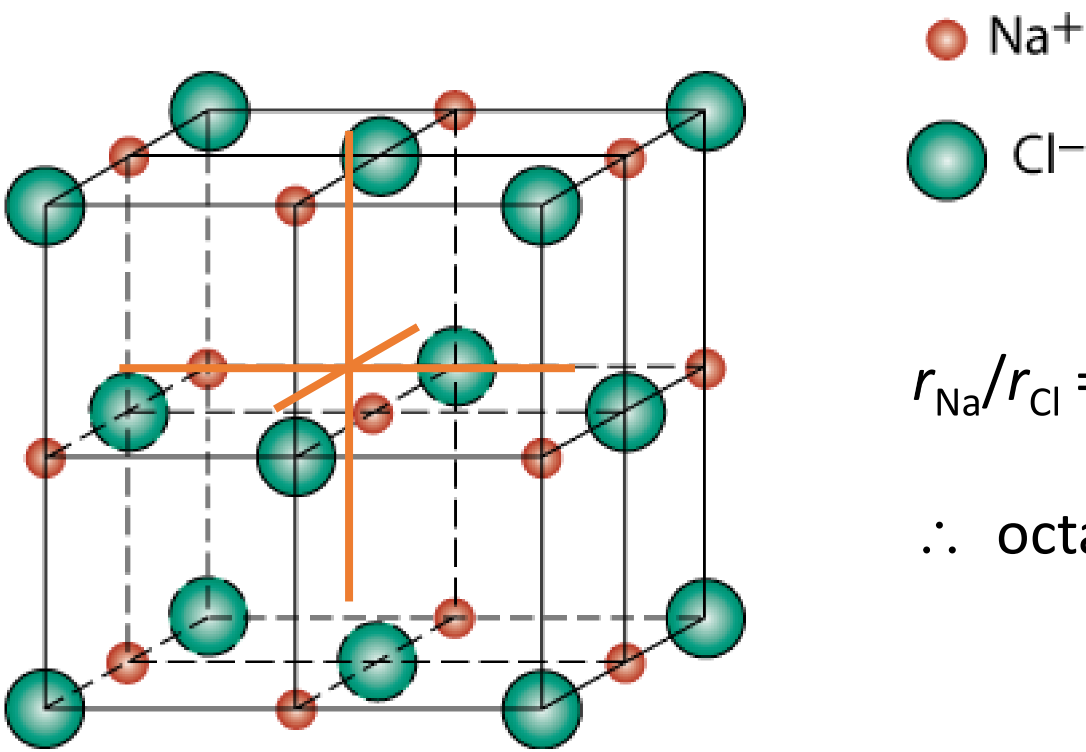
$\therefore$ cubic sites preferred

each Cs^+ has 8 neighbor Cl^-

Rock Salt Structure

Same concepts can be applied to ionic solids in general

Example: NaCl (rock salt) structure



Adapted from Fig. 12.2, *Callister & Rethwisch 10e.*

$r_{Na} = 0.102$ nm

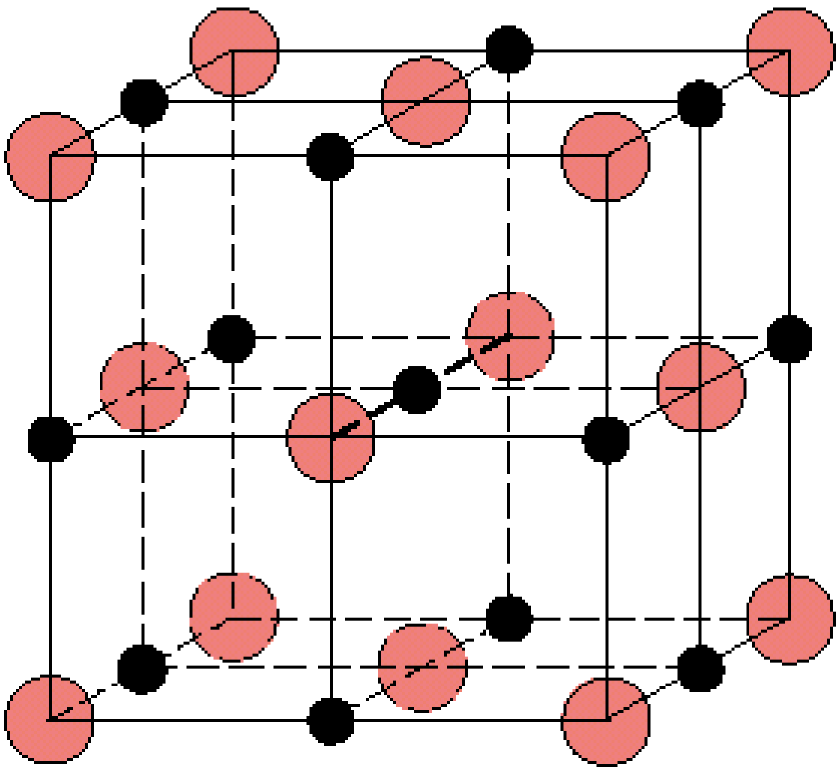
$r_{Cl} = 0.181$ nm

$r_{Na}/r_{Cl} = 0.564$

$\therefore$ octahedral sites preferred

MgO and FeO

MgO and FeO also have the NaCl structure



O^{2-} $r_O = 0.140$ nm

Mg^{2+} $r_{Mg} = 0.072$ nm

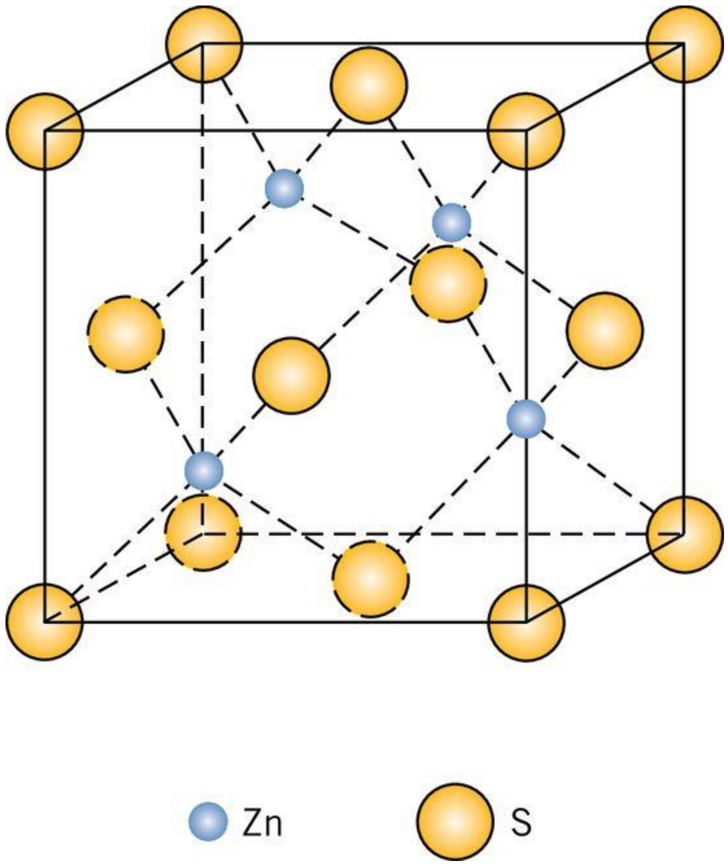
$r_{Mg}/r_O = 0.514$

$\therefore$ octahedral sites preferred

each Mg^{2+} (or Fe^{2+}) has 6 neighbor oxygen atoms

ZnS Structures

ZnS (blend) structure:



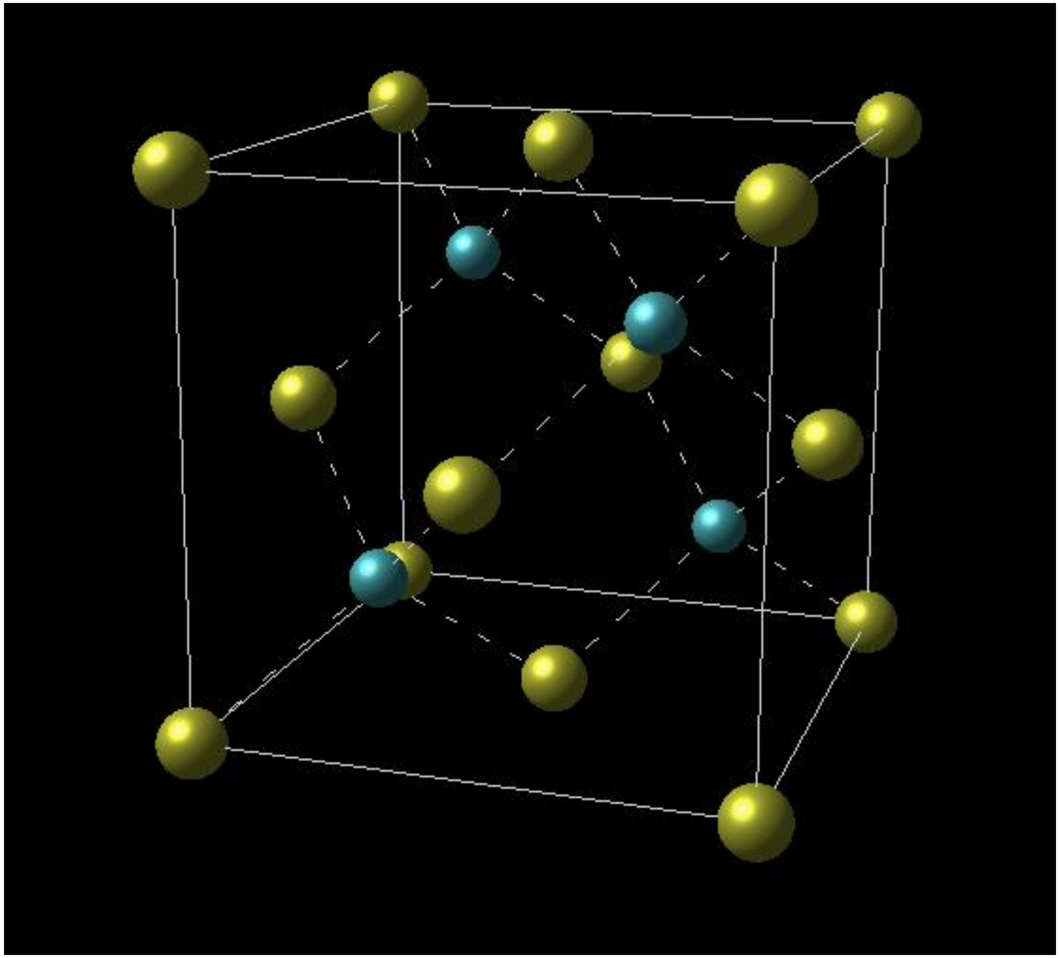
Zn^{2+} $r_{Zn2+} = 0.074$ nm

S^{2-} $r_{S2-} = 0.184$ nm

$r_c/r_a = 0.40$

$\therefore$ tetrahedral sites preferred

VMSE Screenshot – Zinc Blende Unit Cell



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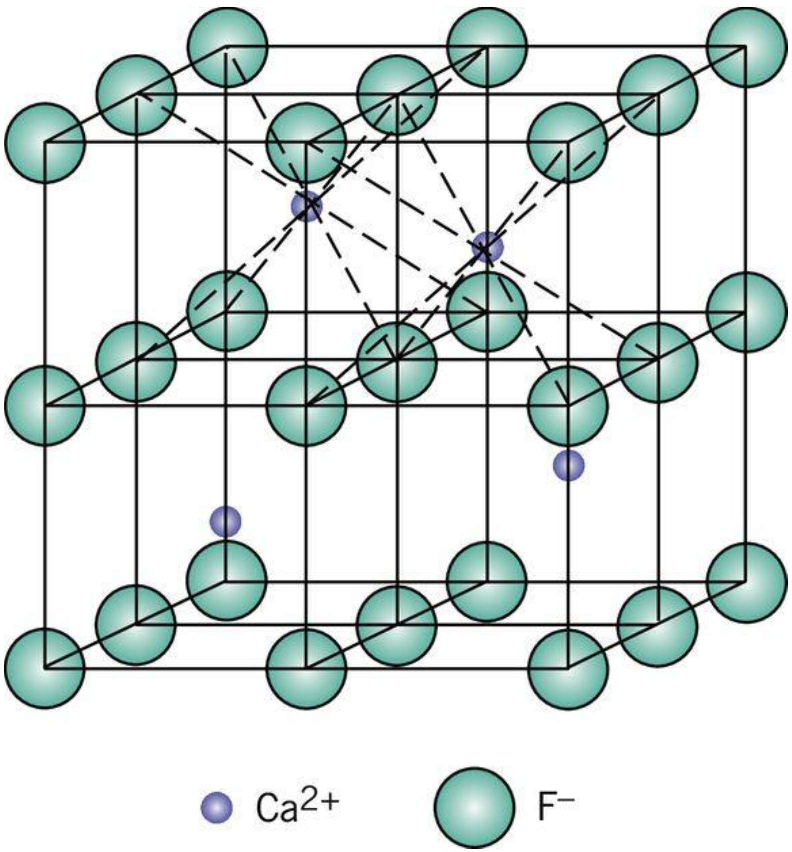
A_mX_p STRUCTURES

A: cation, X: anion different charges



CaF_2 fluorite

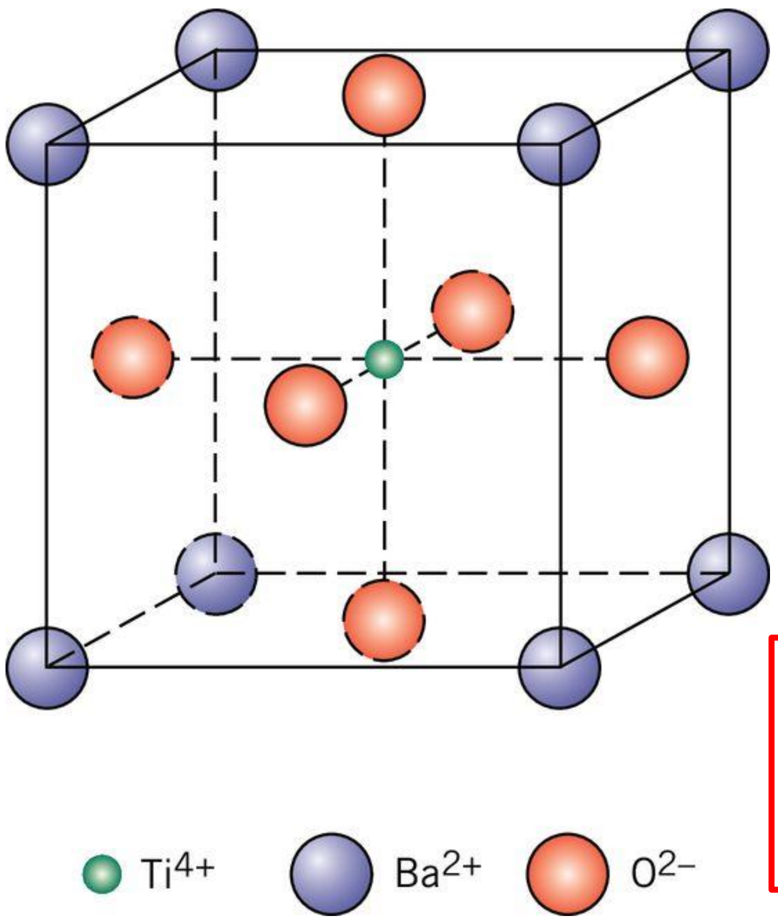
similar to CsCl BUT only half of central position occupied by Ca2+ ions

CN: 8 (cations) , 4 (anions)
structure: sc, 2 atoms basis

CaF_2, ZrO_2 , UO_2, PuO_2, ThO_2

$A_mB_nX_p$ STRUCTURES

- A: cation, B: cation, X: anion different charges



example

$BaTiO_3$

barium titanate

perovskite structure

[Barium Titanate BaTiO3 (chemtube3d.com)]

CN: 12 (A) , 6 (B), 6 (X)

structure: simple cubic

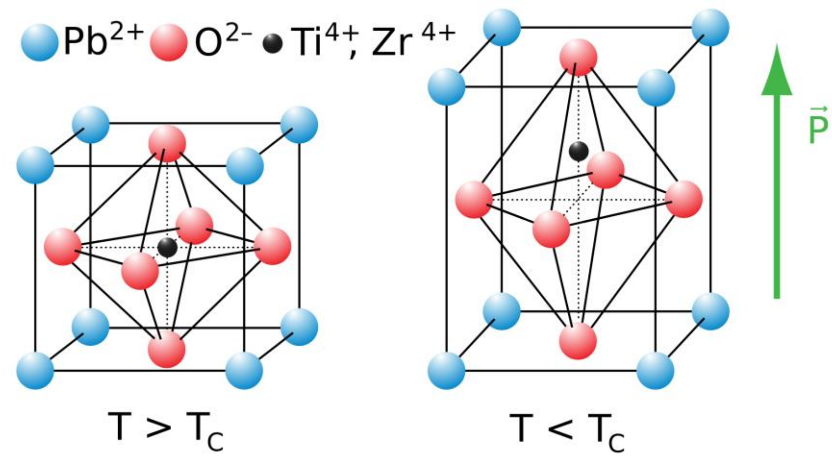
Perovskites exhibit many interesting and useful properties: **piezoelectricity**, **pyroelectricity**, **ferroelectricity**, **electro-optical effects**, **magneto-optical effects**, and **superconductivity**.

PEROVSKITES EXAMPLES

PZT: Lead Zirconate Titanate

$$Pb[Zr_xTi_{1-x}]O_3 \quad 0<x<1$$

In PZT, a fraction *x* of the B sites in the crystal are occupied by Zr atoms and a fraction (1 - *x*) of the B sites are occupied by Ti atoms.



Piezoelectric material: the crystal expands when a voltage is applied across it

actuators in scanning tunneling/atomic force microscopes, inkjet printers, fuel injectors, etc..

pressure sensors: when stress is applied to a crystal, a voltage appears accross it

L6.2

PIEZOCERAMICS

PIEZOELECTRICITY

YOUTUBE VIDEO (channel «Steve Mould»)

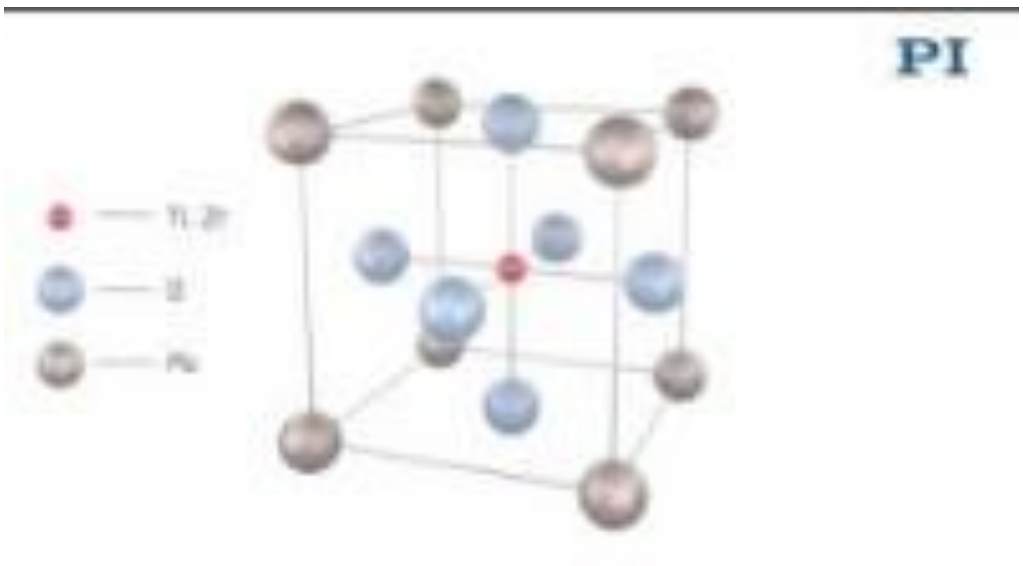
Piezoelectricity - why hitting crystals makes electricity - YouTube

(09:20)

PIEZOELECTRIC CERAMICS

- natural monocrystalline materials - quartz, tourmaline:
  piezoelectric effect is relatively small

- Polycrystalline ferroelectric ceramics - barium titanate (BaTiO3) and lead zirconate titanate (PZT):
  exhibit larger displacements or induce larger electric voltages



Fundamentals of Piezo Technology
www.piceramic.com

PIEZOELECTRIC TRANSDUCERS

YOUTUBE VIDEO (channel «Physik Instrument») (03:19)

https://youtu.be/DeZGc4wufN0

EXAMPLES OF USES OF PIEZOCERAMICS

VIDEO RESOURCES

PICERAMIC – Virtual Trade SHOWS: Medical Technology

- Contactless Patient Monitoring With Ultrasound
- Incisionless Surgery Using Therapeutic Ultrasound
- Miniaturized Tools for Minimally Invasive Medical Procedures
- Ultrafast Liquid Handling in Small Spaces

PICERAMIC – Virtual Trade SHOWS: Industrial Ultrasonics

- Smart Metering for Intelligent Data Acquisition
- Ultrasound for Industrial Automation
- Hydroacoustics in Underwater Communication

PICERAMIC – Virtual Trade SHOWS: Industrial Precision Dosing

- Digital printing – Drop on Demand Inkjet
- Precise Dosing of Highly Viscous Media

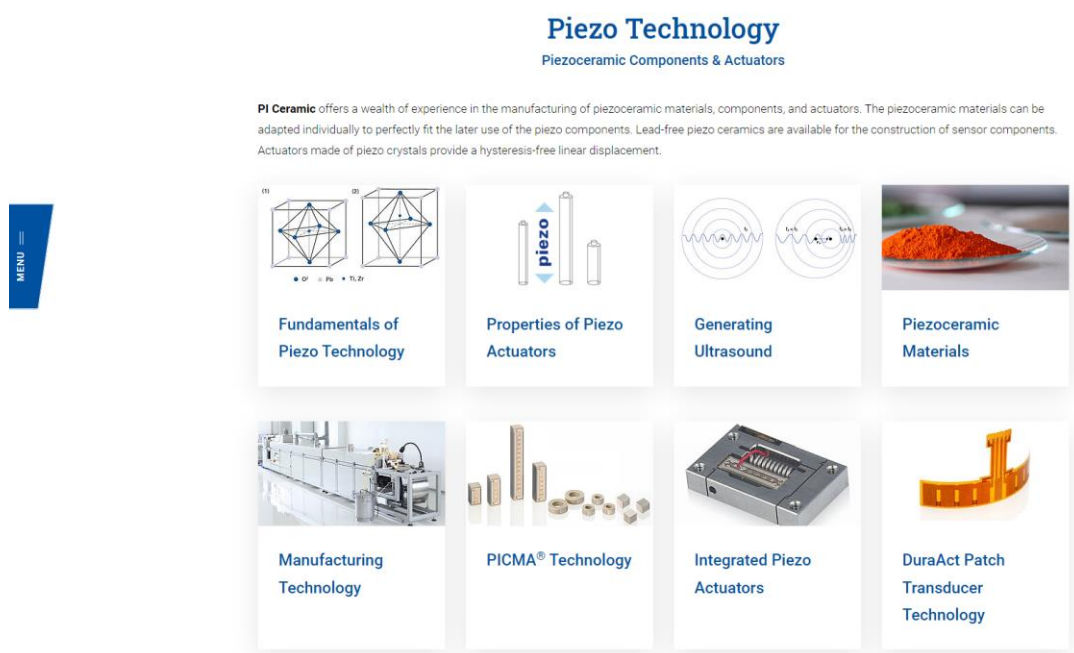
PIEZOELECTRIC CERAMIC TRANSDUCERS

HOME ASSIGNMENT

visit Physik Instrumente (PI) website: [PI – Solutions for Precision Motion and Positioning (physikinstrumente.com)]

Piezo Technology Section, Actuators, Nanopositioning

PI

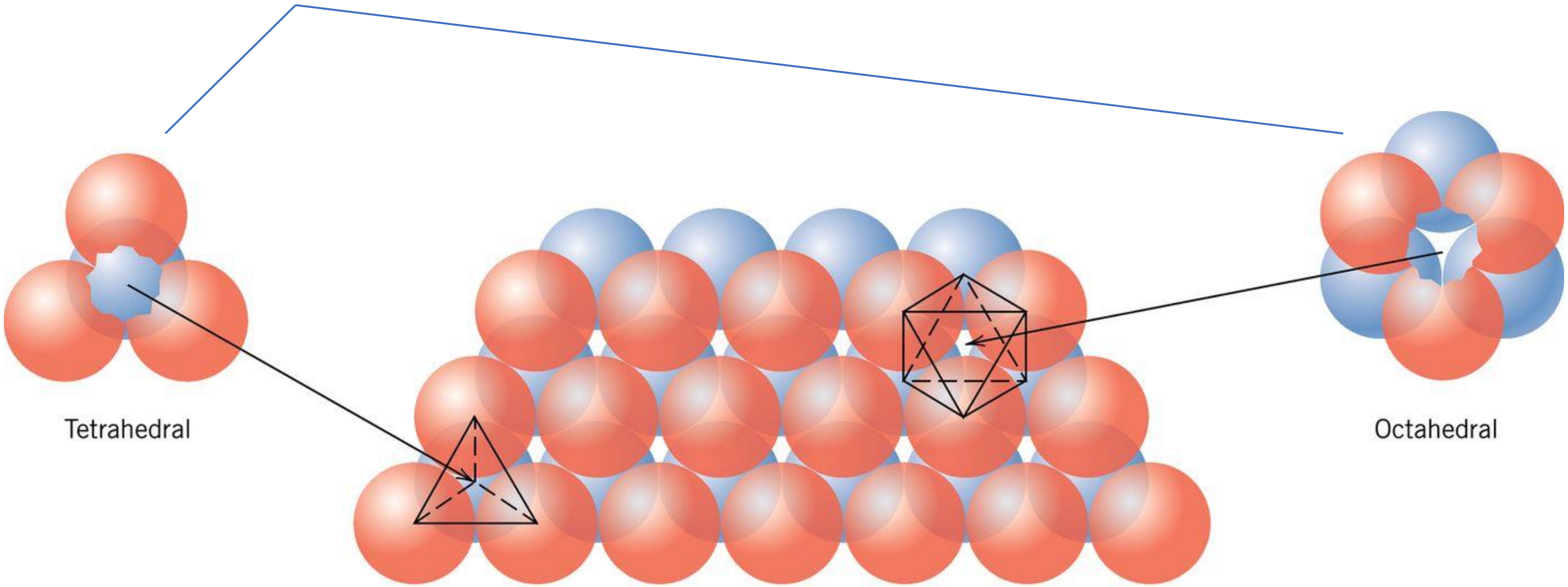


L6.3

OXIDE STRUCTURES, PACKING OF ANIONS, GLASS

Close Packing of Anions

- similar as in metals (FCC, HCP), close-packed planes of ions: large anions
- small interstitial sites between cpp in which the cations may reside



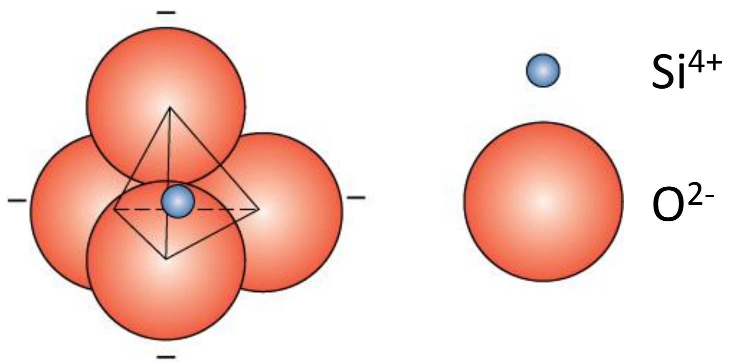
Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, John Wiley & Sons, 1964. Reproduced with permission of Janet M. Moffatt.

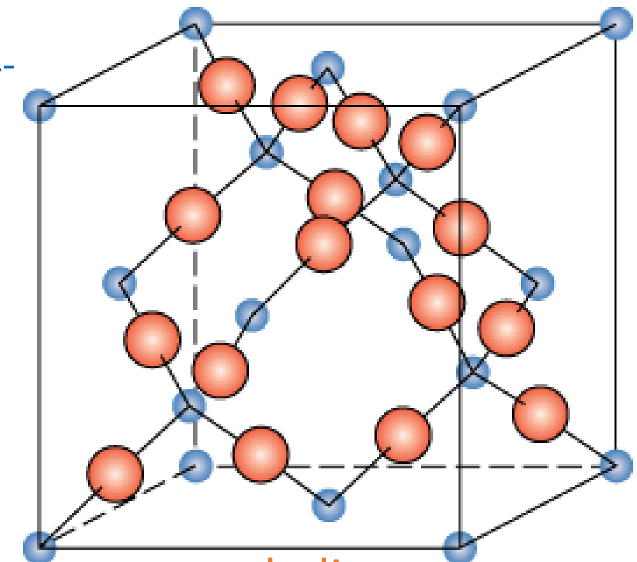
[3D VIEW – VMSE Ceramic Close Packed Structures]

Silicate Ceramics

Most common elements on earth are Si & O

basic unit of all silicates: tetrahedron $(SiO_4)^{4-}$





Figs. 12.9 & 12.10, *Callister & Rethwisch 10e*

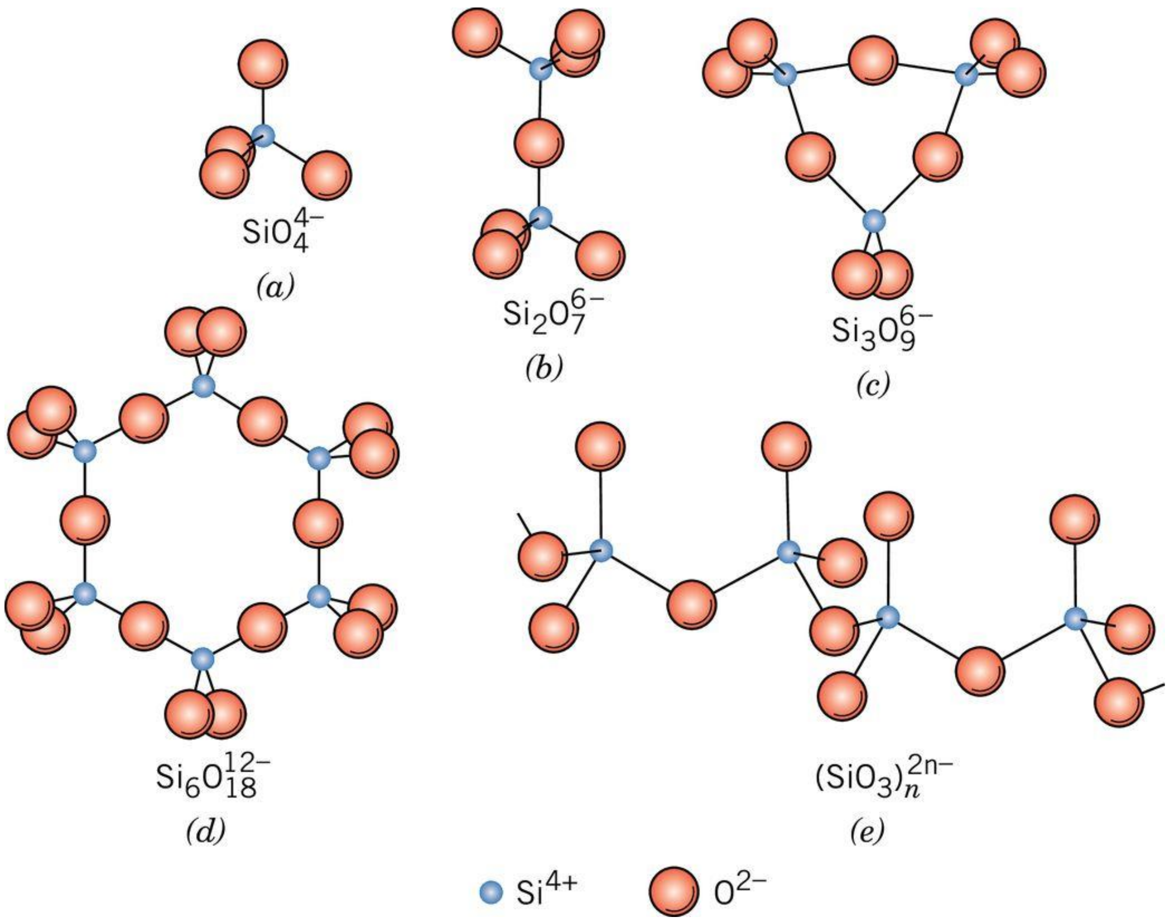
SiO_2 (silica) polymorphic forms are quartz, crystobalite, & tridymite

"open" structures: relatively low density (e.g. quartz 2.65 g/cm^3)

The strong Si-O bonds lead to a high melting temperature (1710ºC) for this material

SILICATES

Bonding of adjacent SiO_4^{4-} : sharing of common corners, edges, or faces



Presence of cations such as Ca^{2+}, Mg^{2+}, & Al^{3+}:

1. maintain charge neutrality,

2. ionically bond SiO_4^{4-} to one another

e.g.

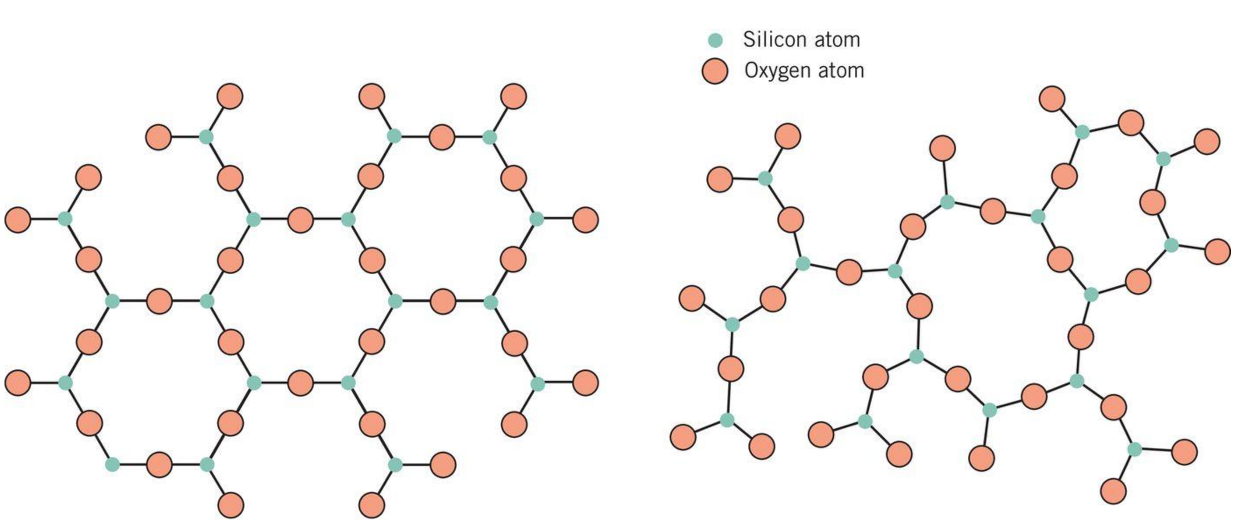
Mg_2SiO_4

$Ca_2MgSi_2O_7$

Glass Structure

Glass is noncrystalline (amorphous)

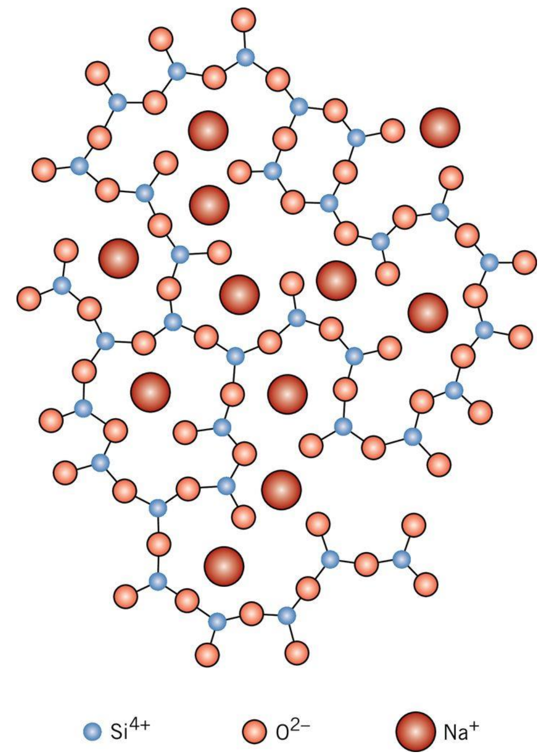
- Fused silica is SiO_2 to which no impurities have been added
- Other common glasses contain impurity ions such as Na^{+}, Ca^{2+}, Al^{3+}, and B^{3+}



(a) (b)

Crystalline silica (quartz)

Non- Crystalline silica



(soda glass)

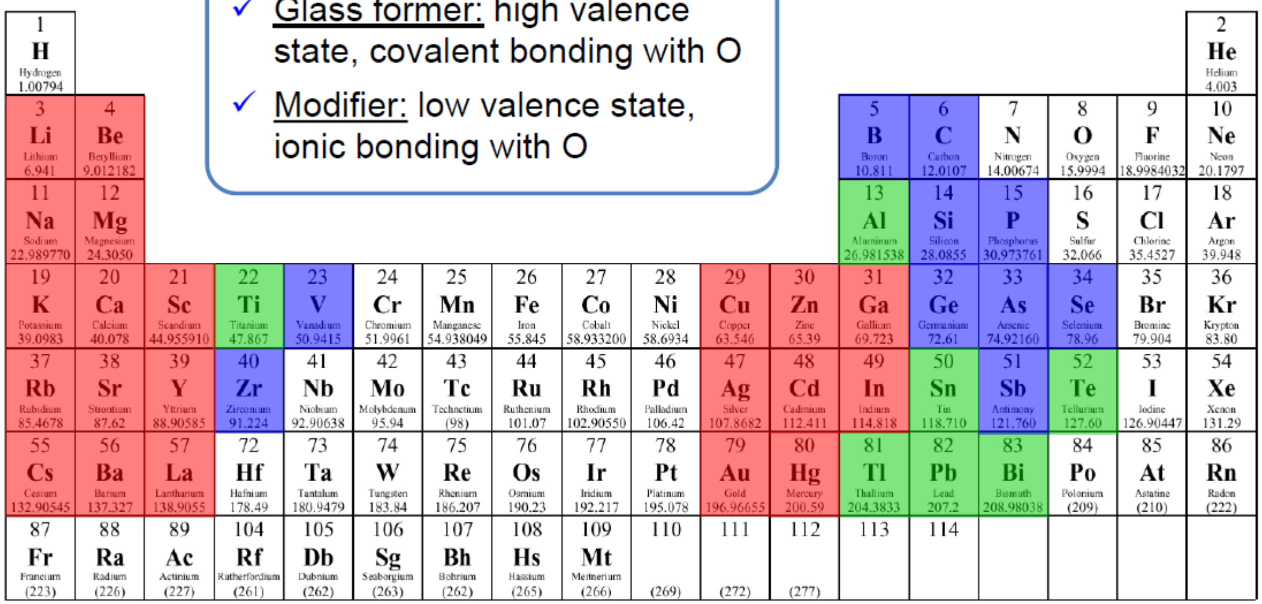
OXIDE GLASSES

oxides of elements from groups III, IV, V & mixtures with metallic oxides form glasses

window glass: 70%SiO_2, + 20% Na_2O, 10% CaO

ions preventing crystallisation: Na, Mg, Ca, …different number of bonds to O

- ✓ Glass former: high valence state, covalent bonding with O
- ✓ Modifier: low valence state, ionic bonding with O



Network modifiers | Glass formers | Intermediates

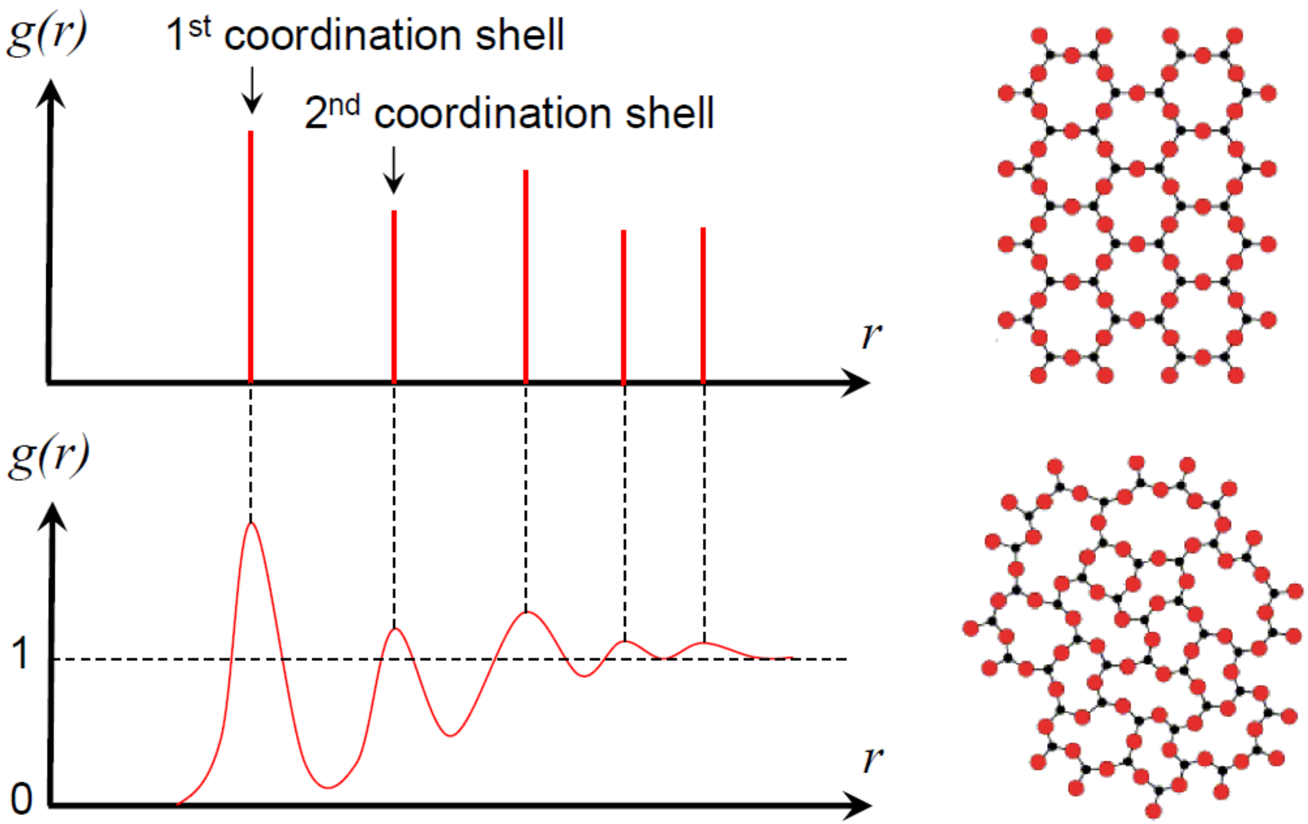
- ea
- re

what is a glass state?

MORE ON GLASSES, GLASS TRANSITION in SECTION 2 of the Course

PDFs of ideal (hard sphere) crystals vs. glasses

radial distribution function



(taken from https://ocw.mit.edu; MIT 3.071 Amorphous Materials, Juejun Hu)

Imperfections in Ceramics

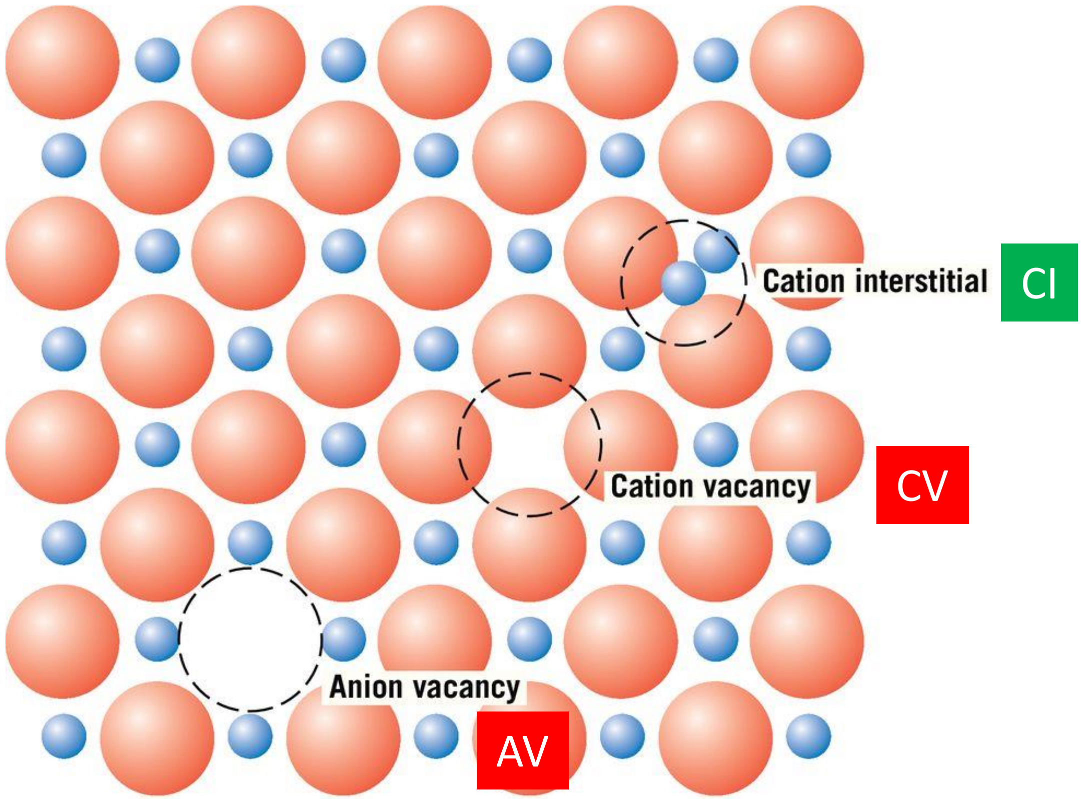
Vacancies

- vacancies exist in ceramics for both cations and anions

Interstitials

- interstitials exist for cations

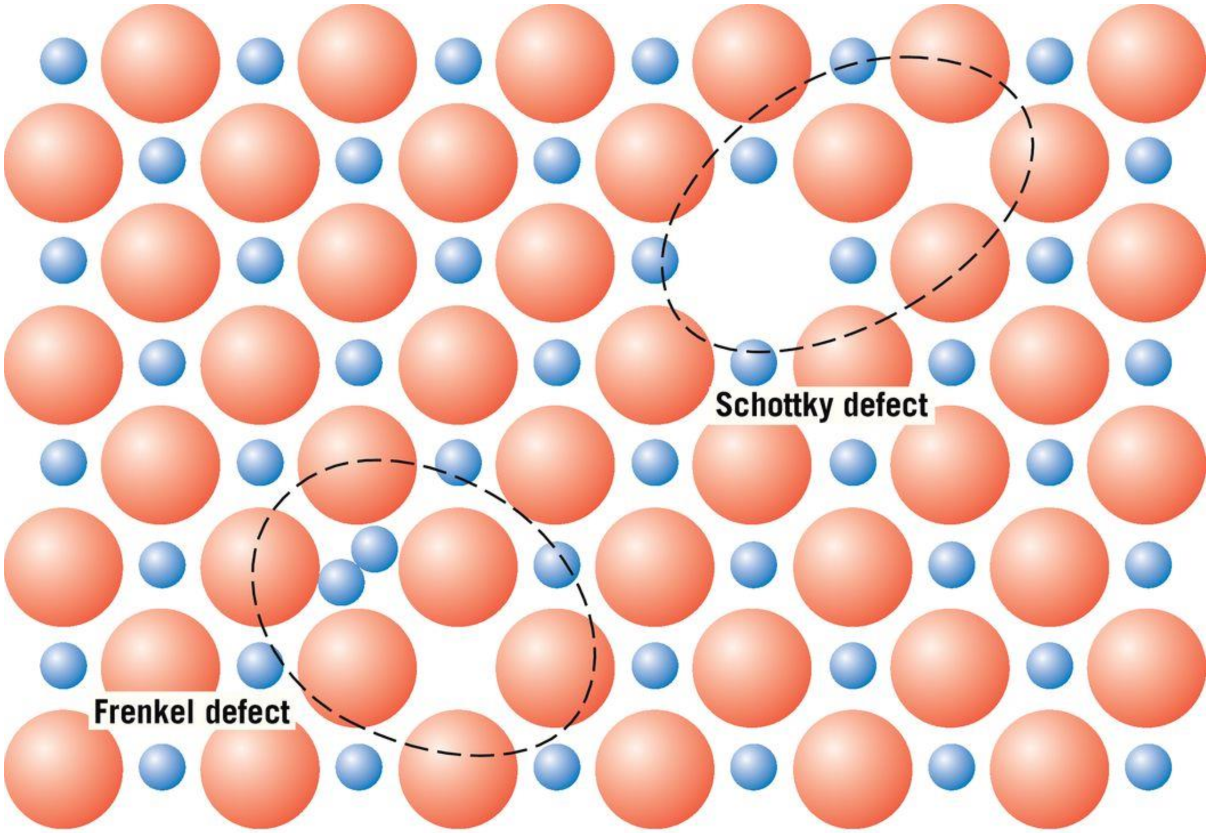
not normally observed for anions because anions are large relative to the interstitial sites



Imperfections in Ceramics

AX type

Schottky defect:
couple CV+AV



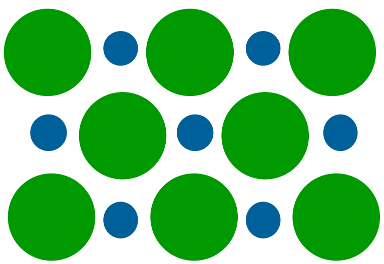
Frenkel defect:
couple CI +CV

Imperfections in Ceramics

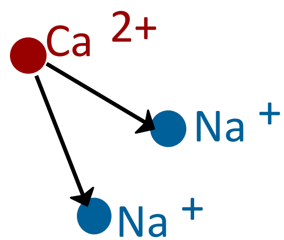
- Electroneutrality (charge balance) must be maintained when impurities are present

NaCl

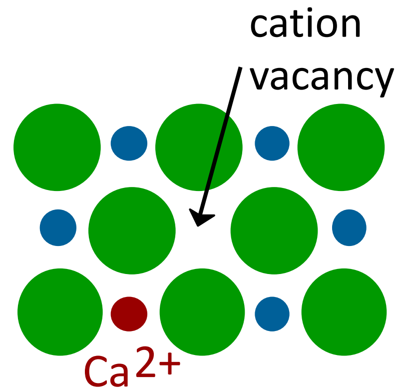
- Substitutional cation impurity



without impurity

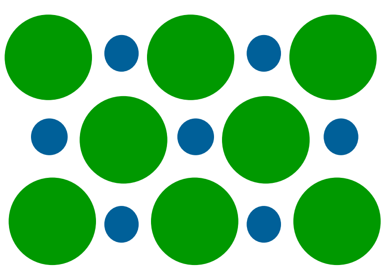


Ca^{2+} impurity

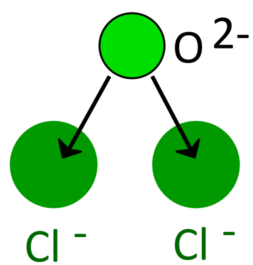


with impurity

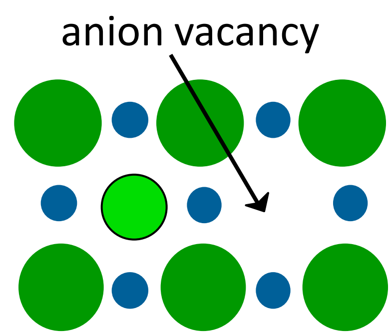
- Substitutional anion impurity



without impurity



O^{2-} impurity



with impurity

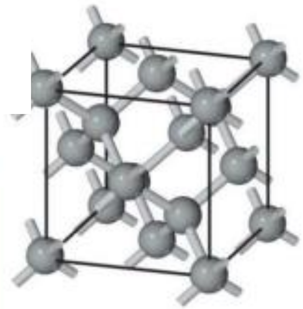
L6.4

PILLS ON SEMICONDUCTORS, SILICON CARBIDE

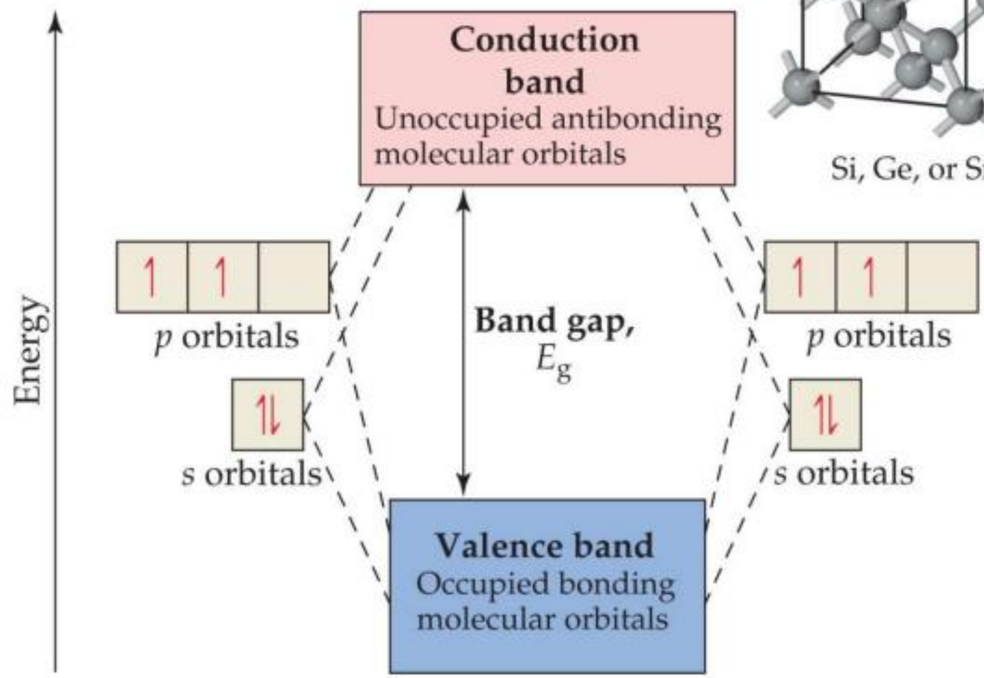
SHORT NOTES: SEMICONDUCTORS

impossible to recap here, please make ref to previous courses!

In the closely packed molecular orbitals, there is a gap between the occupied MOs (valence band) and the unoccupied ones (conduction band).



Si, Ge, or Sn



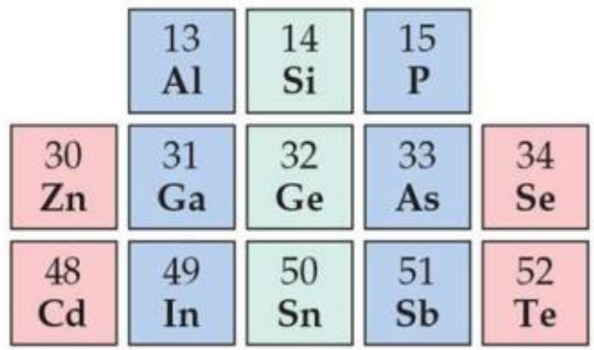
SHORT NOTES: SEMICONDUCTORS

- Band gaps decrease as one proceeds down a group.
- Band gaps greater than 3.5 eV are so large that material is an insulator, not a semiconductor.

TABLE 12.4 Band Gaps of Select Elemental and Compound Semiconductors

Material	Structure Type	E_g, eV†
Si	Diamond	1.11
AlP	Zinc blende	2.43
Ge	Diamond	0.67
GaAs	Zinc blende	1.43
ZnSe	Zinc blende	2.58
Sn‡	Diamond	0.08
InSb	Zinc blende	0.18
CdTe	Zinc blende	1.50

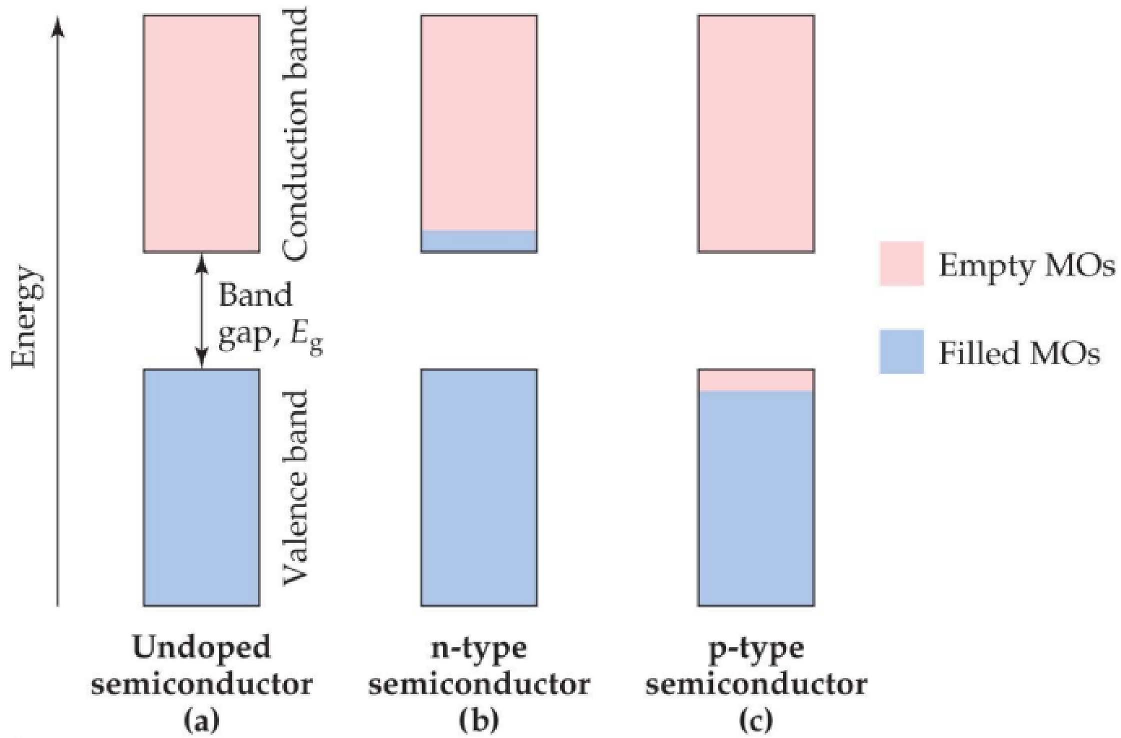
† Band gap energies are room temperature values, $1\ eV = 1.602 \times 10^{-19}$ J.
‡ These data are for gray tin, the semiconducting allotrope of tin. The other allotrope, white tin, is a metal.



SHORT NOTES: SEMICONDUCTORS

Doped semiconductors

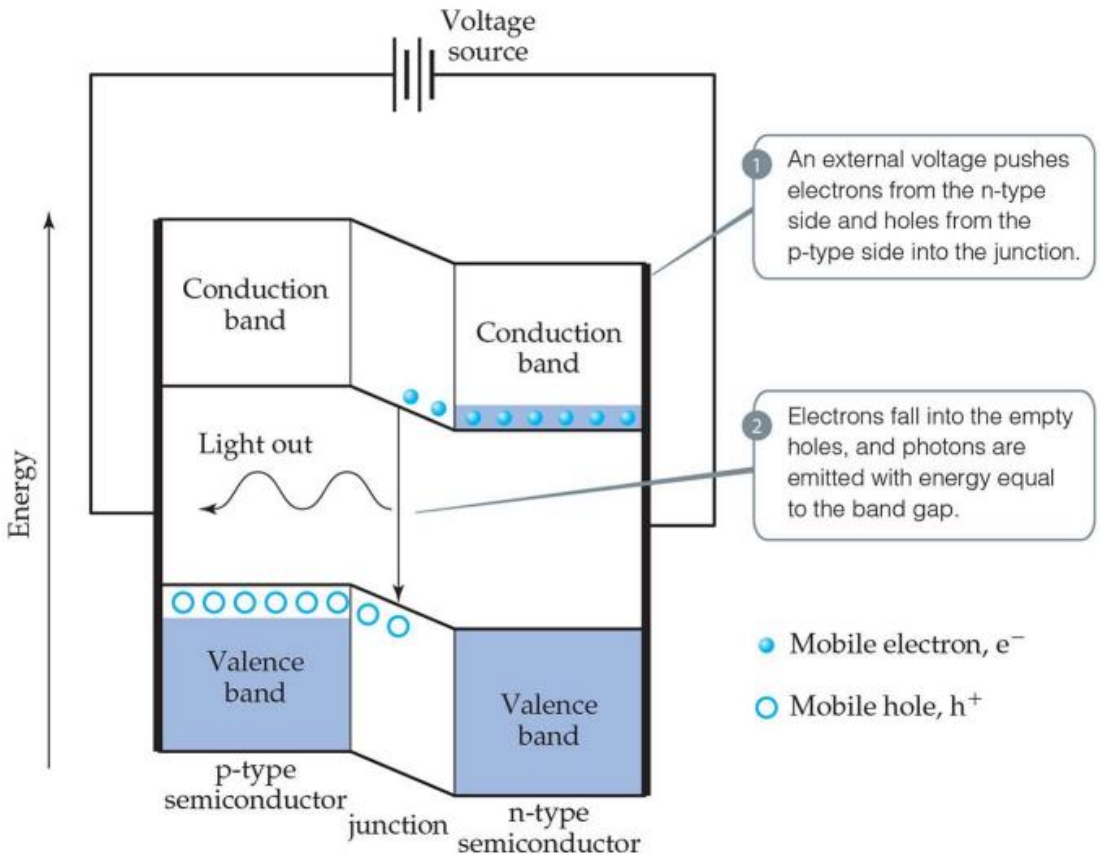
By introducing very small amounts of impurities that have more (*n*-type) or fewer (*p*-type) valence electrons, one can increase the conductivity of a semiconductor.



for Si (val 4):
p-type imp. B (val 3)
n-type imp. P (val. 5)

SHORT NOTES: SEMICONDUCTORS

SOLID-STATE LIGHTING: Light Emitting Diodes (LED)



p-n junction

From Sand to semiconductors – Chip Manufacturing

YOUTUBE VIDEO (channel «Infineon») (13:32)

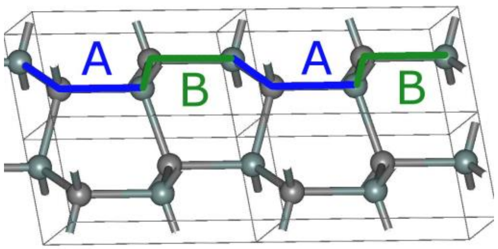
https://youtu.be/bor0qLifjz4

SILICON CARBIDE

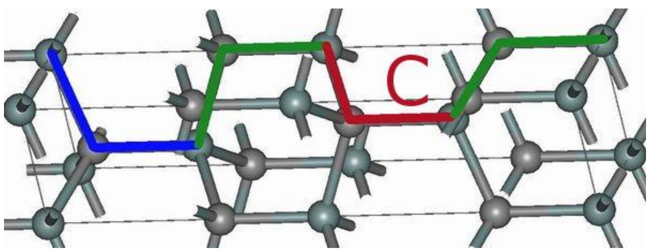
>250 **polymorphs of SiC** had been identified !

Hexagonal structures

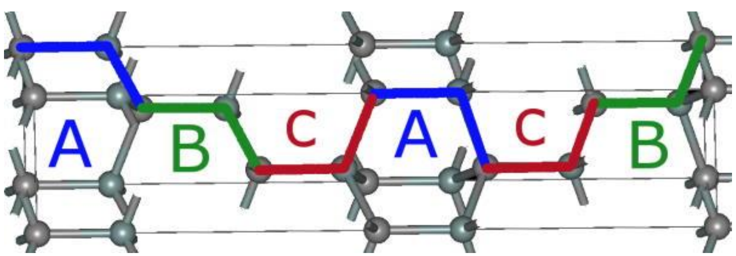
2H SiC



4H SiC



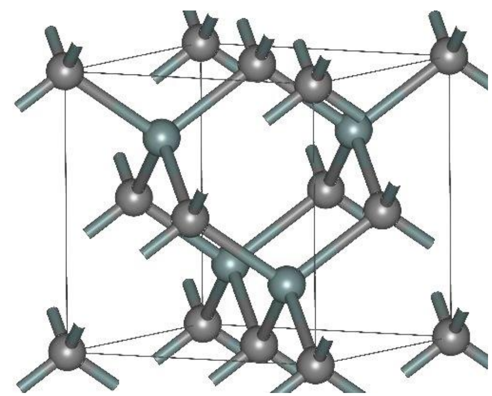
6H SiC



[3D view JSMol SiC 4H (tugraz.at)]

Cubic structure

3C SiC



Silicon Carbide

- low thermal expansion coefficient, high hardness, rigidity, thermal conductivity, resistance to wear, high T stability

Properties of major SiC polytypes[5][27]

Polytype	3C (β)	4H	6H (α)
Crystal structure	Zinc blende (cubic)	Hexagonal	Hexagonal
Space group	T^2_d-F$\bar{4}$3m	C^4_{6v}-P6_3mc	C^4_{6v}-P6_3mc
Pearson symbol	cF8	hP8	hP12
Lattice constants (Å)	4.3596	3.0730; 10.053	3.0810; 15.12
Density (g/cm^3)	3.21	3.21	3.21
Bandgap (eV)	2.36	3.23	3.05
Bulk modulus (GPa)	250	220	220
Thermal conductivity (W·m^{-1}·K^{-1}) @ 300 K (see [36] for temp. dependence)	360	370	490

MAIN FIELDS of APPLICATIONS

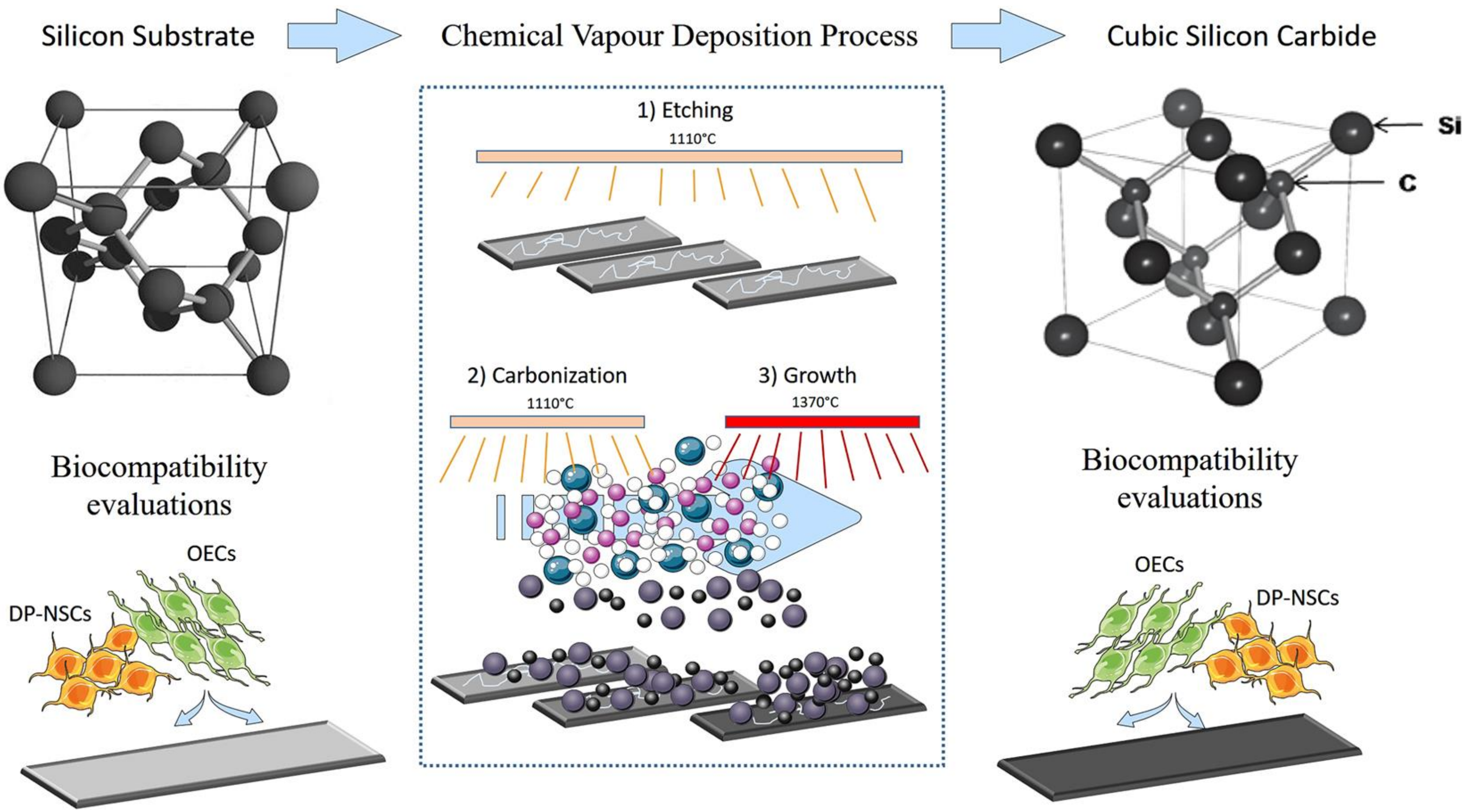
- abrasives, cutting tools
- automotive: high perf. brake disks
- important semiconductor: power electronics

SiC – Silicon Carbide

YOUTUBE VIDEO (channel «Subject Zero Science») (06:51)

[Silicon Carbide - The subtle REVOLUTION - YouTube]

SiC Growth and Biocompatibility

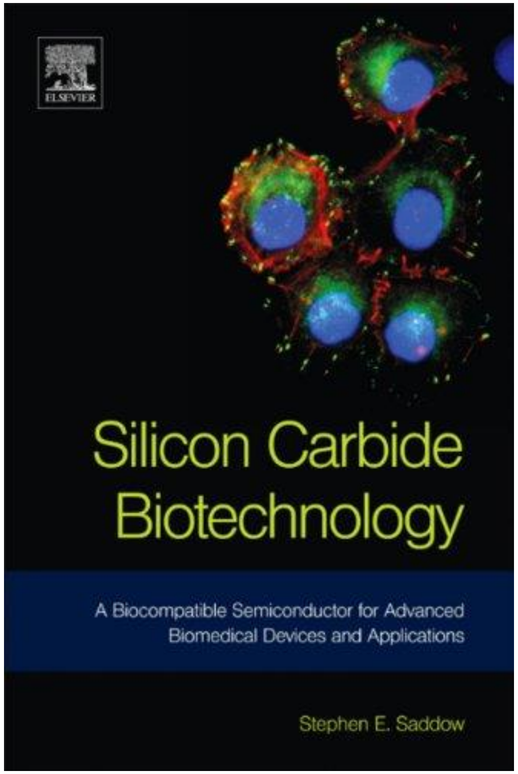


CVD: Trichlorosilane ● and ethylene ● used as Si ● and C ● precursors carried by H2 ○

Bonaventura, G., *et al. Sci Rep* **9,** 11540 (2019). https://doi.org/10.1038/s41598-019-48041-3

SiC – Silicon carbide

- biocompatibility, hemocompatibility
- heart stent coatings and bone implant scaffolds, neurological implants and sensors
- proposed as alternative to Si-based electronics for long term use,
- permanent implanted devices: glucose sensors, brain-machine-interface devices, smart bone and organ implants)



SEMINAR TOPIC	**SiC applications in Biomedicine and Bionics**

L6.5

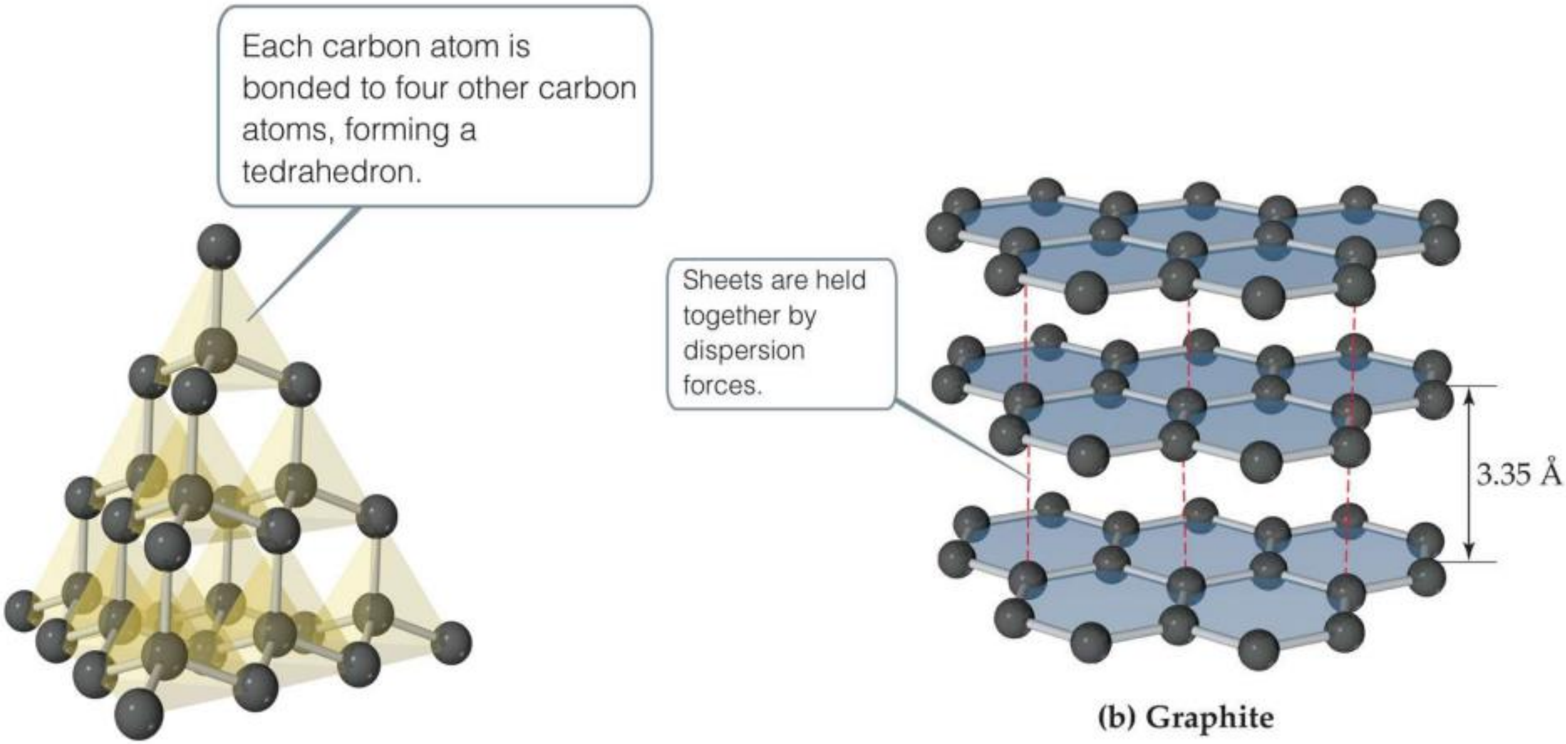
CARBON POLYMORPHS

Classwork 2
Question 5

what is the difference btw.: I) a carbon nanotube, II) a fullerene, III) graphene, IV) graphite? sketch the chem structure of graphene (see instructions for sending sketches)

POLYMORPHS OF CARBON

- covalent network solids



(a) Diamond

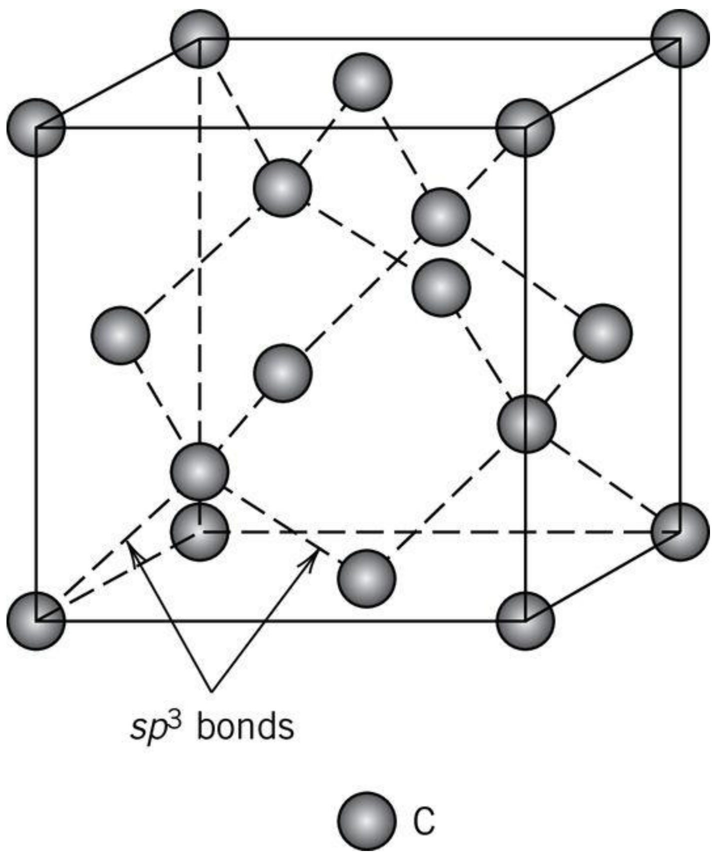
(b) Graphite

Source: https://www.unf.edu/~michael.lufaso/chem204

Polymorphs of Carbon - Diamond

Diamond

- tetrahedral bonding of carbon
  - hardest material known
  - very high thermal conductivity



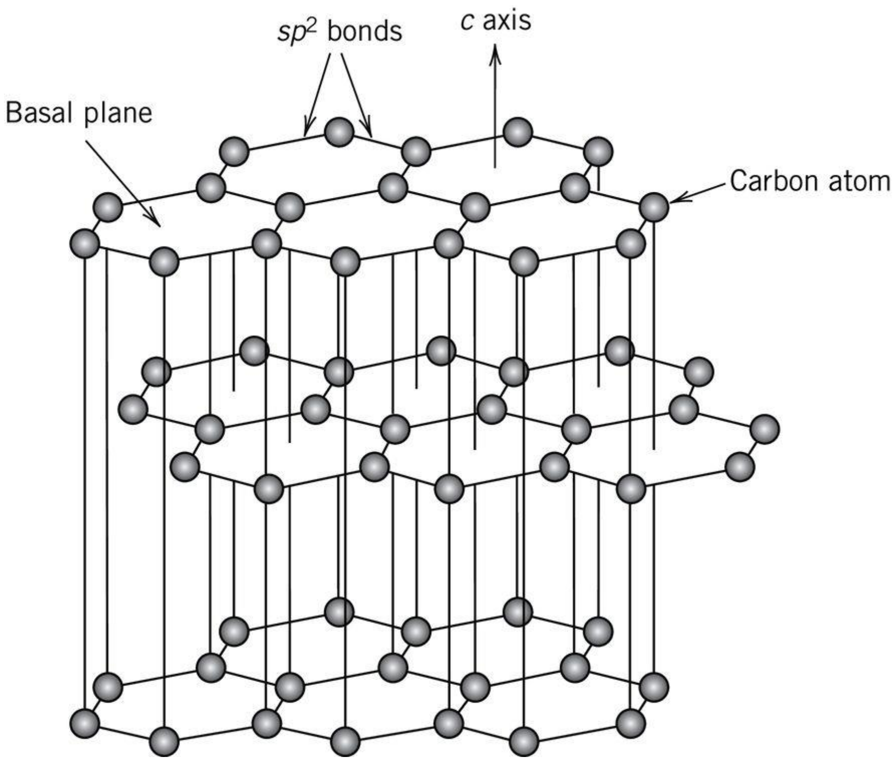
- large single crystals – gemstones
- small crystals – used to grind/cut other materials
- diamond thin films
  - hard surface coatings – used for cutting tools, medical devices, etc.

- transparent in the VIS and IR: widest spectral transmission range of all materials

POLYMORPHS OF CARBON - GRAPHITE

Graphite

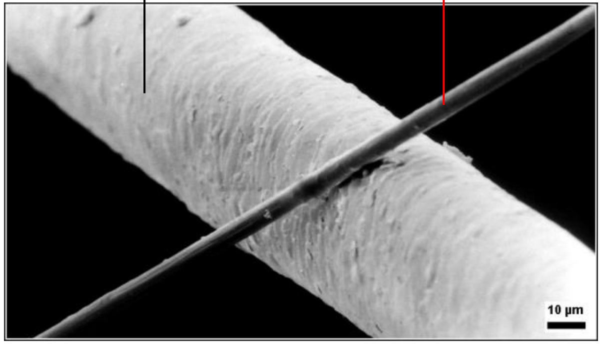
- layered structure – parallel hexagonal arrays of carbon atoms
- weak VdW forces between layers
- planes slide easily over one another -- good lubricant



52

Carbon Fibers

- small-diameter, high-strength, and high-modulus fibers
- used as reinforcements in polymer-matrix composites
- various arrangements of graphene layers.

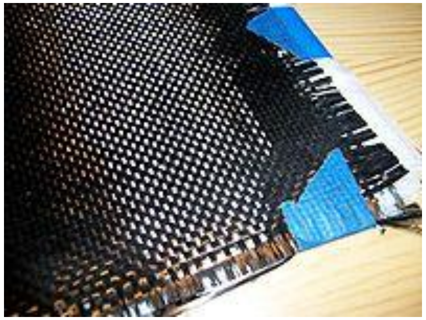


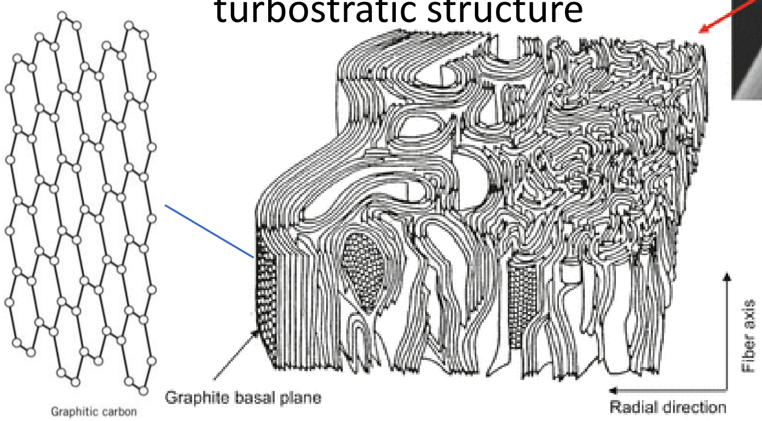
1. graphitic carbon fibers: high Elastic Modulus

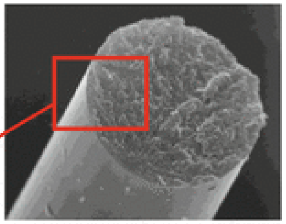
ordered structure of graphite—planes parallel to one another; weak van der Waals interplanar bonds.

2. disordered structure: high Strength

graphene sheets randomly folded, tilted, and crumpled to form **turbostratic carbon**.







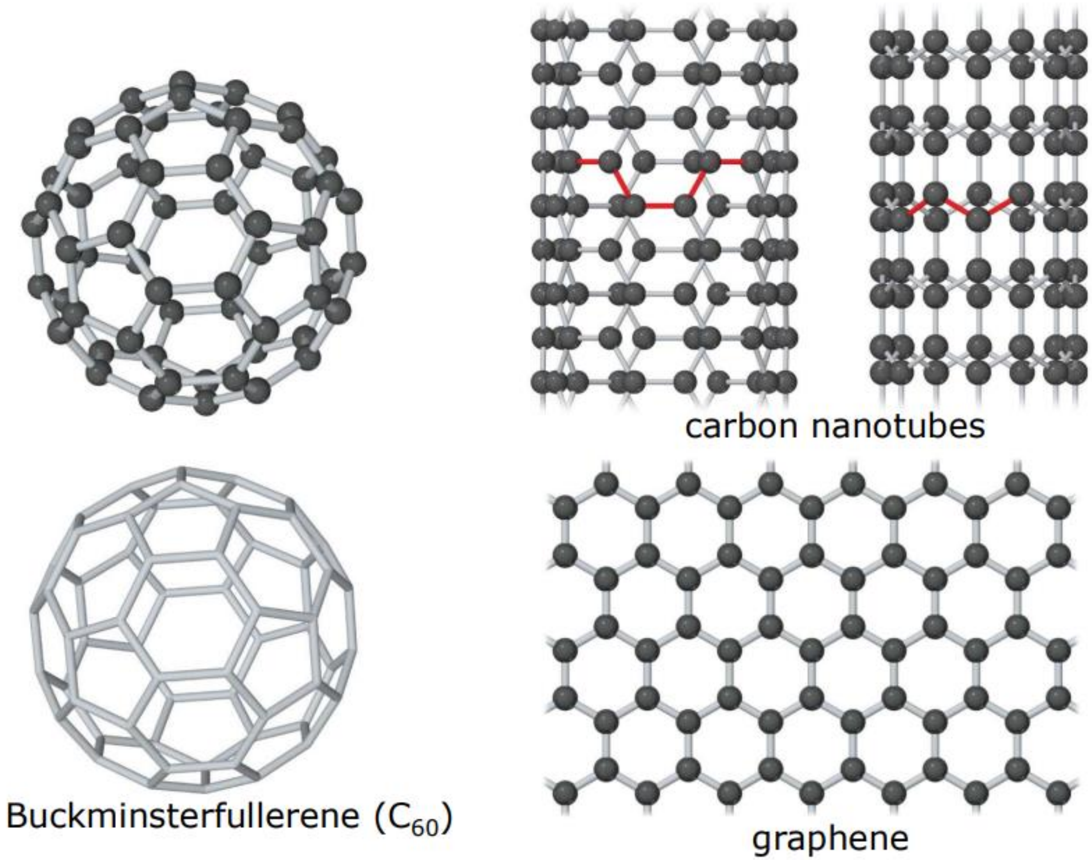
CARBON MATERIALS PROPERTIES

Table 13.3 Properties of Diamond, Graphite, and Carbon (for Fibers)

	Material				
		Graphite			
Property	**Diamond**	**In-Plane**		**Out-of-Plane**	**Carbon (Fibers)**
Density (g/cm^3)	3.51		2.26		1.78–2.15
Modulus of elasticity (GPa)	700–1200	350		36.5	230–725[a]
Strength (MPa)	1050	2500		—	1500–4500[a]
Thermal Conductivity (W/m·K)	$\boxed{2000–2500}$	1960		6.0	11–70[a]
Coefficient, Thermal Expansion (10^{-6} K^{-1})	0.11–1.2	−1		+29	−0.5–−0.6[a] 7–10[b]
Electrical Resistivity (Ω·m)	$\boxed{10^{11} - 10^{14}}$	1.4×10^{-5}		1×10^{-2}	9.5×10^{-6}–17×10^{-6}

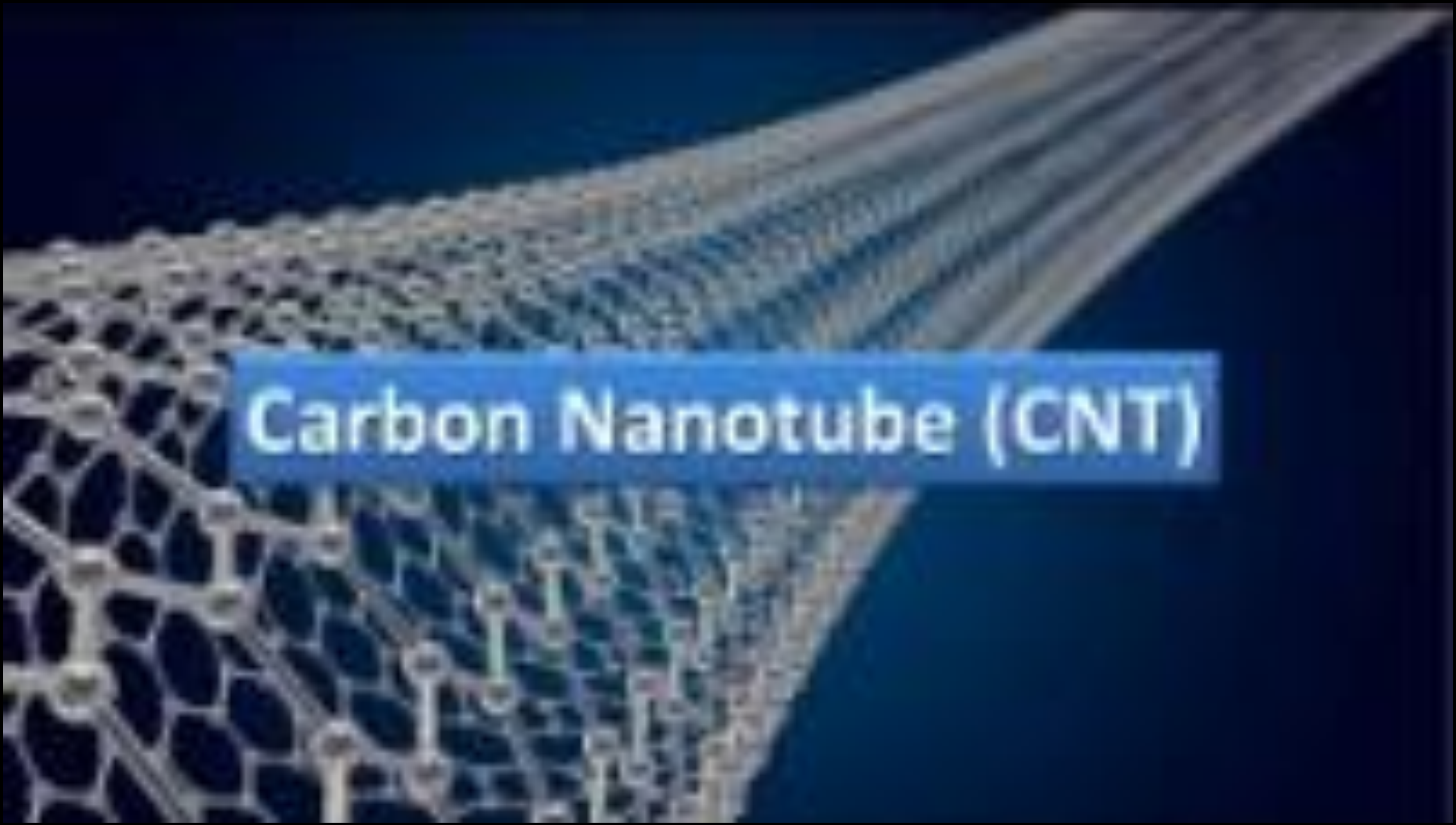
[a] Longitudinal fiber direction.
[b] Transverse (radial) fiber direction.

NANOSCALE C POLYMORPHS



MORE ON NANOSCALE POLYMORPHS in SECT 2:
Graphene
Fullerene
Carbon Nanotubes

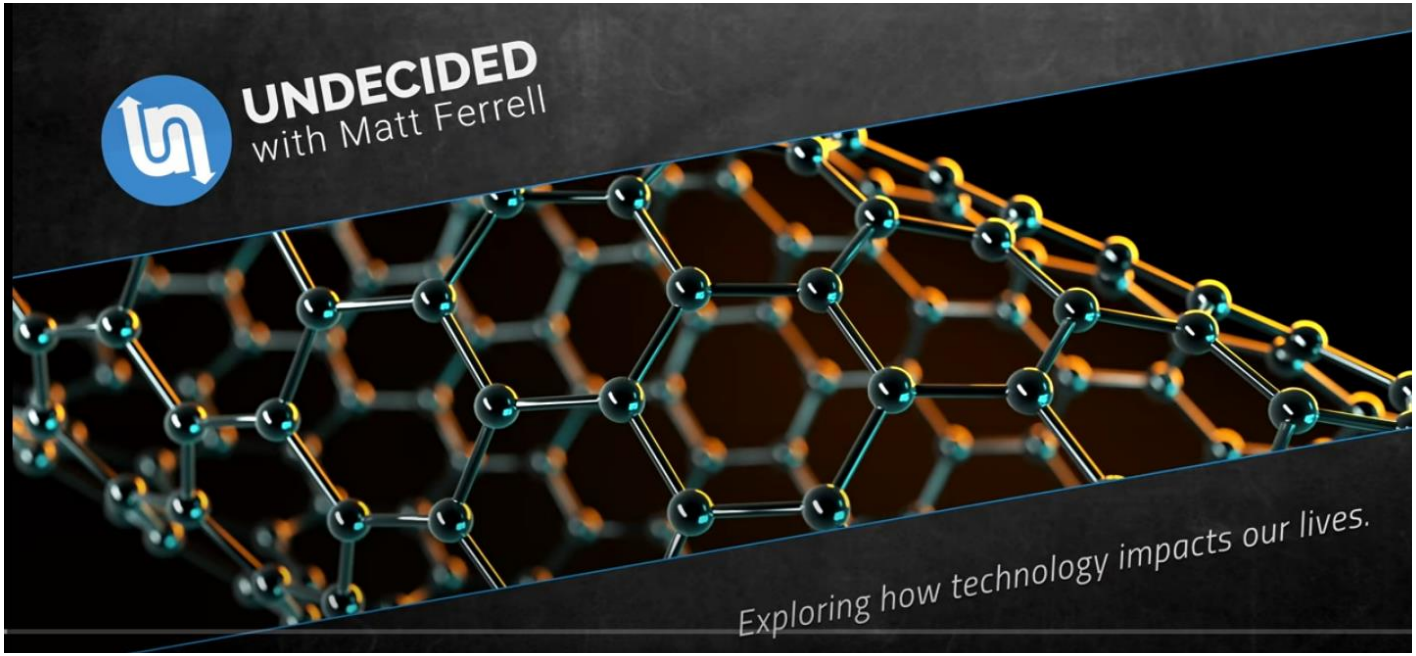
CARBON NANOTUBES (CNTS) STRUCTURE



YOUTUBE VIDEO (channel «RightVision») (10:43)

Carbon Nanotube Review, Definition, Structure, Properties, Applications - YouTube

CNTS AND RENEWABLE ENERGY



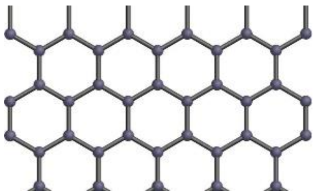
Revisiting How Carbon Nanotubes Will Change Renewable Energy

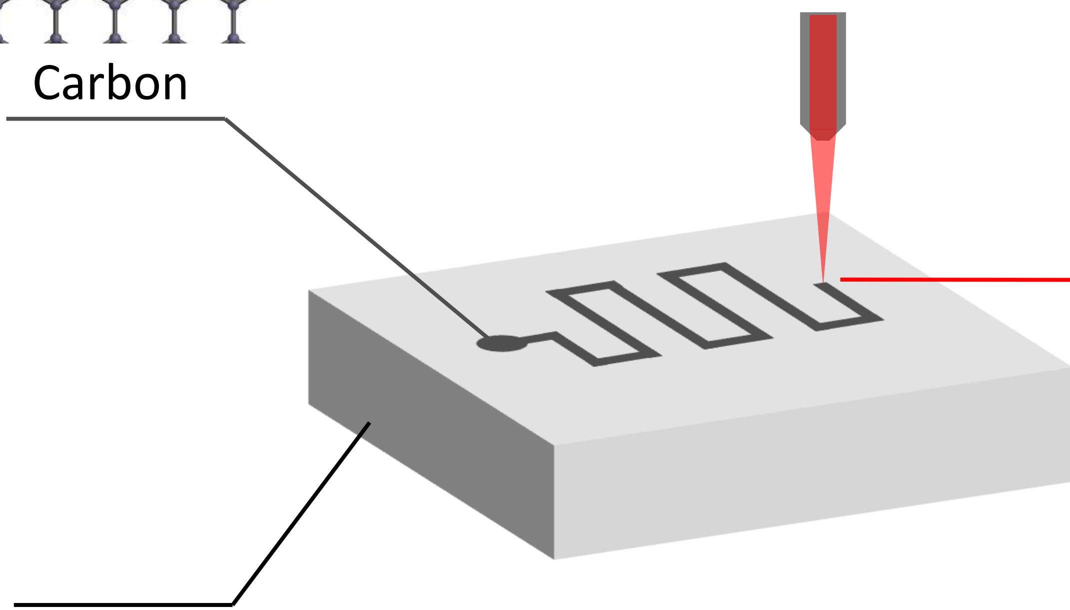
YOUTUBE VIDEO (Undecided_Matt Ferrell)

https://youtu.be/QEAmTvan0EU

NEW APPROACH: LASER INDUCED GRAPHENE (LIG)

laser-scribing graphene conductors into polymer precursors





Laser Induced Pyrolysis

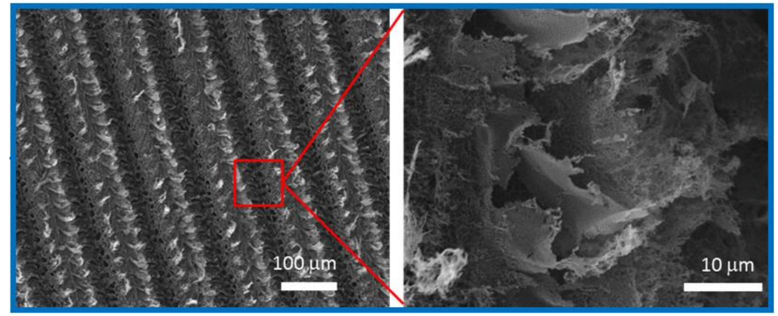
Laser Induced Graphene
LIG

J. Lin, J. M. Tour, *et al., Nature Commun.* 5, 5714 **2014**

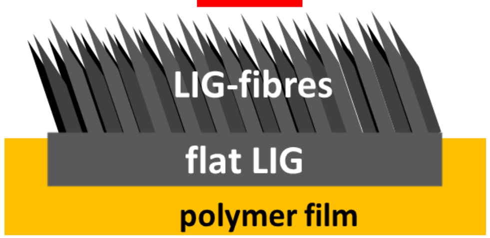
TUNING LASER INDUCED GRAPHENE (LIG)

LIG P

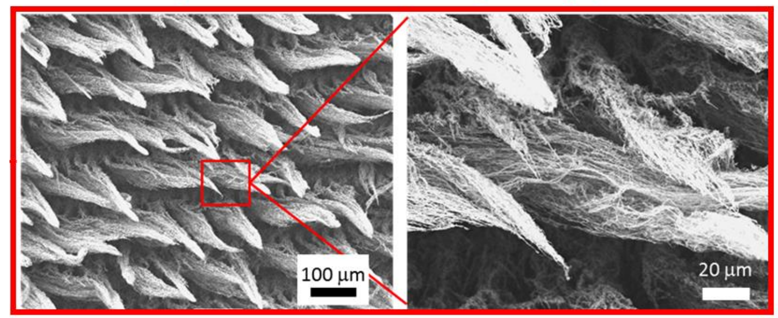
Porous structure(LIG-P)



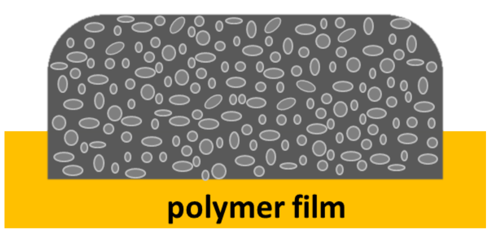
LIG F



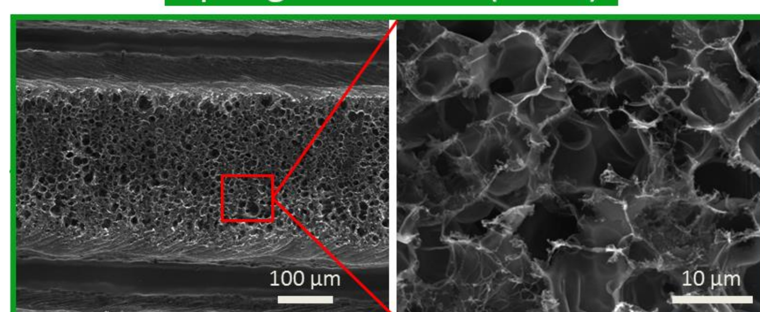
Fiber structure (LIG-F)



LIG S



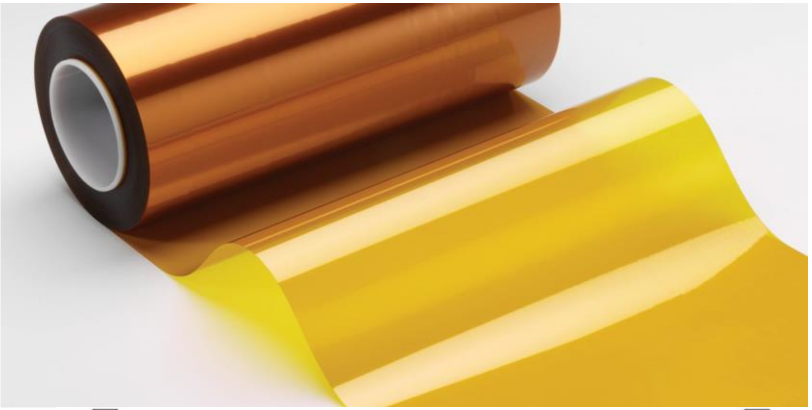
Sponge structure (LIG-S)

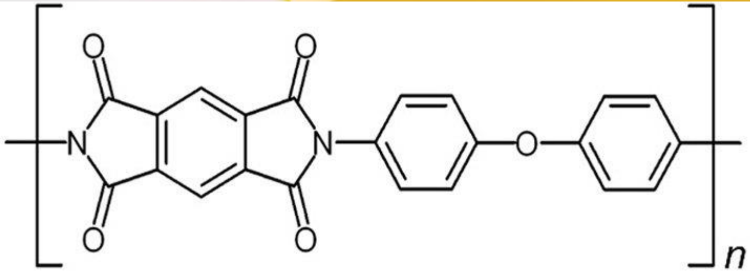


A. Dallinger, K. Keller, H. Fitzek F. Greco *ACS Appl. Mater. Interfaces* **2020**, 12, 17, 19855-19865

Standard LIG precursor

- Polyimide film
  - Kapton ®

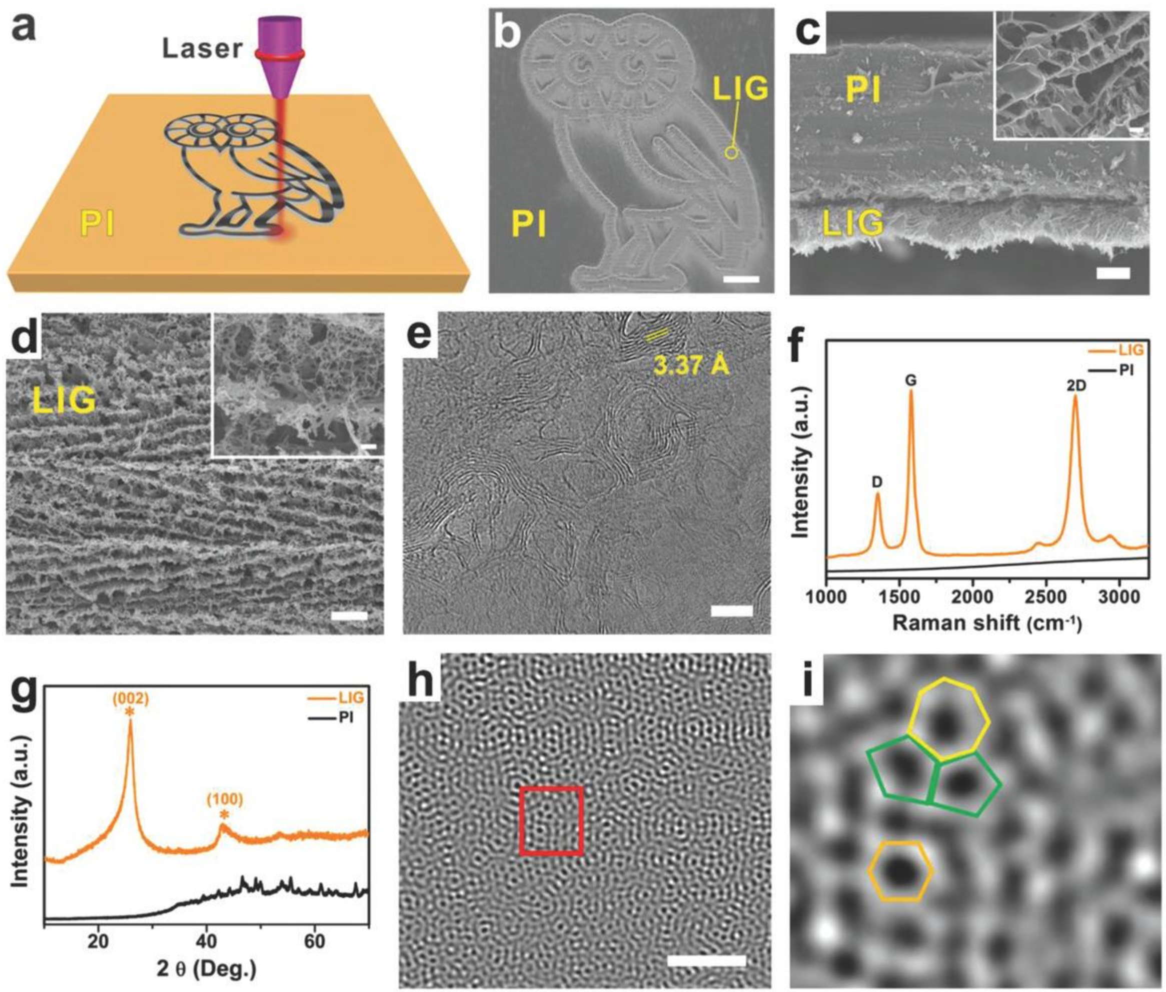




- Other synthetic and bio-derived precursors:
  BUT in some cases require inert atmosphere, or addition of flame/retardants, catalysts (e.g. $Fe(NO_3)_3$)

LASER INDUCED GRAPHENE (LIG)

- LIG from polyimide (PI)
- accidental discovery! Tour Group, Rice Univ. 2014



MORE ON LIG
& soft LIG-based
sensors/actuators
in following lectures !

J. Lin, J. M. Tour, *et al., Nature Commun.* 5, 5714 **2014**

CARBON

YOUTUBE & TEDED VIDEO (Periodic Videos-Univ Nottingham) (10:03)

[Carbon - Periodic Table of Videos - YouTube]

L6.6

BIOCERAMICS

BIOCERAMICS

- biomedical applications: main use in implants (bones, teeth,..)
- desirable properties: chemical inertness, hardness, wear resistance, and low coefficient of friction;
- crystalline oxide materials, glasses, and glass-ceramics

Al_2O_3 : alumina

YSZ: Yttria Stabilized- Zirconia (ZrO_2)

Calcium Phosphate materials

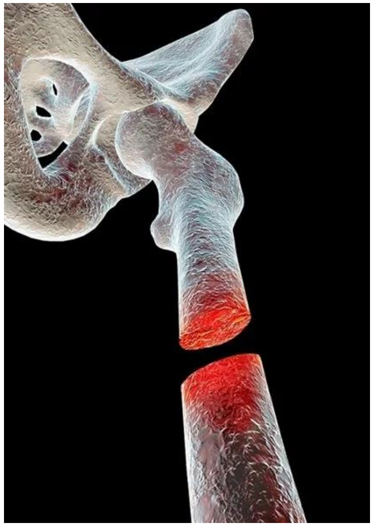
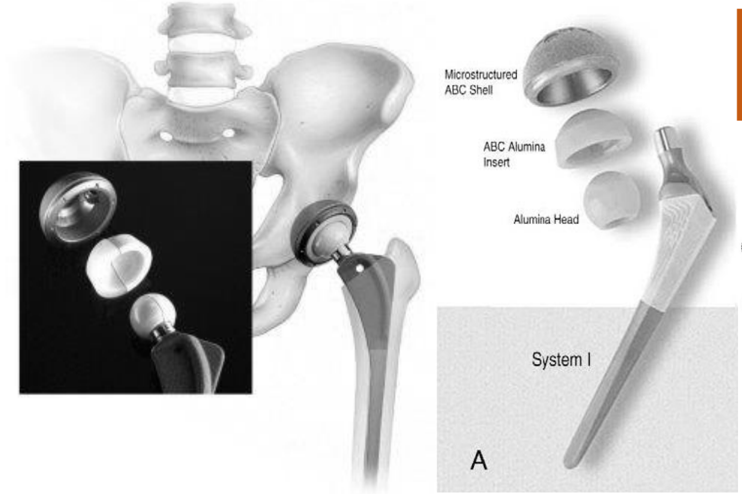
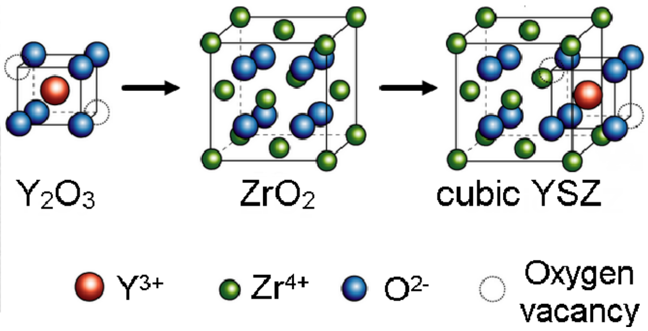


Image Credits: Naeblys/shutterstock.com

SEMINAR TOPIC 10	Zirconia and Alumina ceramics in Biomedicine/Bionics



https://doi.org/10.1016/j.arth.2008.06.003



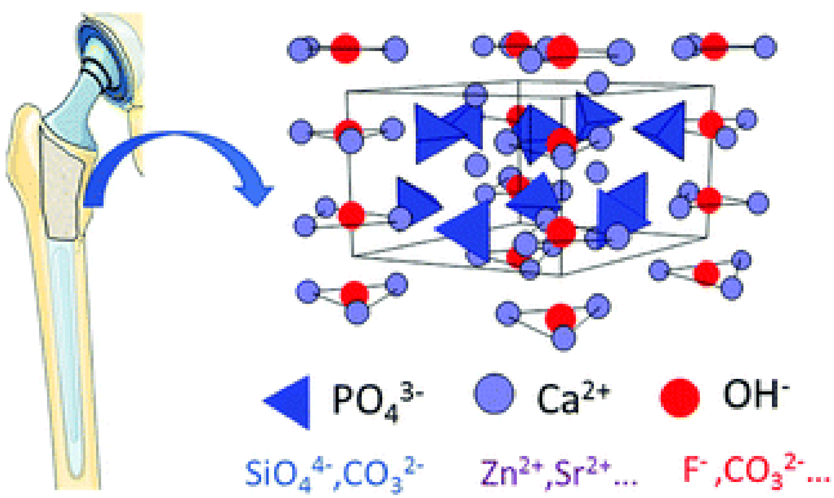
BIOCERAMICS

WAIKATO UNIV. NZ - [What are bioceramics and biomaterials? — Science Learning Hub]

Calcium Phosphate

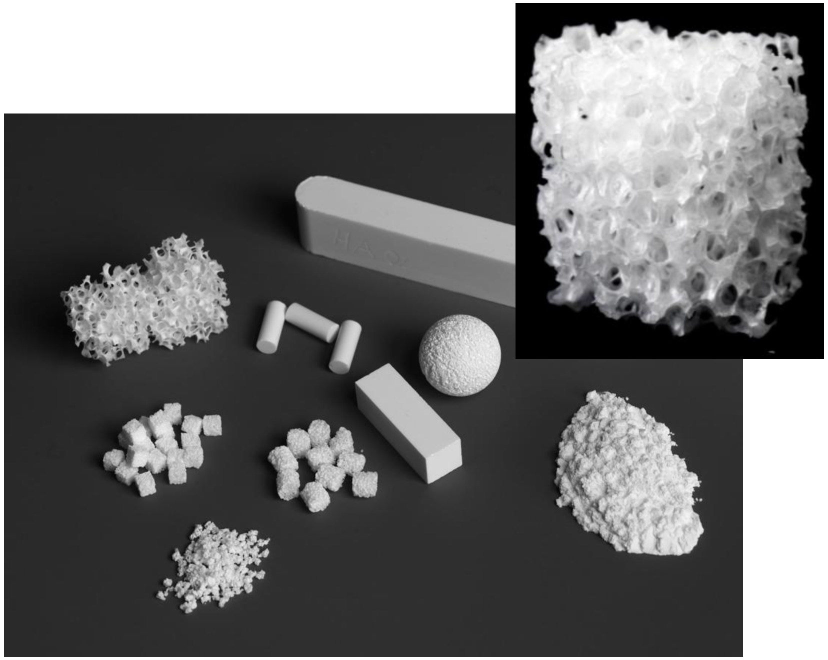
- implant material that is gradually infiltrated with and replaced by natural bone tissue during the healing process
- implant ultimately dissolves into the body of the host.
- Two types of calcium phosphate materials for resorbable implants:

  TCP - tricalcium phosphate $Ca_3(PO_4)_2$ HAP - hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$
- also used for implantable drug-delivery systems.



HAP coating of bone implants

from: D. Arcos et al. J. Mat Chem B, 2020, https://doi.org/10.1039/C9TB02710F



Source: https://www.cambioceramics.com/products/#blcks

BIOCERAMICS USES

Table 1: Bioceramics Applications[12]

Devices	Function	Biomaterial
Artificial total hip, knee, shoulder, elbow, wrist	Reconstruct arthritic or fractured joints	High-density alumina, metal bioglass coatings
Bone plates, screws, wires	Repair fractures	Bioglass-metal fibre composite, Polysulphone-carbon fibre composite
Intramedullary nails	Align fractures	Bioglass-metal fibre composite, Polysulphone-carbon fibre composite
Harrington rods	Correct chronic spinal curvature	Bioglass-metal fibre composite, Polysulphone-carbon fibre composite
Permanently implanted artificial limbs	Replace missing extremities	Bioglass-metal fibre composite, Polysulphone-carbon fibre composite
Vertebrae Spacers and extensors	Correct congenital deformity	Al_2O_3
Spinal fusion	Immobilise vertebrae to protect spinal cord	Bioglass
Alveolar bone replacements, mandibular reconstruction	Restore the alveolar ridge to improve denture fit	Polytetra fluro ethylene (PTFE) - carbon composite, Porous Al_2O_3, Bioglass, dense-apatite
End osseous tooth replacement implants	Replace diseased, damaged or loosened teeth	Al_2O_3, Bioglass, dense hydroxyapatite, vitreous carbon
Orthodontic anchors	Provide posts for stress application required to change deformities	Bioglass-coated Al_2O_3, Bioglass coated vitallium

Source: Wikipedia,
data taken from: Thamaraiselvi, T., and S. Rajeswari. "Biological evaluation of bioceramic materials-a review." *Carbon* 24.31 (2004): 172.

BIOCERAMIC PROPERTIES

Table 2: Mechanical Properties of Ceramic Biomaterials[12]

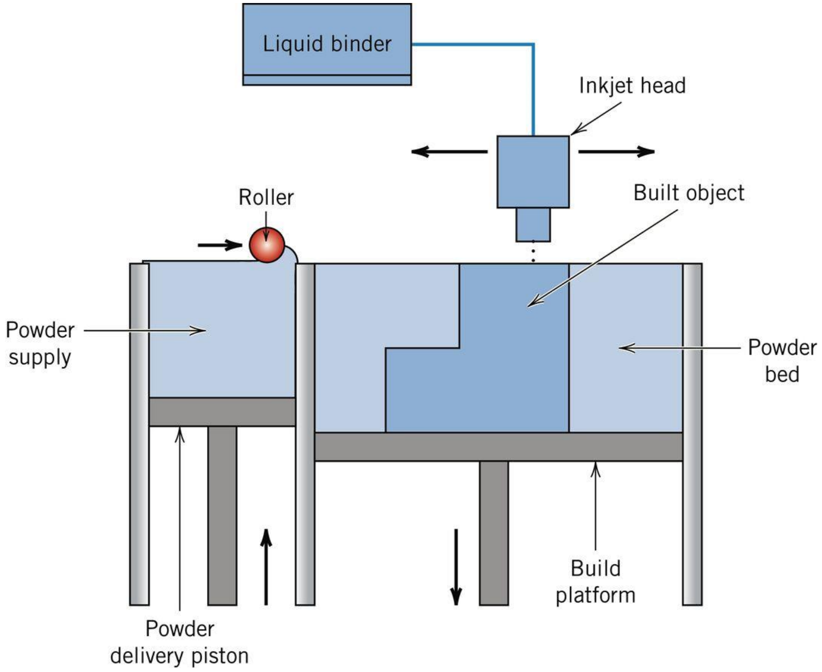
Material	Young's Modulus (GPa)	Compressive Strength (MPa)	Bond strength (GPa)	Hardness	Density (g/cm^3)
Inert Al_2O_3	380	4000	300-400	2000-3000(HV)	>3.9
ZrO_2 (PS)	150-200	2000	200-500	1000-3000(HV)	≈6.0
Graphite	20-25	138	NA	NA	1.5-1.9
(LTI)Pyrolitic Carbon	17-28	900	270-500	NA	1.7-2.2
Vitreous Carbon	24-31	172	70-207	150-200(DPH)	1.4-1.6
Bioactive HAP	73-117	600	120	350	3.1
Bioglass	≈75	1000	50	NA	2.5
AW Glass Ceramic	118	1080	215	680	2.8
Bone	3-30	130-180	60-160	NA	NA

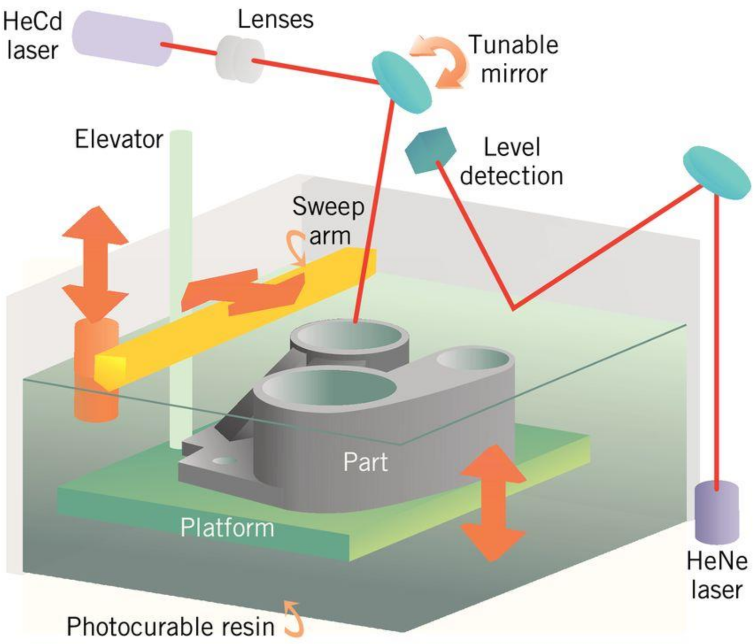
The variation in Young's Modulus noted for some of the materials listed is due to variation in density of test specimens. PS - Partially Stabilized; HA - Hydroxyapatite; NA - Not Available; AW - Apatite-Wallastonite; HV - Vickers Hardness; DPH - Diamond Pyramid Hardness

Source: Wikipedia,
data taken from: Thamaraiselvi, T., and S. Rajeswari. "Biological evaluation of bioceramic materials-a review." *Carbon* 24.31 (2004): 172.

3D Printing of Ceramics

- more about this (and other 3d printing/additive manufacturing techniques) in a **dedicated LESSON**





© I. A. Aksay, R. Garg, and D. M. Dabbs, Princeton University.

3D PRINTED BIOCERAMICS

YOUTUBE VIDEO (channel «Additive Manufacturing») (12:57)

3D Printed Bioceramics for Bone Replacement: The Cool Parts Show S3E2 - YouTube

Y-STABILIZED ZIRCONIA

HOME ASSIGNMENT

- how can you tell the difference between a real and a fake diamond?

YOUTUBE VIDEO (channel «Mat Sci Guy») (08:24)

[The Story of Cubic Zirconia: Far More than just Fake Diamond - YouTube]

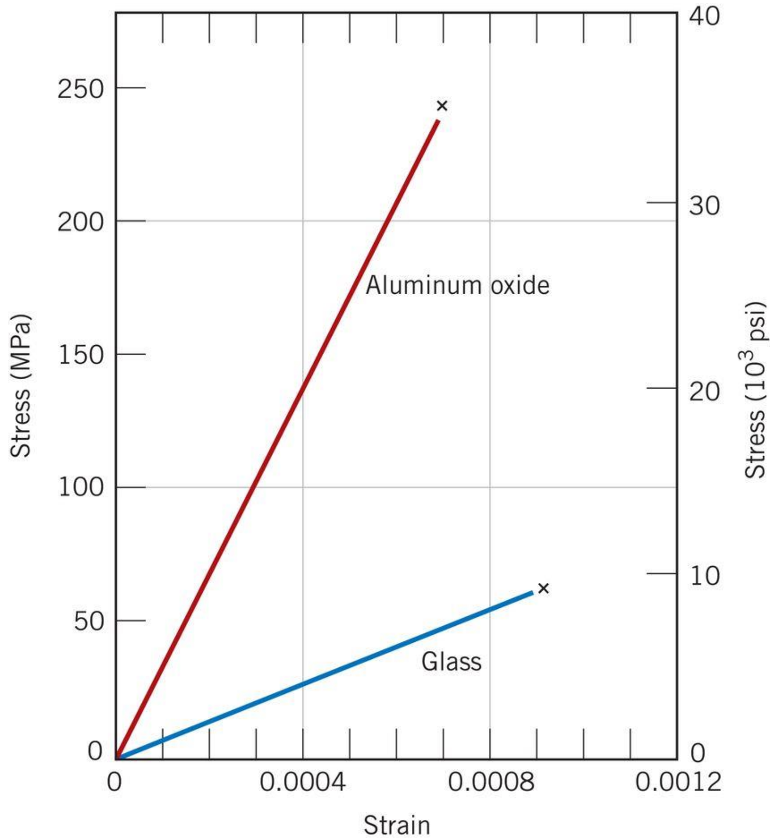
L6.7

MECH PROPERTIES OF CERAMICS

Mechanical Properties

- more brittle than metals: break at ε ≈ 0.1%
- E = 70 – 500 GPa

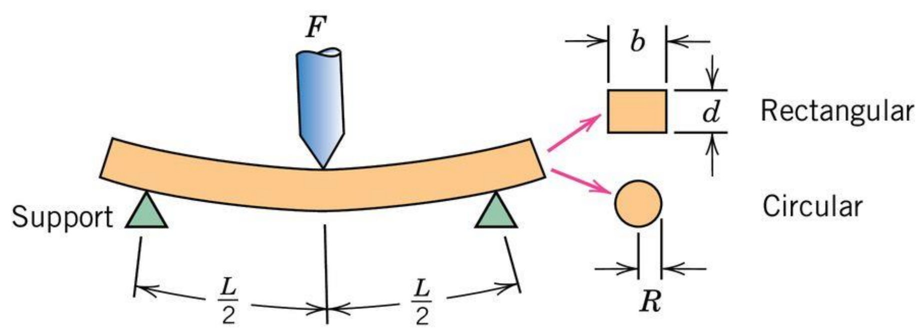
elastic behaviour



Flexural Tests – Measurement of Elastic Modulus

- RT behavior is usually elastic, with brittle failure
- 3-Point Bend Testing often used - tensile tests are difficult for brittle materials

Possible cross sections



$$\sigma = \text{stress} = \frac{Mc}{I}$$

where M = maximum bending moment
c = distance from center of specimen to outer fibers
I = moment of inertia of cross section
F = applied load

	M	c	I	σ
Rectangular	$\frac{FL}{4}$	$\frac{d}{2}$	$\frac{bd^3}{12}$	$\frac{3FL}{2bd^2}$
Circular	$\frac{FL}{4}$	R	$\frac{\pi R^4}{4}$	$\frac{FL}{\pi R^3}$

Mechanical Properties

Table 12.5 **Tabulation of Flexural Strength (Modulus of Rupture) and Modulus of Elasticity for Ten Common Ceramic Materials**

	Flexural Strength		**Modulus of Elasticity**	
Material	**MPa**	**ksi**	**GPa**	**10^6 psi**
Silicon nitride (Si_3N_4)	250–1000	35–145	304	44
Zirconia[a] (ZrO_2)	800–1500	115–215	205	30
Silicon carbide (SiC)	100–820	15–120	345	50
Aluminum oxide (Al_2O_3)	275–700	40–100	393	57
Glass-ceramic (Pyroceram)	247	36	120	17
Mullite ($3Al_2O_3$–$2SiO_2$)	185	27	145	21
Spinel ($MgAl_2O_4$)	110–245	16–35.5	260	38
Magnesium oxide (MgO)	105[b]	15[b]	225	33
Fused silica (SiO_2)	110	16	73	11
Soda-lime glass	69	10	69	10

[a] Partially stabilized with 3 mol% Y_2O_3.
[b] Sintered and containing approximately 5% porosity.

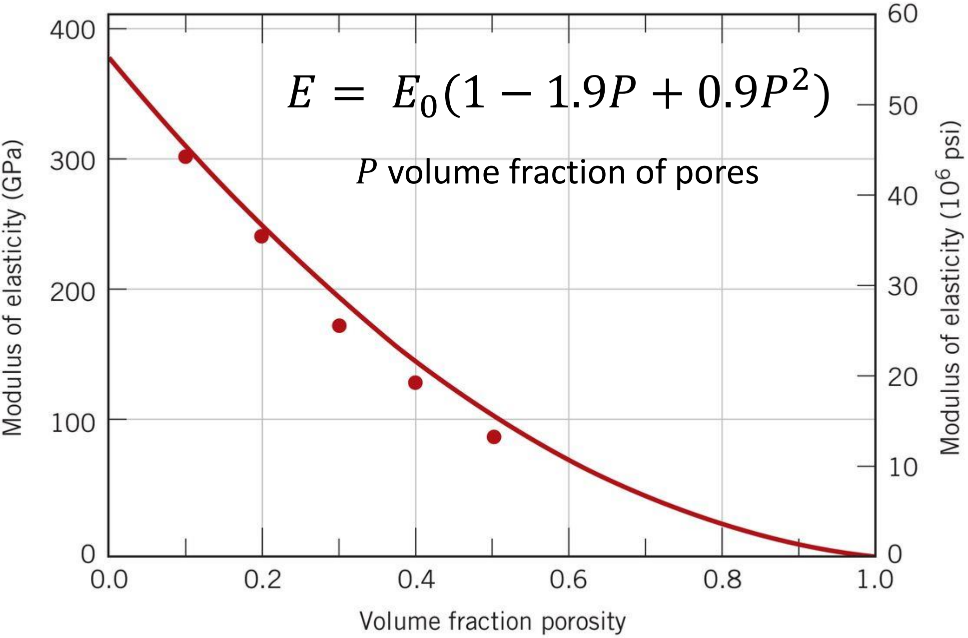
Mechanical Properties

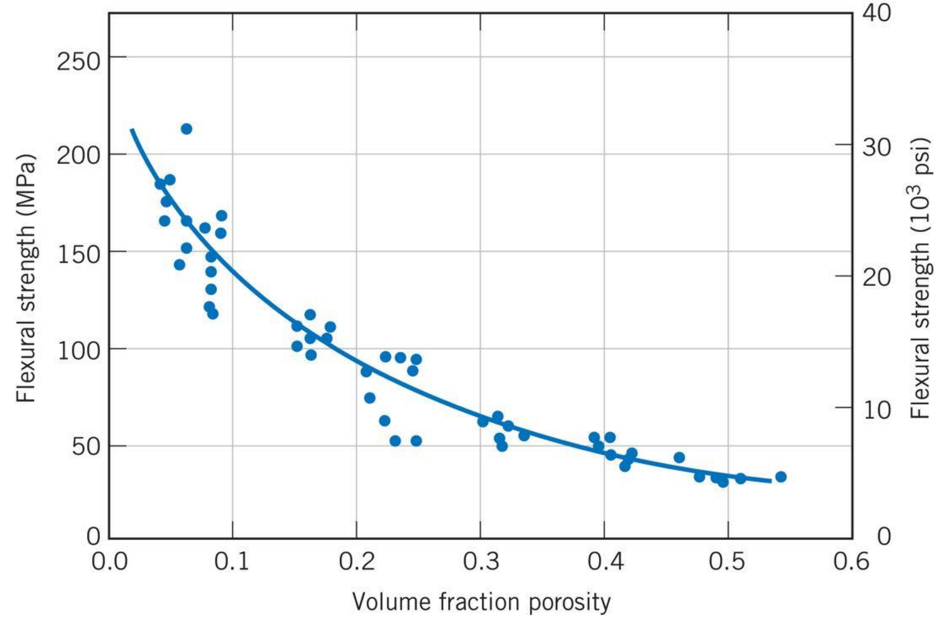
Porous ceramics

Pores

- reduction of real section resistant to load
- stress concentrators

example: porous Aluminum oxide (@RT)





SUMMARY L6

L6.1 • Structures and properties of ceramics

L6.2 • Piezoceramics

L6.3 • Oxide Structures, Packing of Anions, Glass

L6.4 • Semiconductors, SiC

L6.5 • Carbon Polymorphs

L6.6 • Bioceramics

L6.7 • Mech Properties of Ceramics

READINGS

READINGS:

- Callister Rethwisch – Chapters 12, 13

Network Covalent Solids

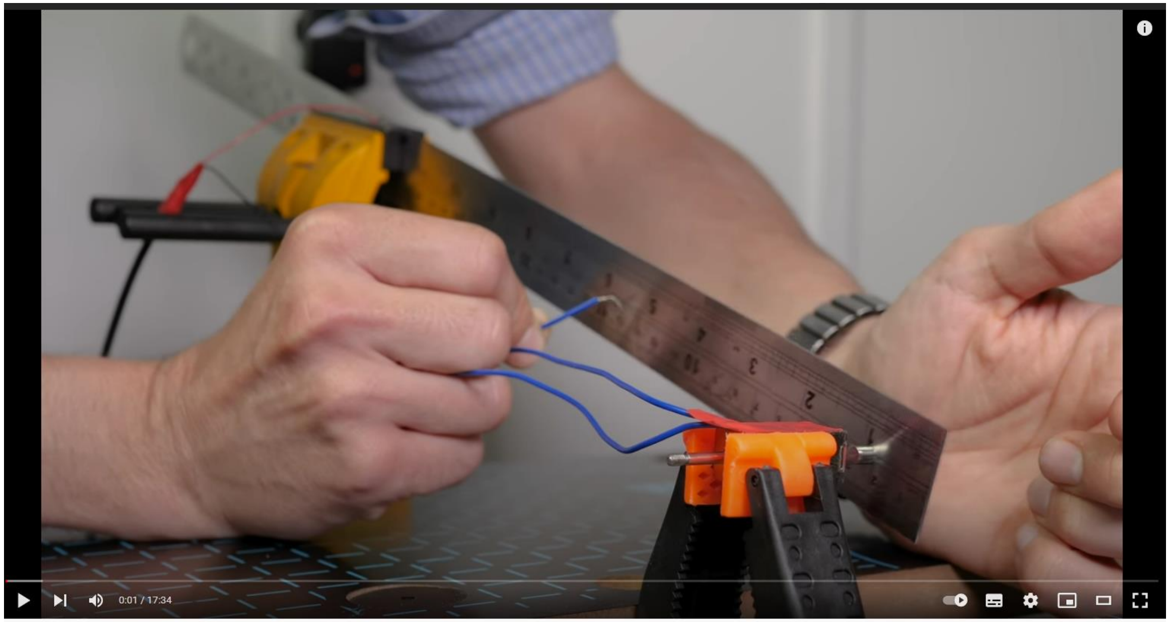
Network Covalent solids

JoVE VIDEO

https://www.jove.com/it/science-education/11358/network-covalent-solids

ADDITIONAL RESOURCES

- connected to video about piezoelectricity and piezoelectric crystals



How a quartz watch works - its heart beats 32,768 times a second

YOUTUBE VIDEO (Steve Mould channel)

https://youtu.be/_2By2ane2I4

ADDITIONAL RESOURCES

Silicon Carbide, it's all about the Bandgap!

YOUTUBE VIDEO (ST Microelectronics)

https://youtu.be/hV5mqmuozlA

ADDITIONAL RESOURCES

Wolfspeed Silicon Carbide 101

YOUTUBE VIDEO (Wolfspeed Inc.)

https://youtu.be/kcWKDYmk5qY

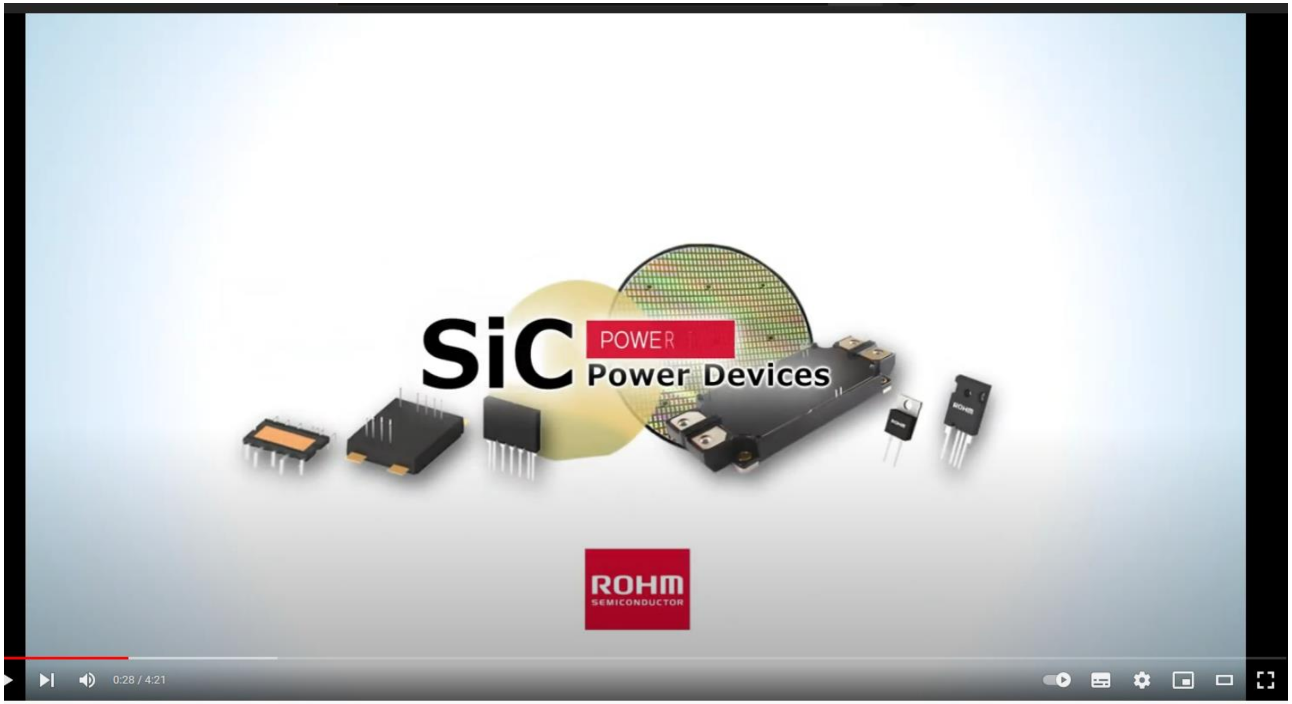
ADDITIONAL RESOURCES

Growth of SiC crystals

YOUTUBE VIDEO (ROHM Semiconductors Europe)

https://youtu.be/LeHE-7KmVvE

ADDITIONAL RESOURCES



Power the Future with ROHM's SiC Power Devices

YOUTUBE VIDEO (ROHM Semiconductors Europe)

https://youtu.be/r6FLeK8QRss

ADDITIONAL RESOURCES

How Carbon Nanotubes will change the world

YOUTUBE VIDEO (Real Engineering)

https://youtu.be/SIif11QOsRI

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ADDITIONAL RESOURCES

Webinar | The Benefits of Ceramics for AM Applications

YOUTUBE VIDEO (LITHOZ)

52 min !!!

https://youtu.be/CVLWb6JnH4E