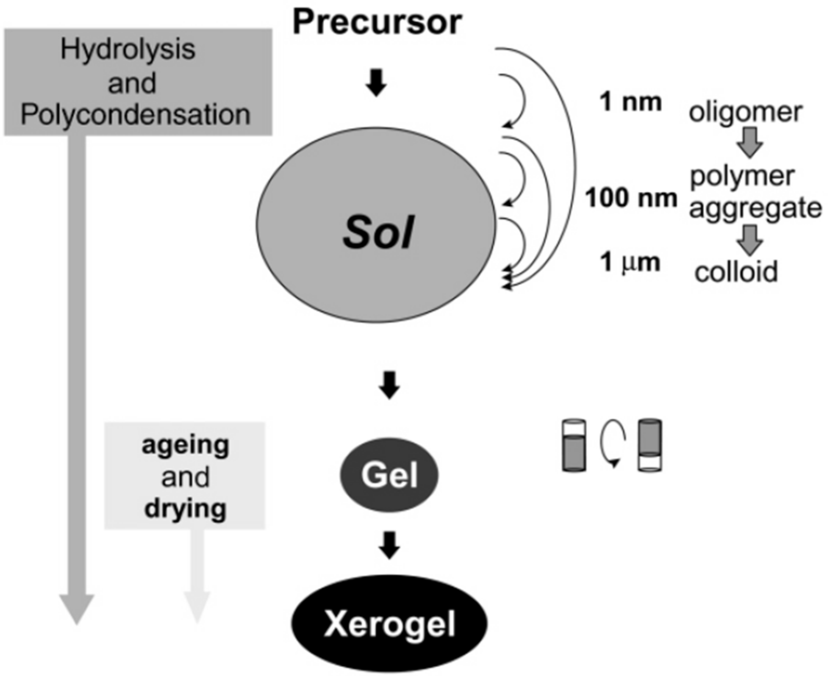
Sol-Gel Methods

PRECURSOR

Sol-gel process

- **Hydrolysis**
- **Polycondensation**
- **Gelation**
- **Ageing**
- **Drying**
- **Densification**



Powders: microcrystalline, nanocrystalline, amorphous

Monoliths, Coatings, Films, Fibers

Xerogels, Aerogels, Ionogels, Cryogels

Glasses, Ceramics, Hybrid materials

Sol-Gel Methods

Sol = a fluid system of stable suspension of colloidal (1 nm – 1 μm) solid particles or polymeric molecules in a liquid

(Below 1 μm – Brownian motion, larger than 1 μm – sedimentation)

Gel = nonfluid, porous, three-dimensional, continuous solid network (elastic or rigid) surrounded by a continuous liquid phase

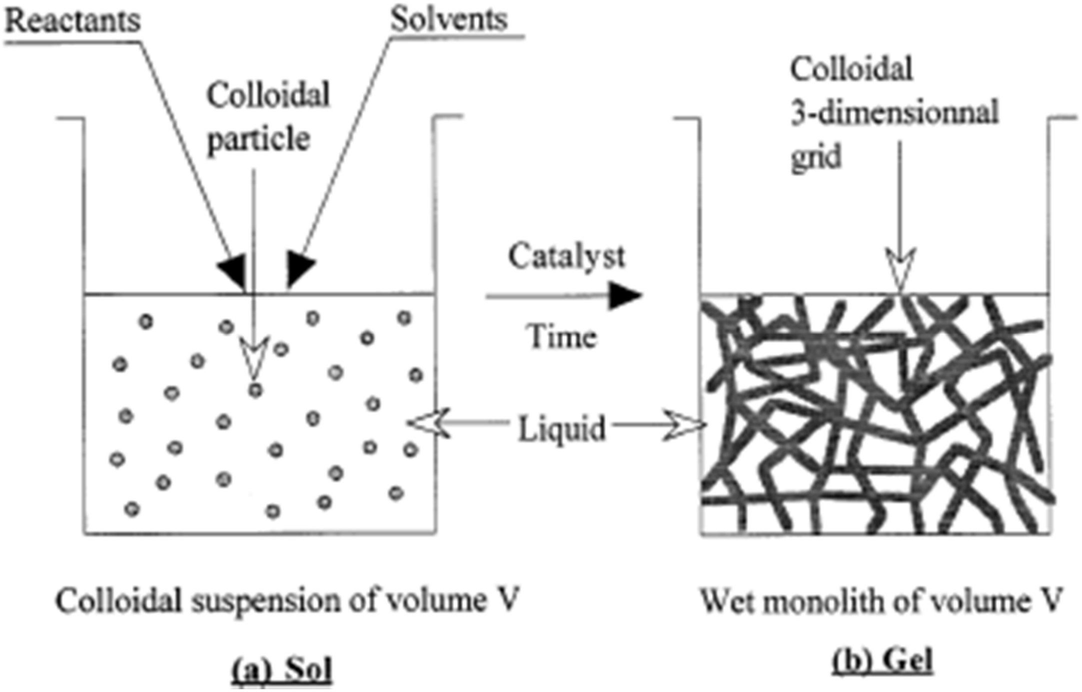
Colloidal (particulate) gels = agglomeration of dense colloidal particles

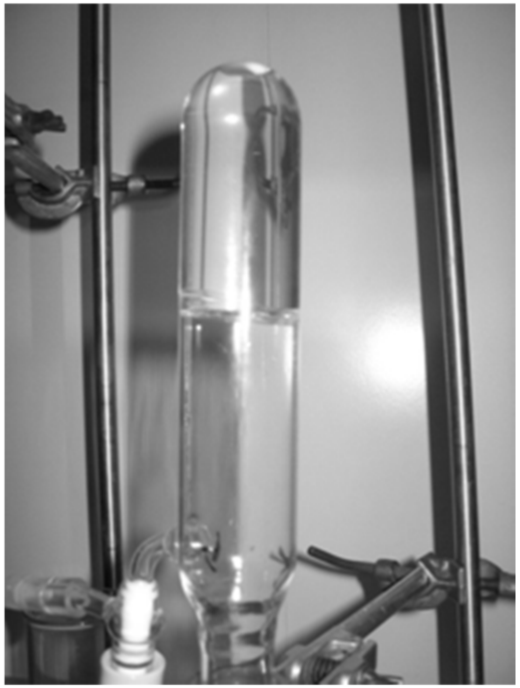
Polymeric gels = agglomeration of polymeric particles made from subcolloidal units

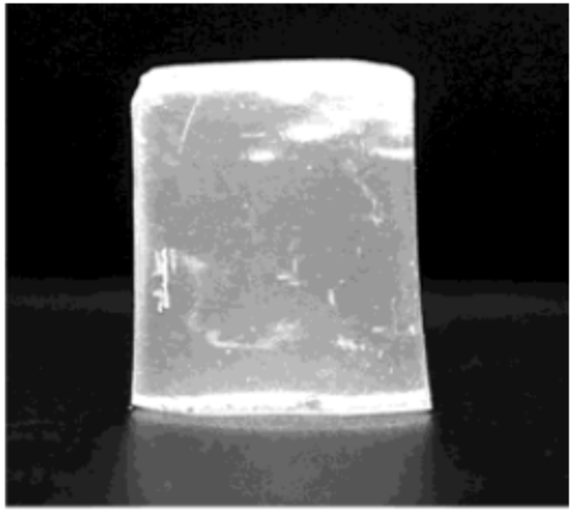
Agglomerate = assemblage of particles rigidly joined together, as by partial fusion (sintering) or by growing together, covalent bonds, hydrogen bonds, polymeric chain entanglement

Aggregate = assemblage of particles which are loosely coherent, van der Walls forces

Sol and Gel





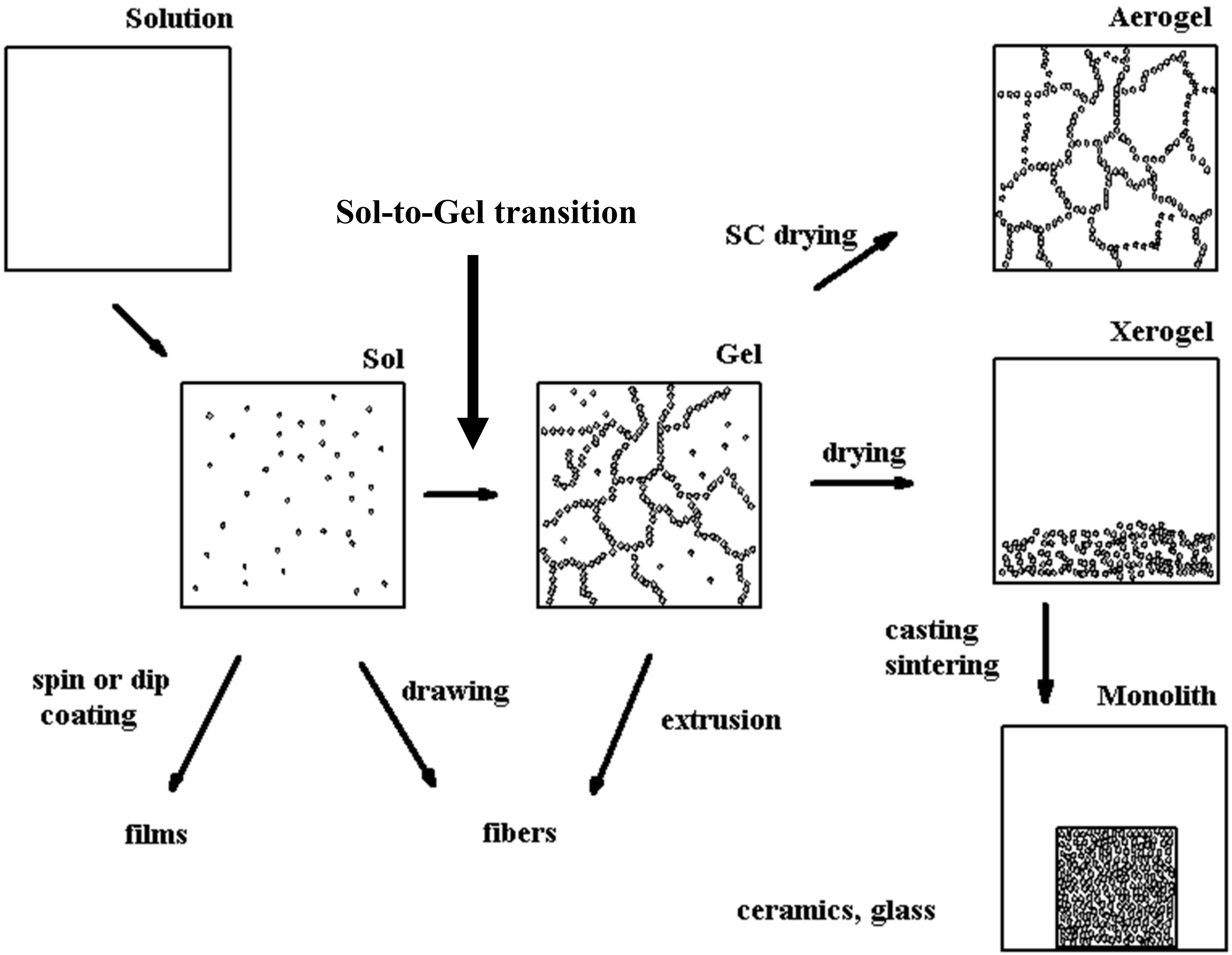


Gel point = point of incipient network formation

Sol-to-Gel transition is difficult to define

Rheological methods = viscosity increases

Sol-Gel Process



Solution

Sol

Sol-to-Gel transition

Gel

SC drying

Aerogel

drying

Xerogel

casting
sintering

Monolith

ceramics, glass

spin or dip
coating

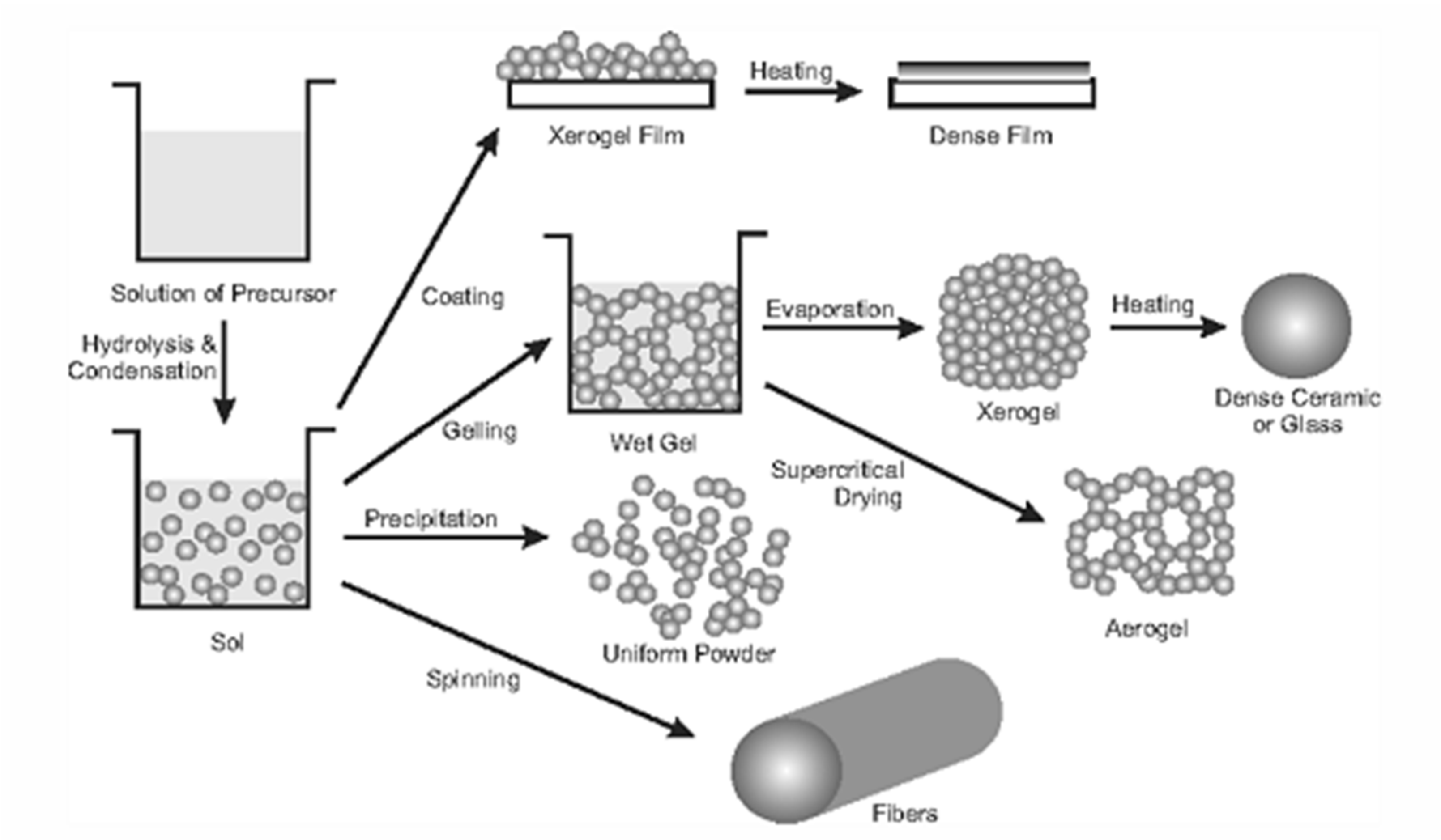
films

drawing

extrusion

fibers

Sol-Gel Methods



Sol-Gel Chemistry

Aqueous

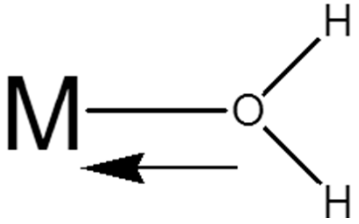
- **Colloid Route – inorganic salts, water glass, pH, hydrolysis, polycondensation**
- **Metal-Oragnic Route – metal alkoxides, amides, hydrolysis, polycondensation**
- **Pechini and Citrate Gel Method – inorganic metal salts, complexing agent, chelate formation, polyesterification with polyfunctional alcohol**

Nonaqueous

- **Hydroxylation**
- **Heterofunctional Condensations**

Colloid Route

Metal salts in aqueous solution, pH and temperature control



Solvation – water molecule becomes more acidic

$M^{z+} + :OH_2 \rightarrow [M \leftarrow OH_2]^{z+}$

For transition metal cations, charge transfer occurs from the filled bonding orbital of the water molecule to the empty d orbitals of the transition metal. Therefore, the partial positive charge on the H of water molecule increases, making the water molecule more acidic.

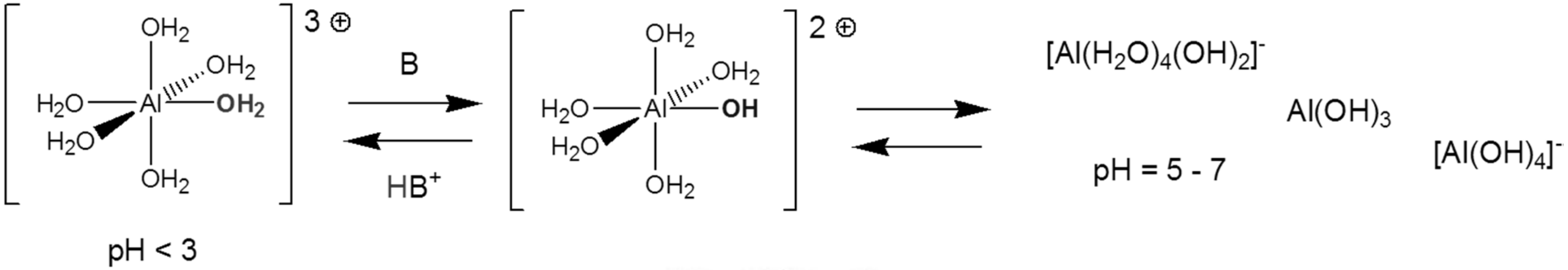
Hydrolysis

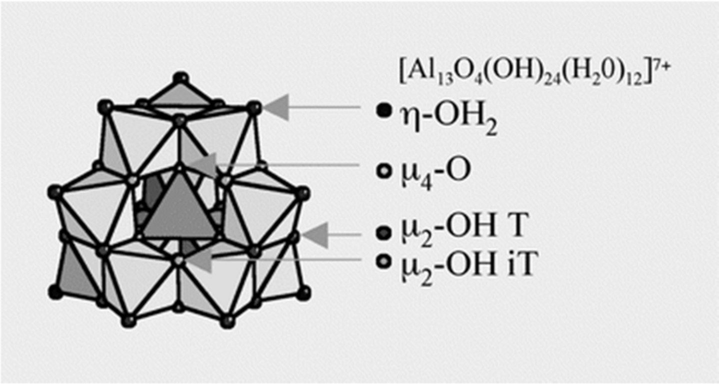
$[M(H_2O)_b]^{Z+} \rightleftarrows [M(H_2O)_{b-1}OH]^{(Z-1)+} + H^+$

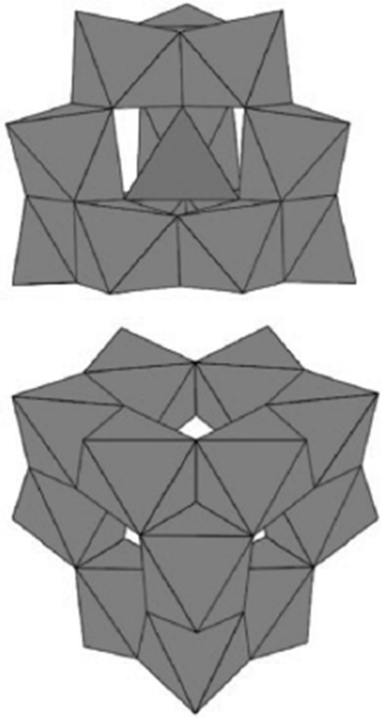
Condensation-polymerization

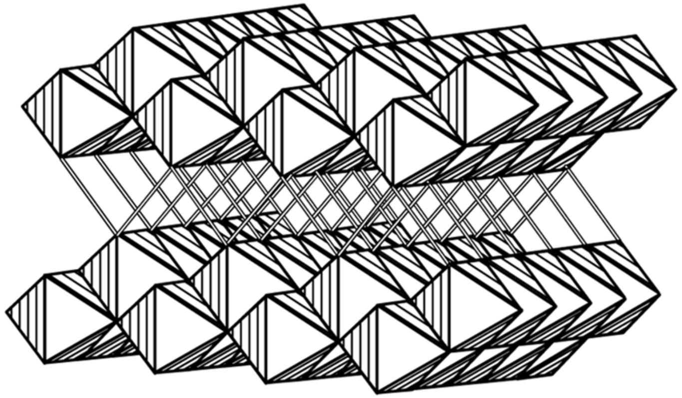
$[M(H_2O)_b]^{Z+} \rightleftarrows [(H_2O)_{b-1}M(OH)_2M(H_2O)_{b-1}]^{(2Z-2)+} + 2H^+$

Colloid Route









the Keggin cation
$[Al_{13}O_4(OH)_{24}(OH_2)_{12}]^{7+}$

Gibbsite
$Al(OH)_3$

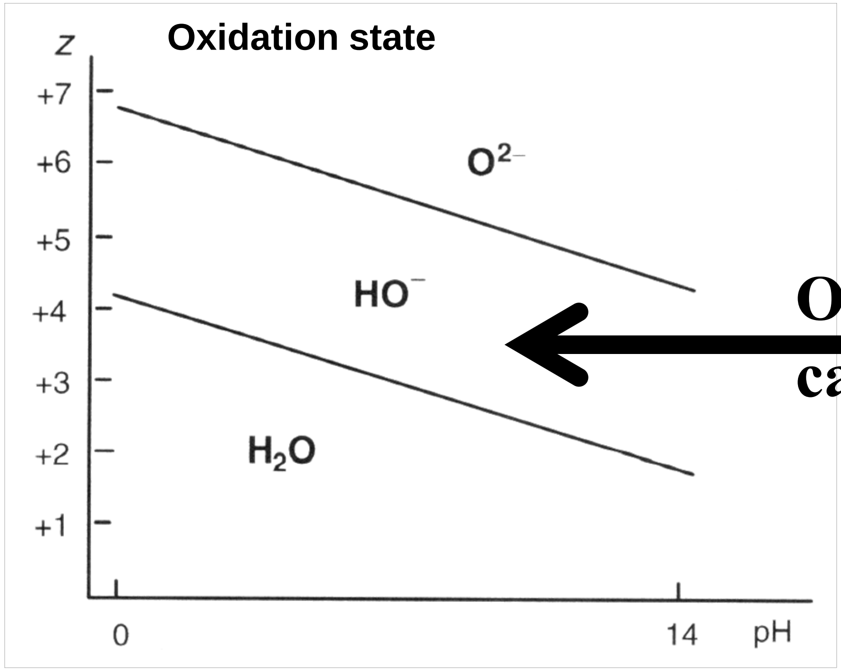
Colloid Route

Depending on the water acidity and the charge transfer, the following equilibria are established:

$$[M(OH_2)]^{z+} \rightleftarrows [M{-}OH]^{(z-1)+} + H^+ \rightleftarrows [M{=}O]^{(z-2)+} + 2\ H^+$$

Aqua **Hydroxo** **Oxo**

Composition of complexes depends on:
- nature of transition metal
- oxidation state
- charge
- ionic radius
- electronegativity
- nature of ligands
- coordination abilities
- pH of solution



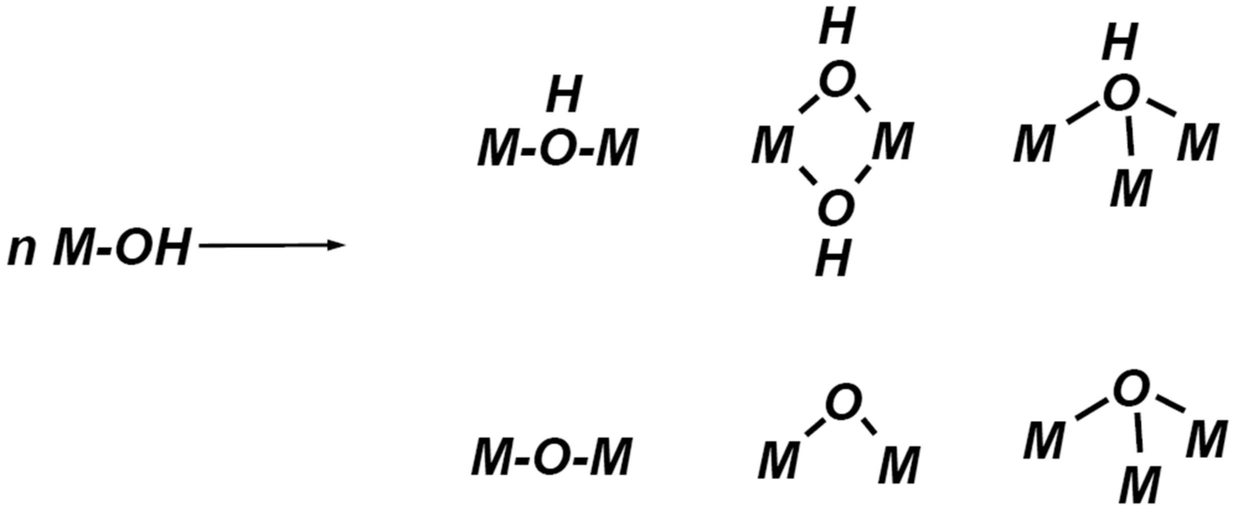
Only hydroxo can condense

Colloid Route

Only hydroxo groups can condense

Olation

= a hydroxo bridge (-OH- “ol” bridge) is formed between two metals centers



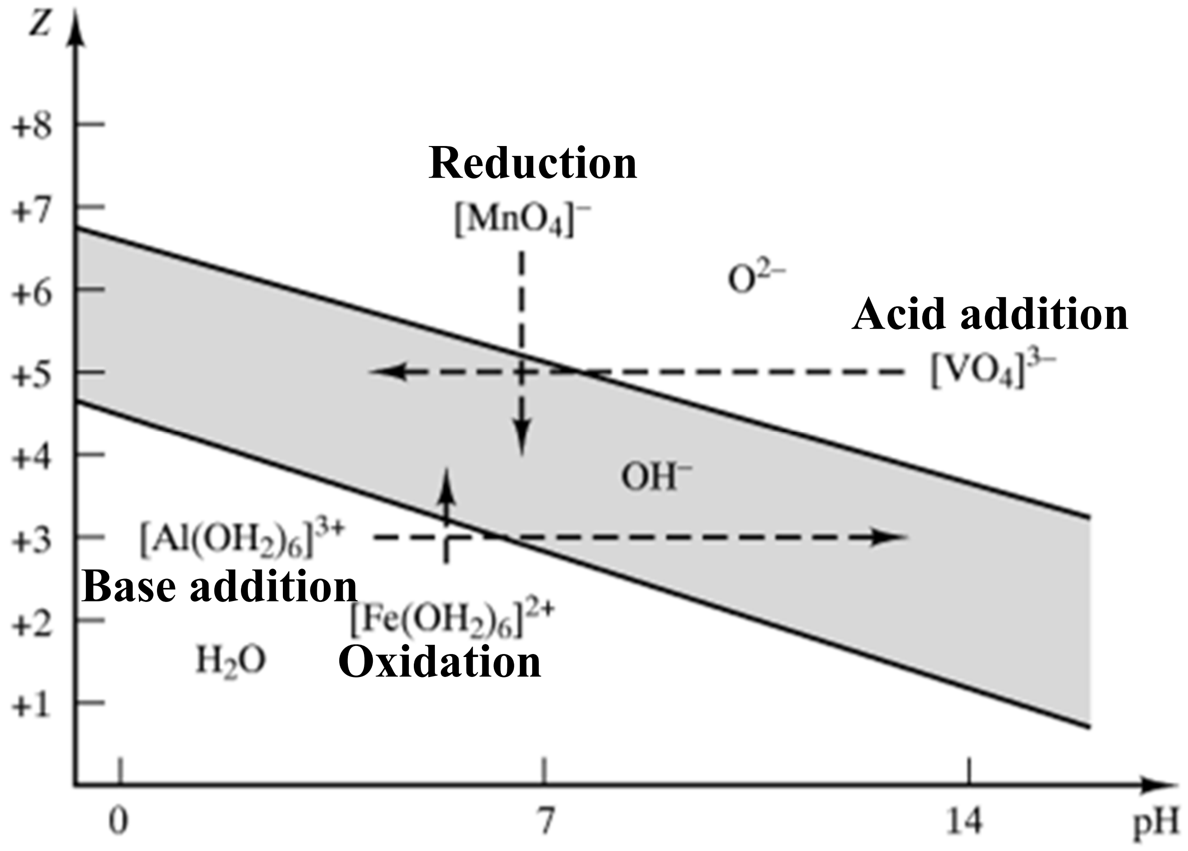
Oxolation

= an oxo bridge (–O–) is formed between two metals centers

$Fe^{2+}(aq) + CO_3^{2-} \rightarrow ?$

Colloid Route

$Fe^{3+}(aq) + CO_3^{2-} \rightarrow ?$

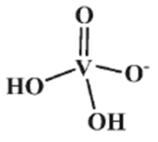


Colloid Route

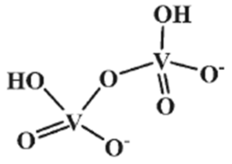
Electronegativity **Partial charges on ions and H_2O molecule**

Complex	χ	$\delta(M)$	$\delta(O)$	$\delta(H)$	$\delta(H_2O)$
$[Mn(OH_2)_6]^{2+}$	2.657	+0.59	−0.33	+0.28	+0.23
$[Cr(OH_2)_6]^{3+}$	2.762	+0.68	−0.29	+0.34	+0.39
$[Ti(OH_2)_6]^{4+}$	2.848	+0.98	−0.25	+0.38	+0.51
$[V(OH_2)_6]^{5+}$	2.983	+0.84	−0.20	+0.45	+0.70

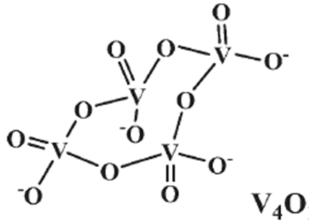
The higher a charge on ion, the more acidic coordinated waters are



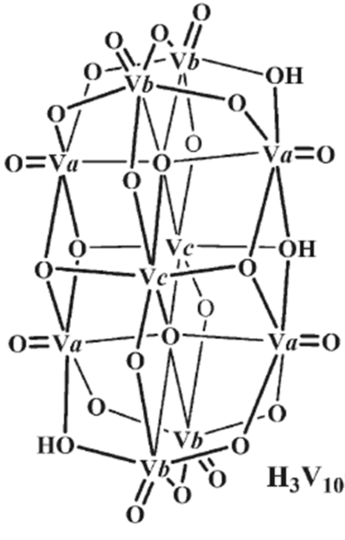
$H_2VO_4^-$



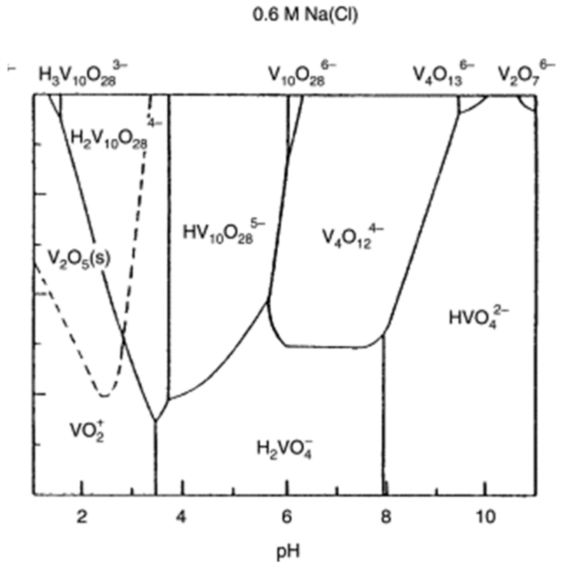
$H_2V_2O_7^{2-}$



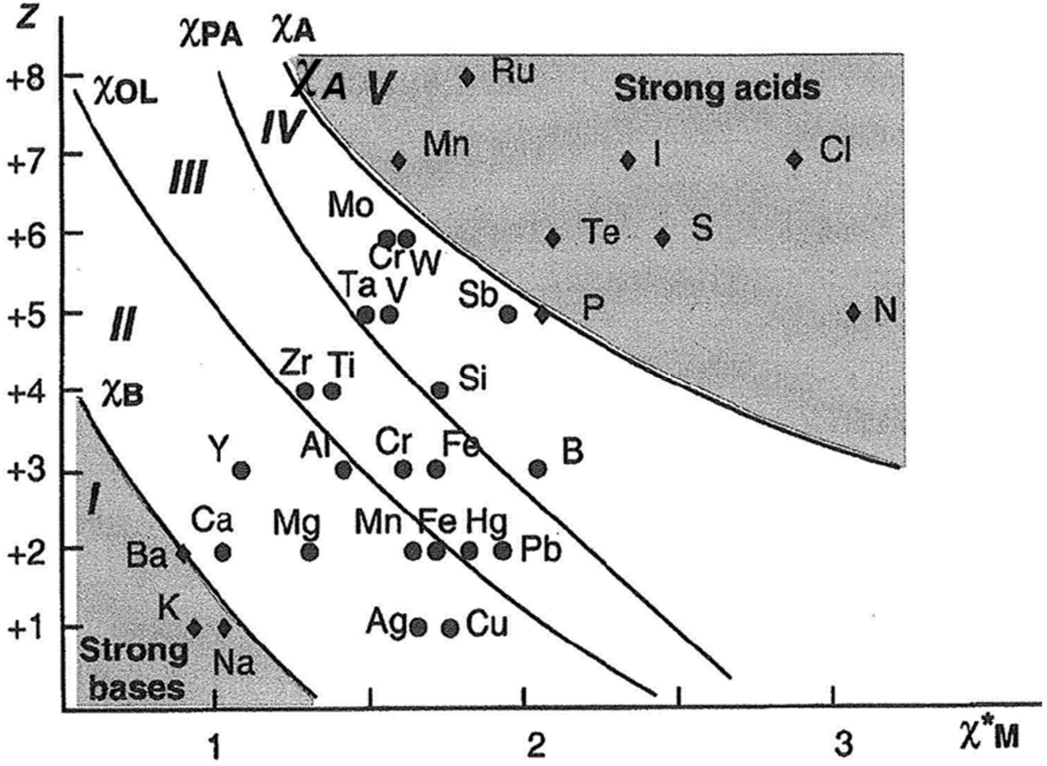
$V_4O_{12}^{4-}$



$H_3V_{10}O_{28}^{3-}$



Colloid Route



Electronegativity of a central atom

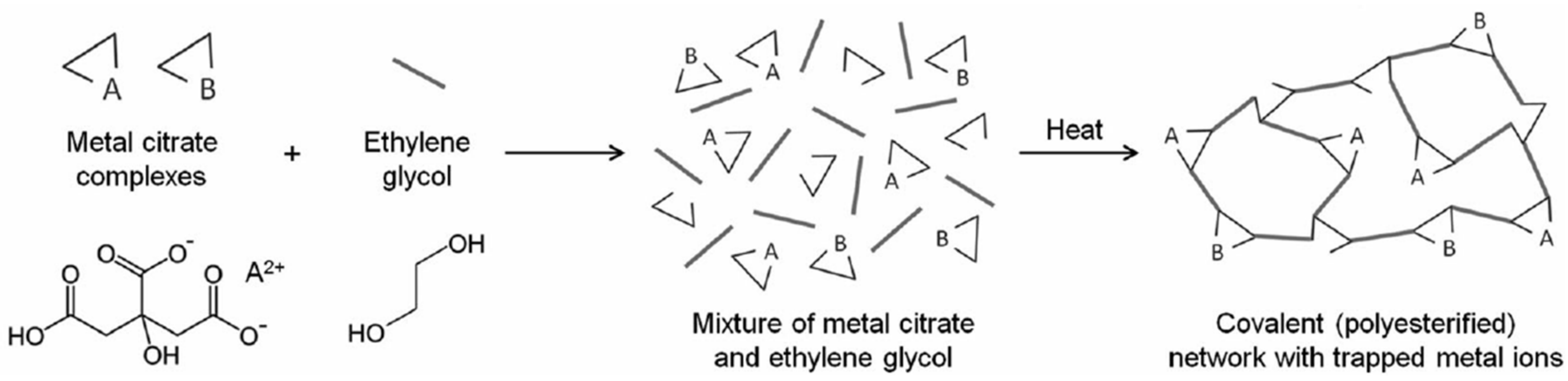
χ_M

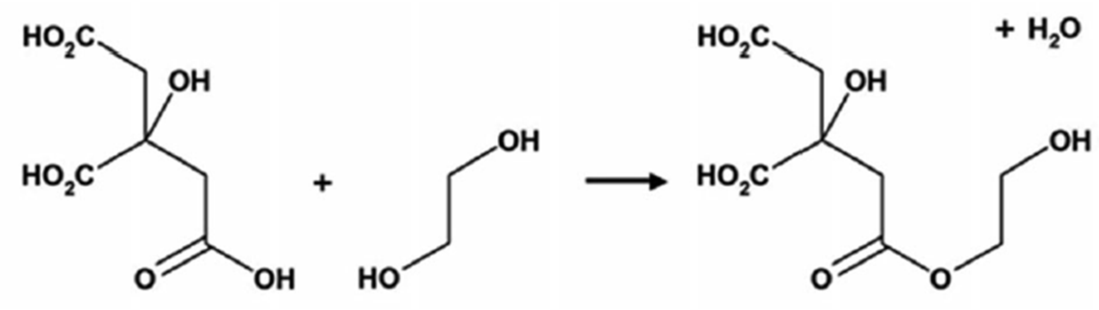
determines degree and mechanism of condensation for neutral hydroxo containing species

Area I : monomeric and soluble cations
Area II : condensation by olation
Area III : condensation by olation or oxolation
Area IV : condensation by oxolation
Area V : monomeric and soluble anions

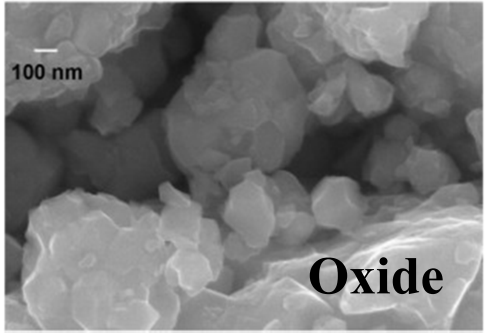
Pechini Sol-Gel Route

The transesterification reaction between citric acid and ethylene glycol





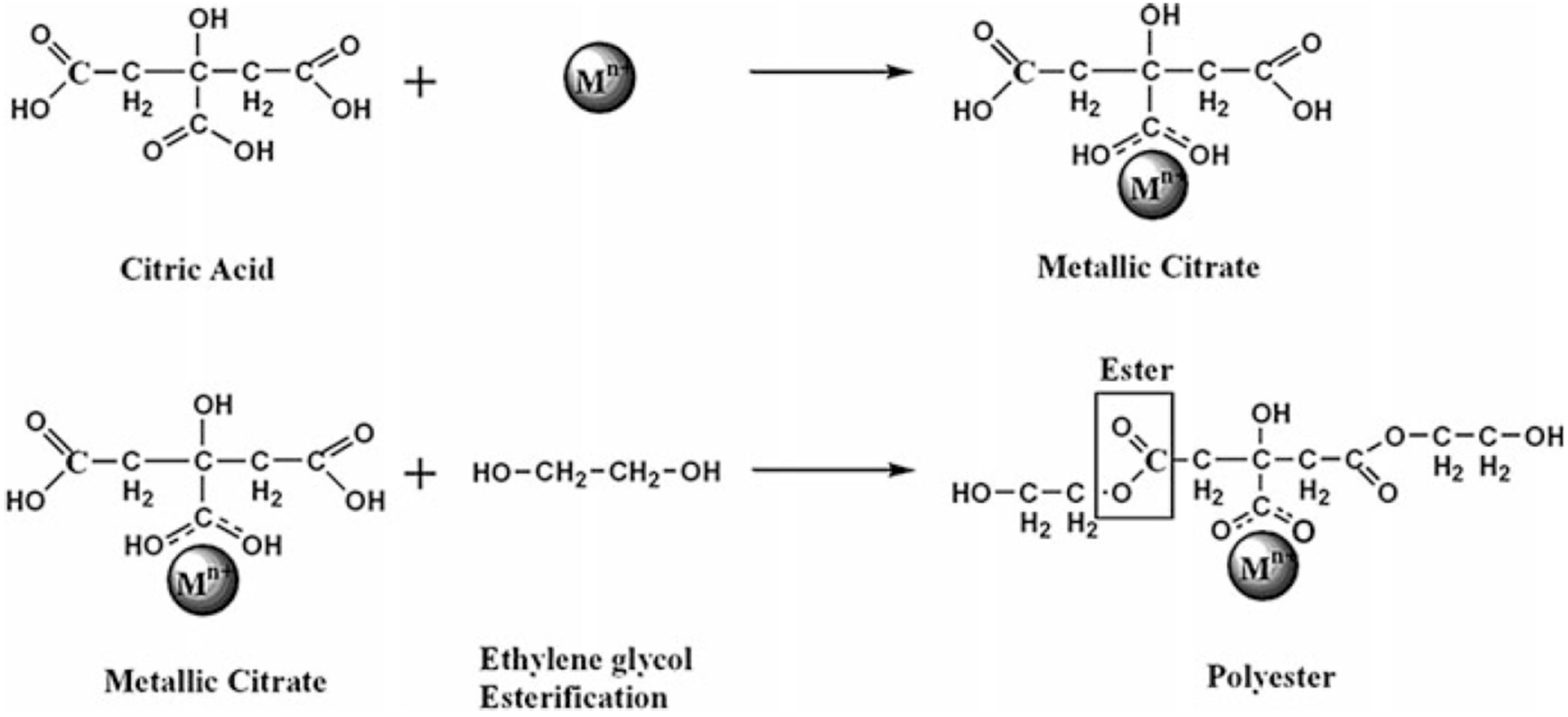
Calcination



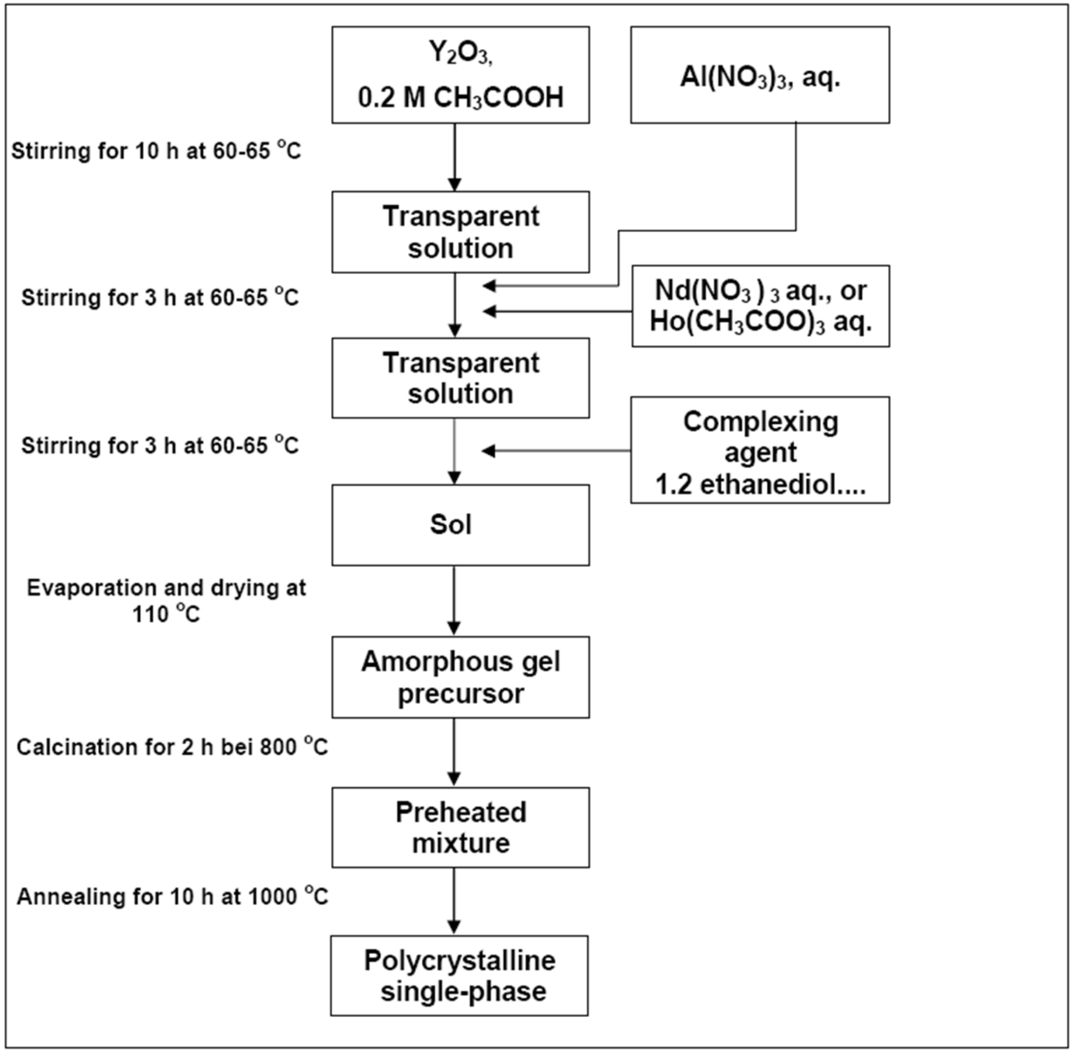
Oxide

Pechini Sol-Gel Route

The transesterification reaction between citric acid and ethylene glycol



Pechini Sol-Gel Route



Y_2O_3, 0.2 M CH_3COOH

$Al(NO_3)_3$, aq.

Stirring for 10 h at 60-65 °C

Transparent solution

$Nd(NO_3)_3$ aq., or $Ho(CH_3COO)_3$ aq.

Stirring for 3 h at 60-65 °C

Transparent solution

Complexing agent 1.2 ethanediol....

Stirring for 3 h at 60-65 °C

Sol

Evaporation and drying at 110 °C

Amorphous gel precursor

Calcination for 2 h bei 800 °C

Preheated mixture

Annealing for 10 h at 1000 °C

Polycrystalline single-phase

Major components

Dopants

Gelling agent

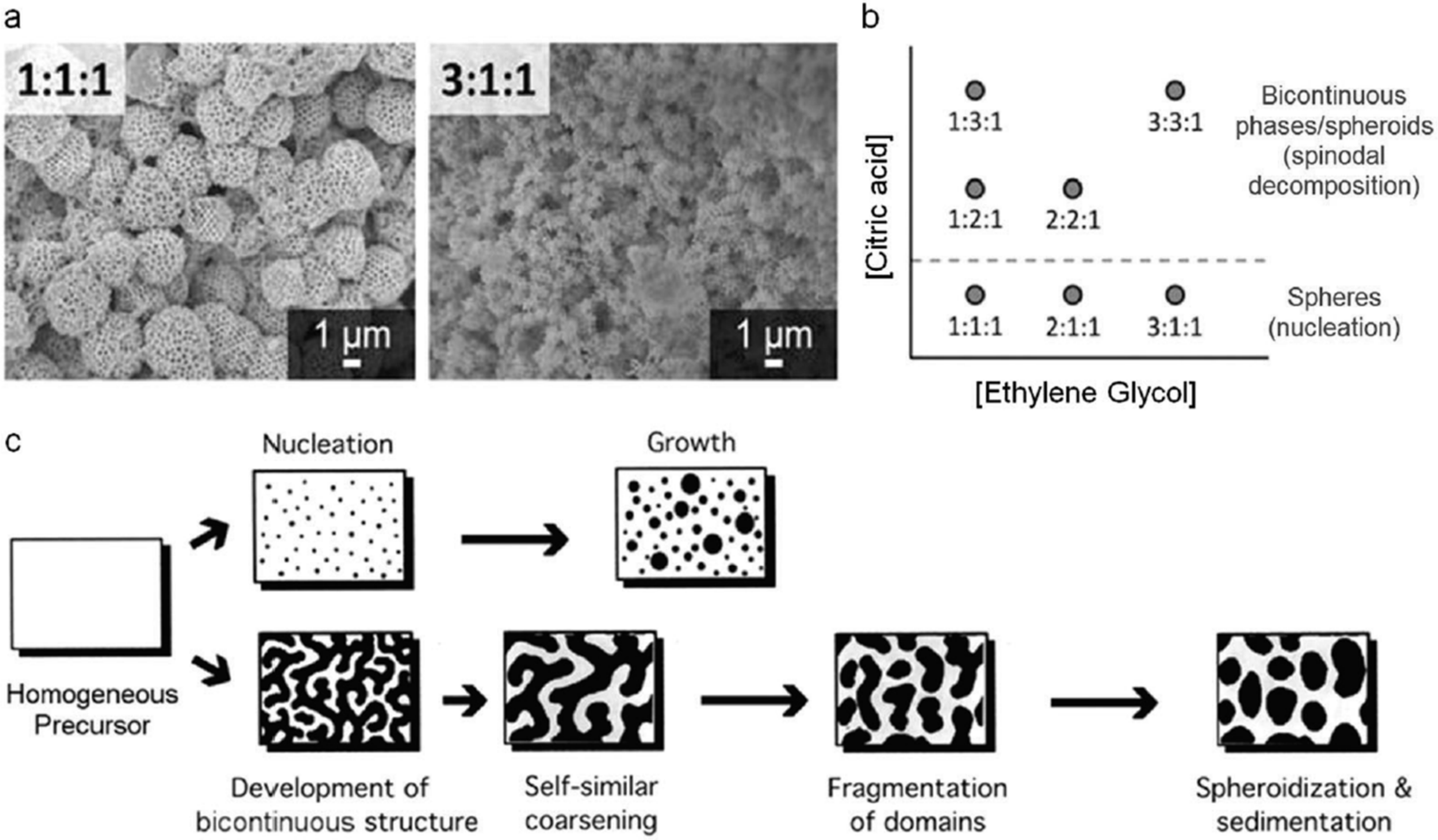
Removal of solvents

Removal of organics

Doped YAG product

Pechini Sol-Gel Route

EG : CA : M



Metal-Organic (Alkoxide) Route

Hydrolysis

Metal Alkoxides

$[M(OR)_x]_n + H_2O \rightarrow ROH + M\text{-}O\text{-}H$

Metal Amides

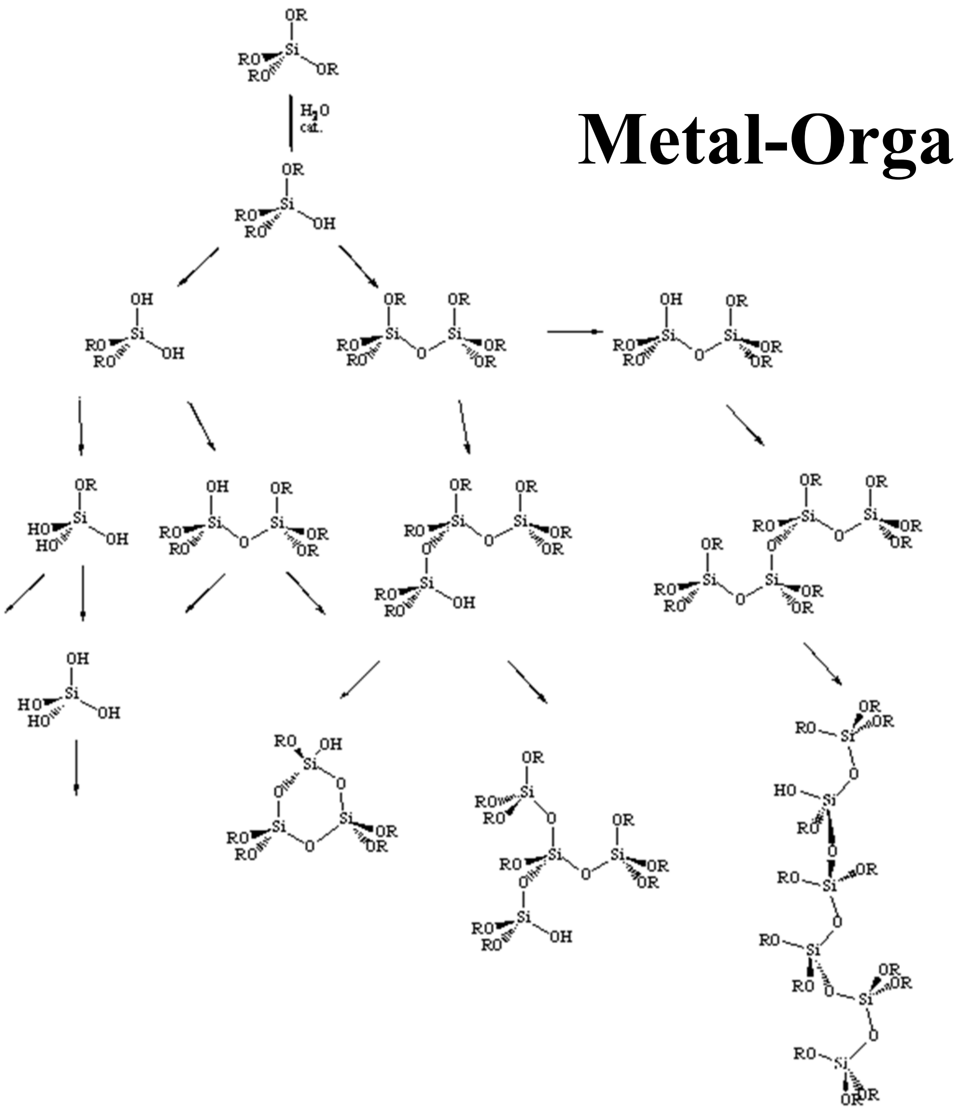
$[M(NR_2)_x]_n + H_2O \rightarrow R_2NH + M\text{-}O\text{-}H$

Polycondensation

$$2\ M\text{-}O\text{-}H \rightarrow M\text{-}O\text{-}M + H_2O$$

OXIDE

Metal-Organic (Alkoxide) Route



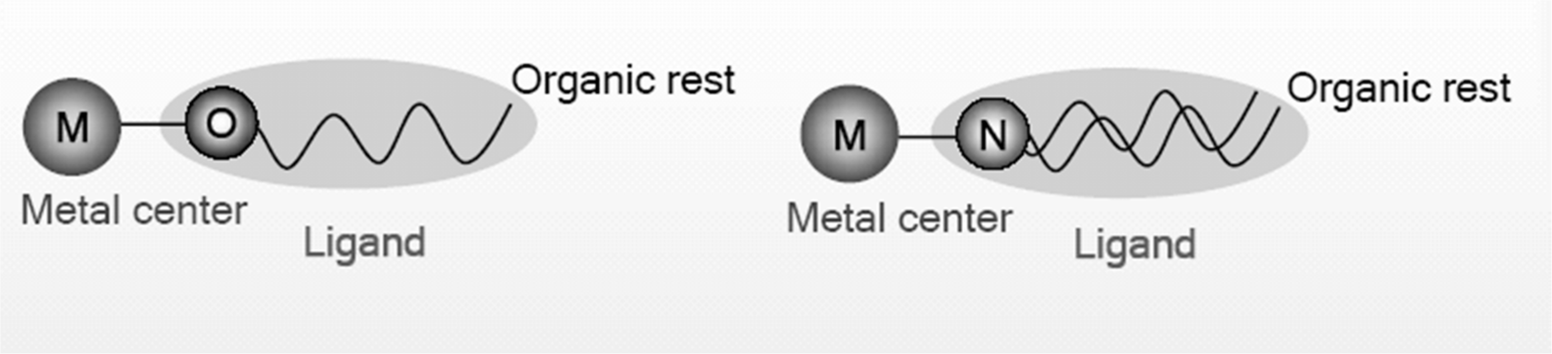
Oligomers formed by hydrolysis-condensation process

-linear
-branched
-cyclic
-polyhedral

Never goes to pure SiO_2

$$n\ Si(OR)_4 + 2n+(a-b)/2\ H_2O \rightarrow Si_nO_{2n-(a+b)/2}(OH)_a(OR)_b + (4n-b)\ ROH$$

Metal Alkoxides and Amides as Precursors



Metal Alkoxides $[M(OR)_x]_n$
formed by the replacement of the hydroxylic hydrogen of an alcohol (ROH) through a metal atom

Most frequently used precursor for sol-gel: TEOS = $Si(OEt)_4$

Metal Amides $[M(NR_2)_x]_n$
formed by the replacement of one of the hydrogen atoms of an amine (R_2NH) through a metal atom

Metal Alkoxides and Amides as Precursors

Homometallic Alkoxides

General Formula: $[M(OR)_x]_n$

Heterometallic Alkoxides

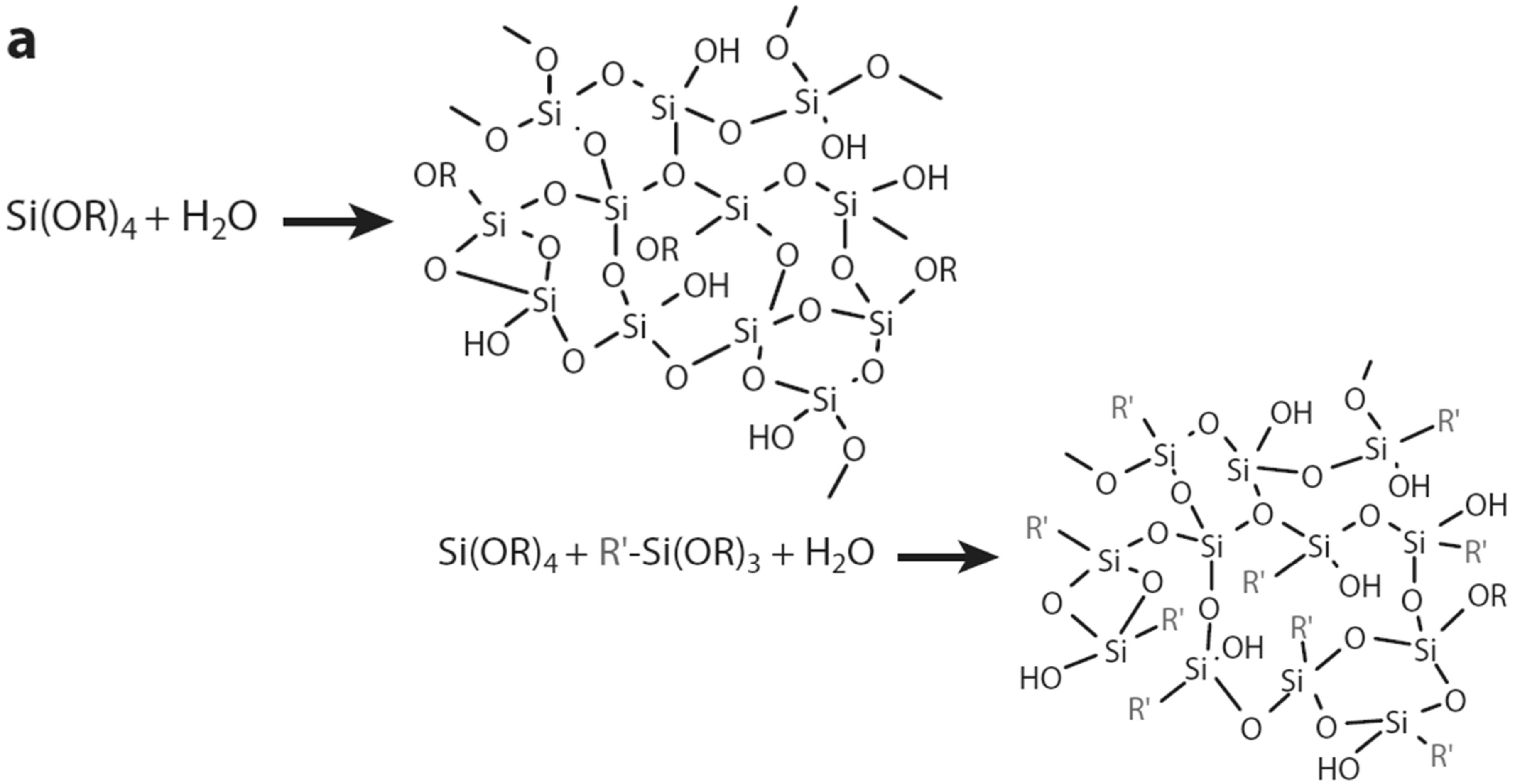
General Formula: $M_aM'_b(OR)_x]_n$

Metal Amides

General Formula: $[M(NR_2)_x]_n$

M = Metal or metalloid of valency x
O = Oxygen Atom
N = Nitrogen atom
R = simple alkyl, substituted alkyl or aryl group
n = degree of molecular association

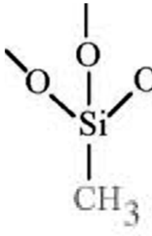
Modified Silicon Alkoxides as Precursors



R' = methyl, ethyl, butyl, CN, etc.

Modified Silicon Alkoxides as Precursors

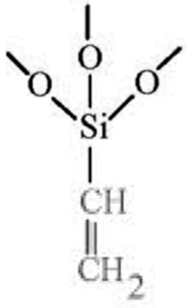
Silsesquioxanes = $RSiO_{1.5}$ (= 3/2)



Methyl

Hydrophobicity

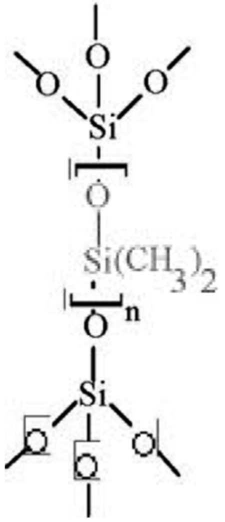
Terminal groups



Vinyl

Crosslinking with acrylic

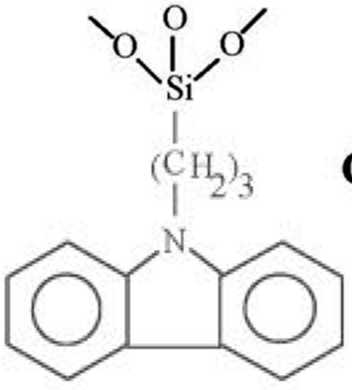
Polymerizable groups



Polydimethylsiloxane

Rubbery behavior

Bridging groups

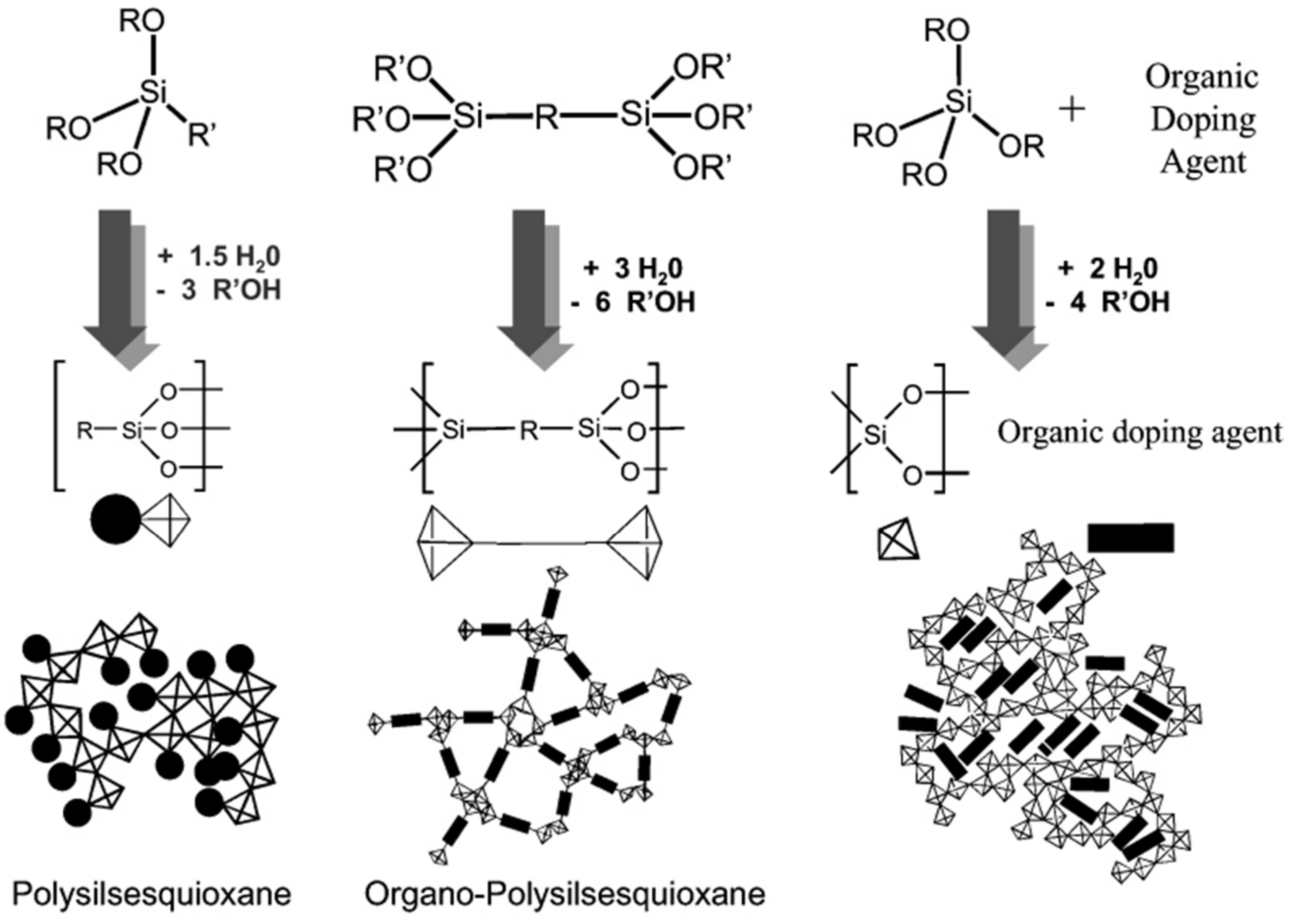


Carbazole

Charge transport properties

Functional groups

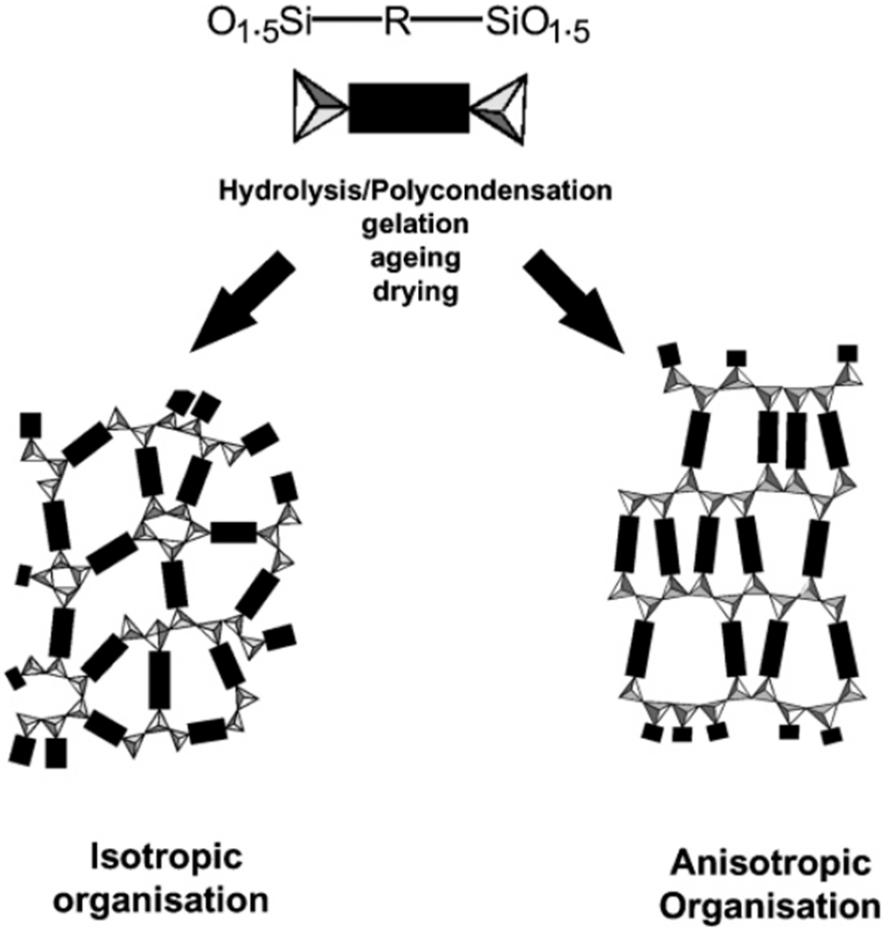
Hybrid Inorganic-Organic Materials



Nanostructured silica-based Hybrid Organic Inorganic Materials (Class II)

Nanocomposite silica-based Hybrid Organic Inorganic Materials (Class I)

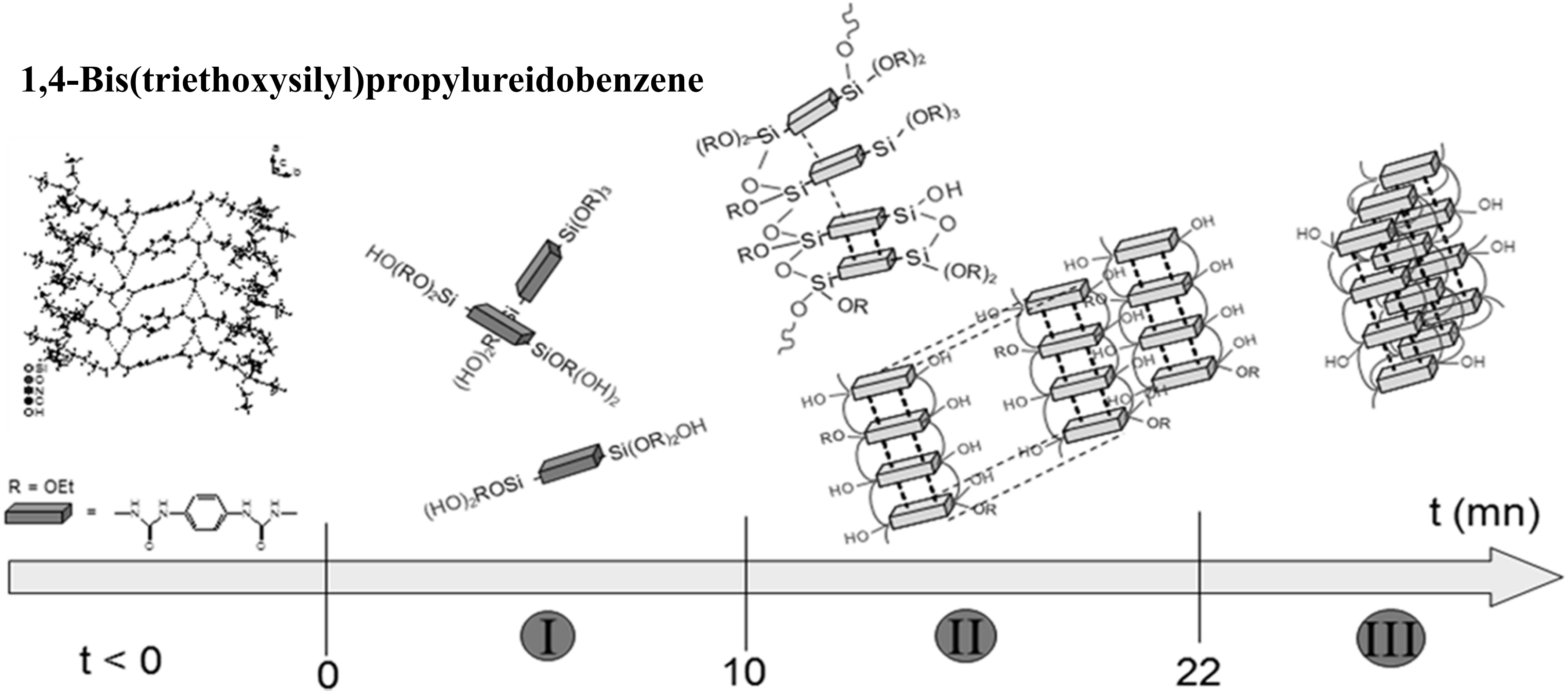
Organization in Xerogels of Bridged Silicon Alkoxide Precursors



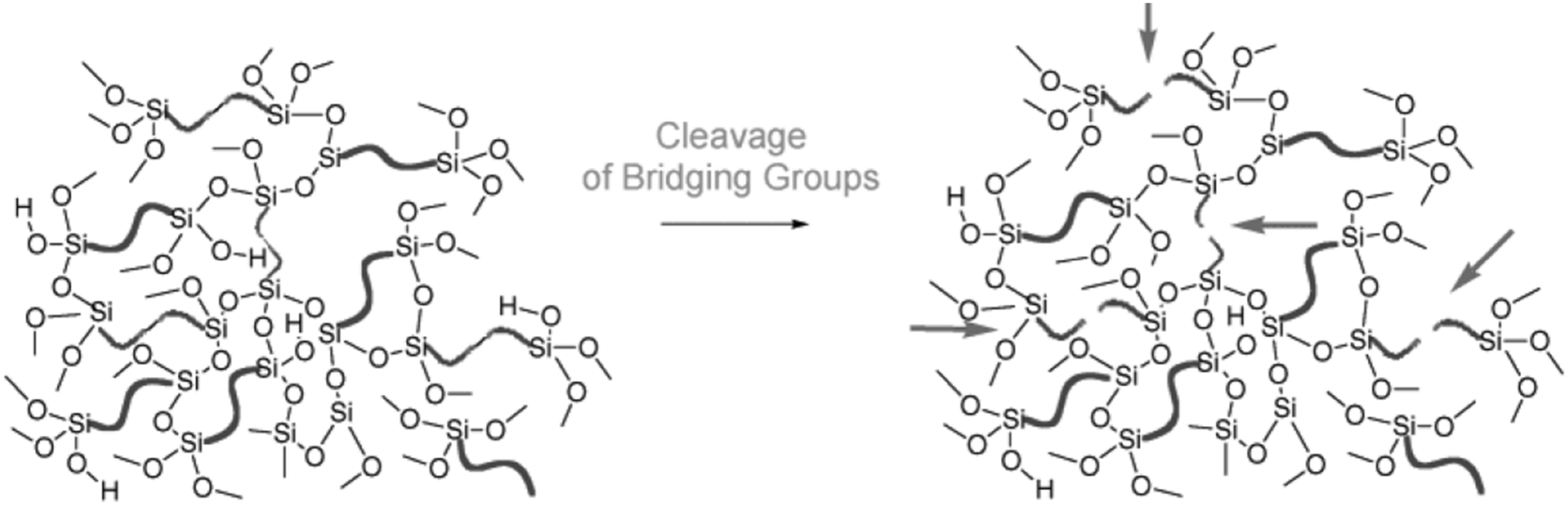
Self-Assembly of Bridged Silsesquioxanes

Nanostructuring of hybrid silicas through a Self-Recognition Process - the crystallization of the hydrolyzed species by H-bonding followed by their polycondensation in solid state

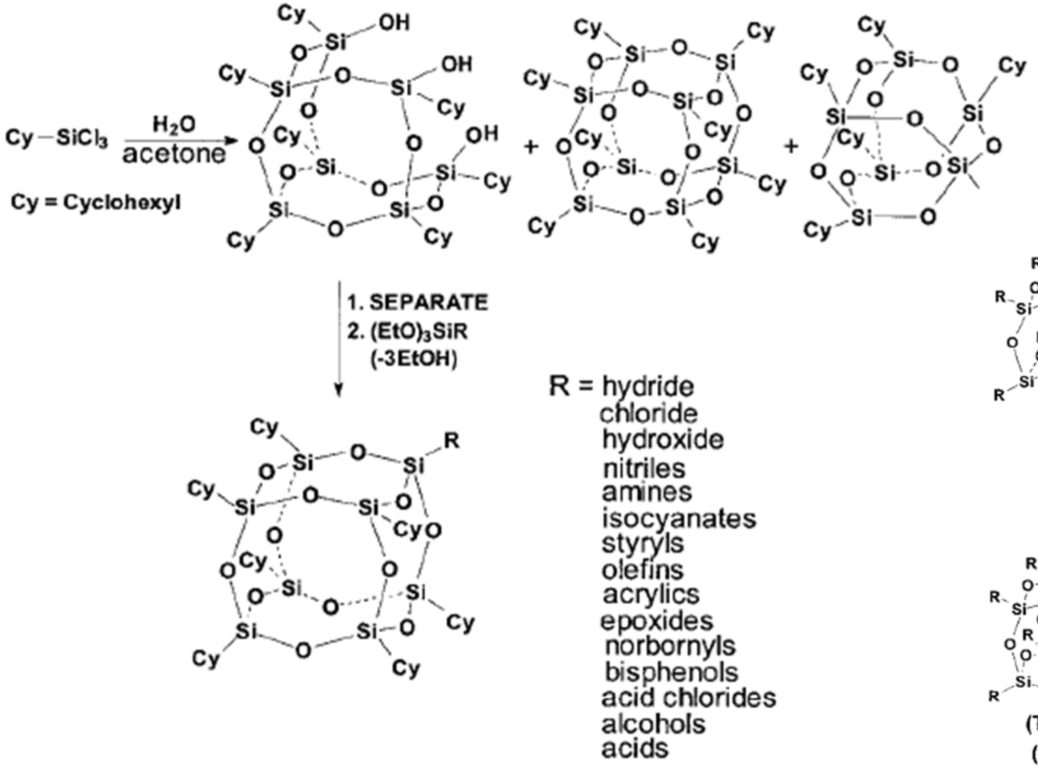
1,4-Bis(triethoxysilyl)propylureidobenzene

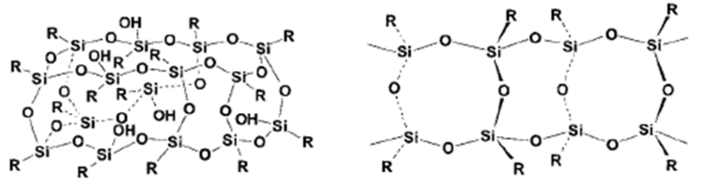


Templating Porosity in Bridged Polysilsesquioxanes

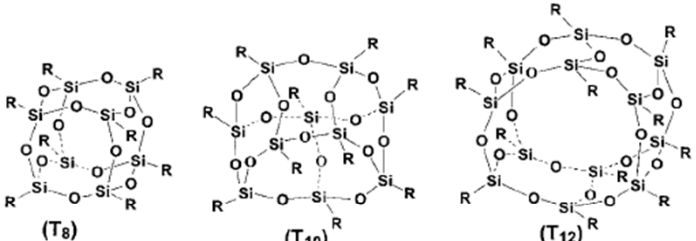


Polyhedral Oligomeric Silsesquioxanes (POSS)

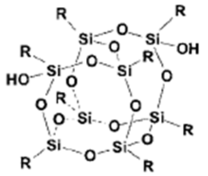



(a) Random structure

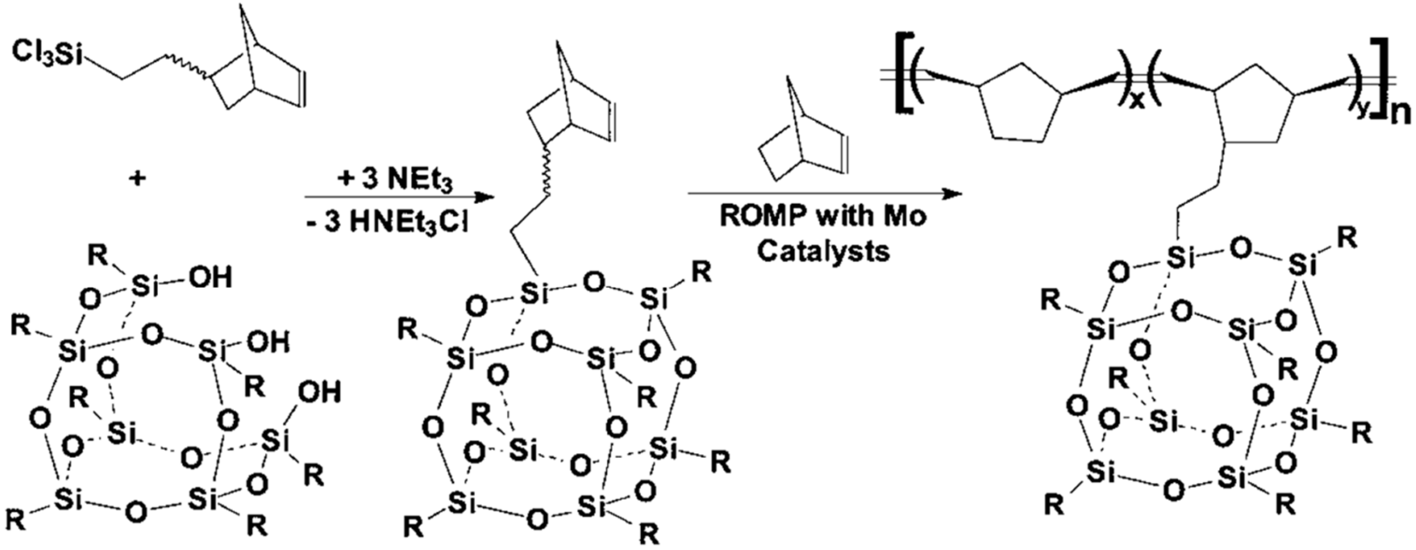
(b) Ladder structure



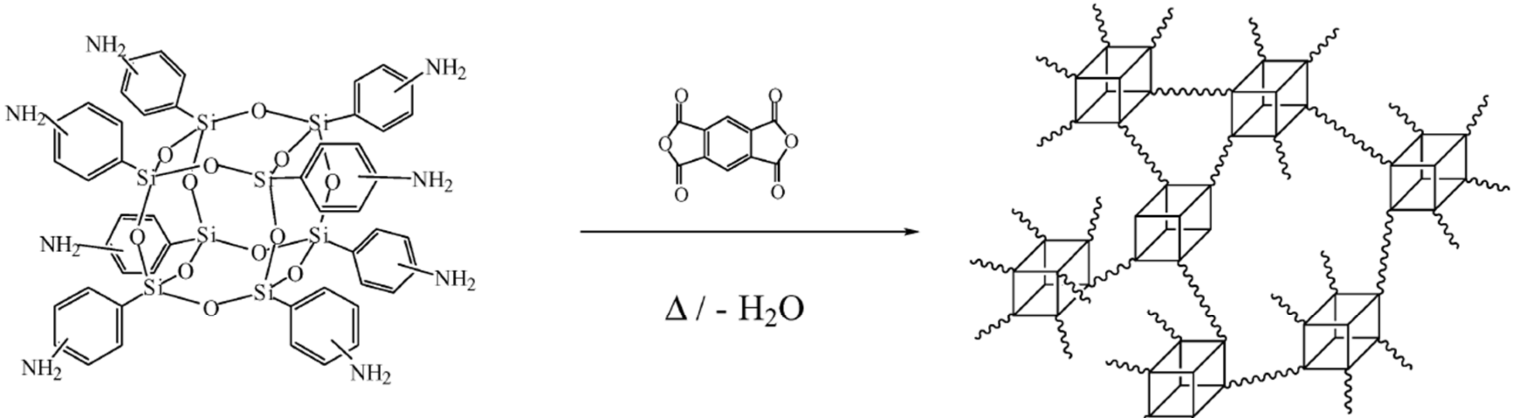
(c) (d) (e)
Cage structures

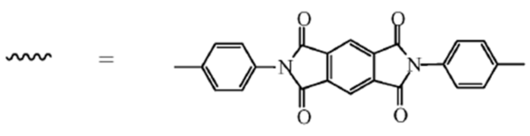

(f) Partial cage structure

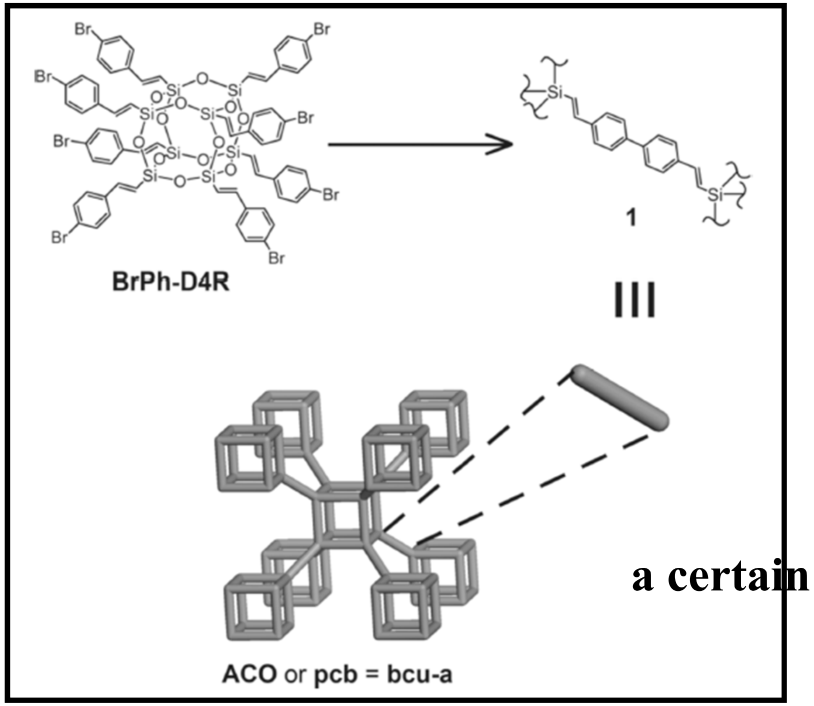
Polymers and Copolymers of POSS



Polymers and Copolymers of POSS

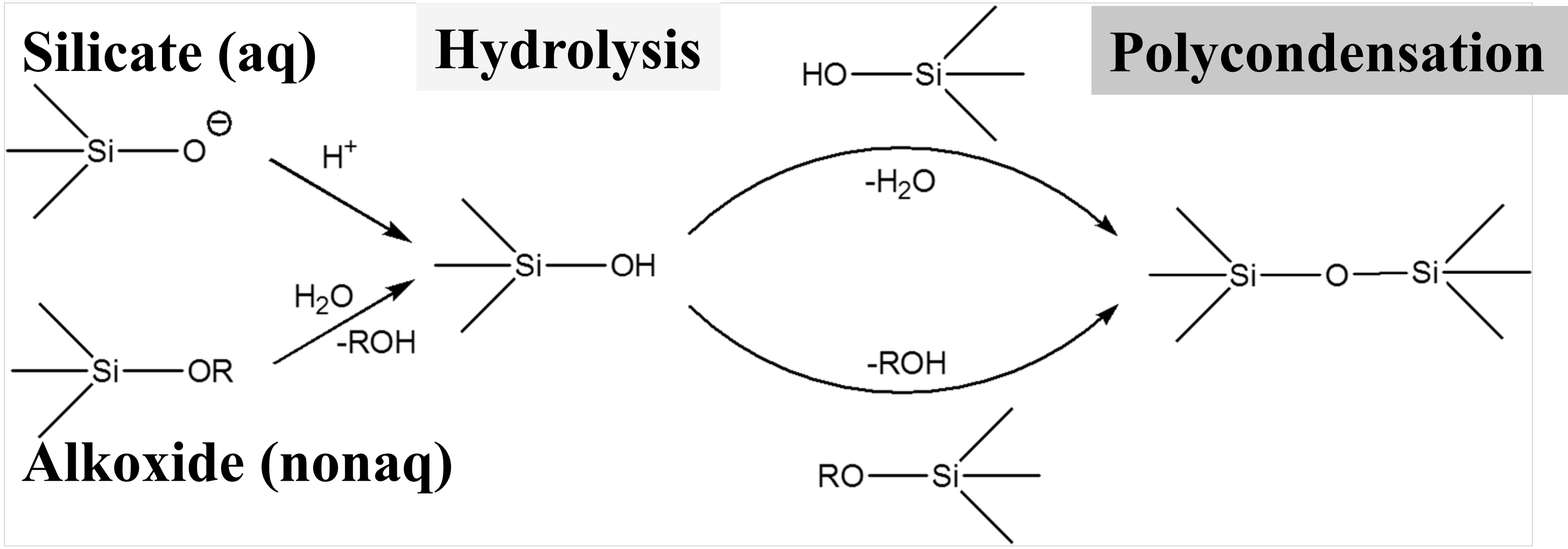






a certain degree of crystallinity

Sol-Gel in Silica Systems



Silicate (aq)

Hydrolysis

Polycondensation

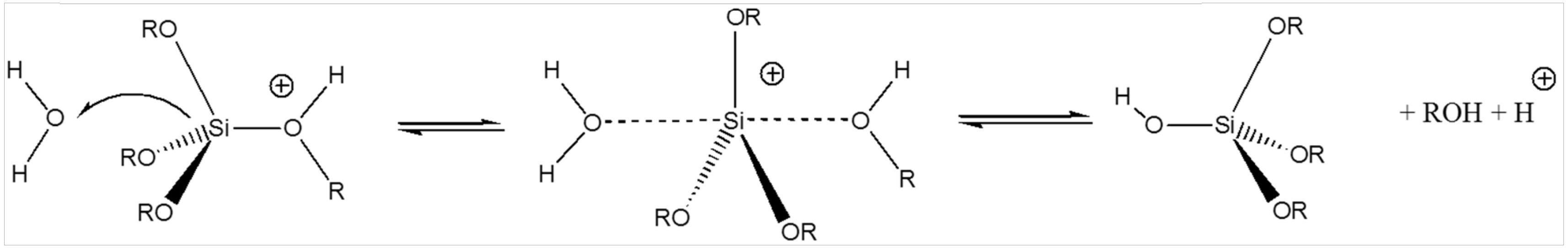
Alkoxide (nonaq)

Metal-Oragnic (Alkoxide) Route

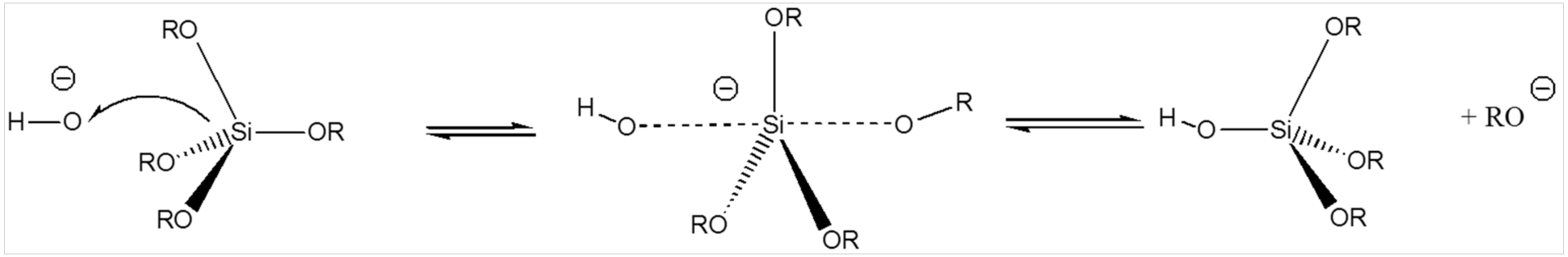
- **Metal-organic Route**

metal alkoxide in alcoholic solution, water addition

Acid catalysed hydrolysis



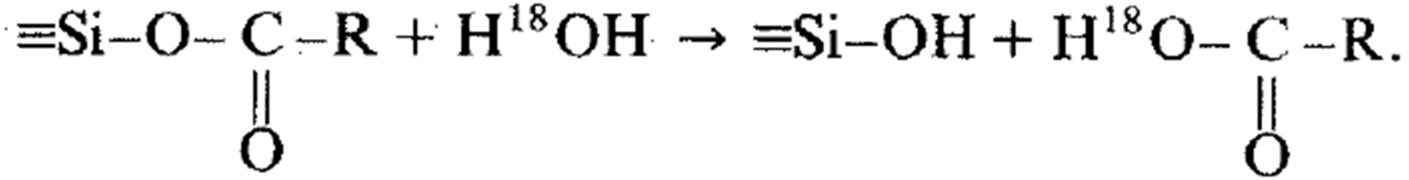
Base catalysed hydrolysis



Metal-Oragnic (Alkoxide) Route

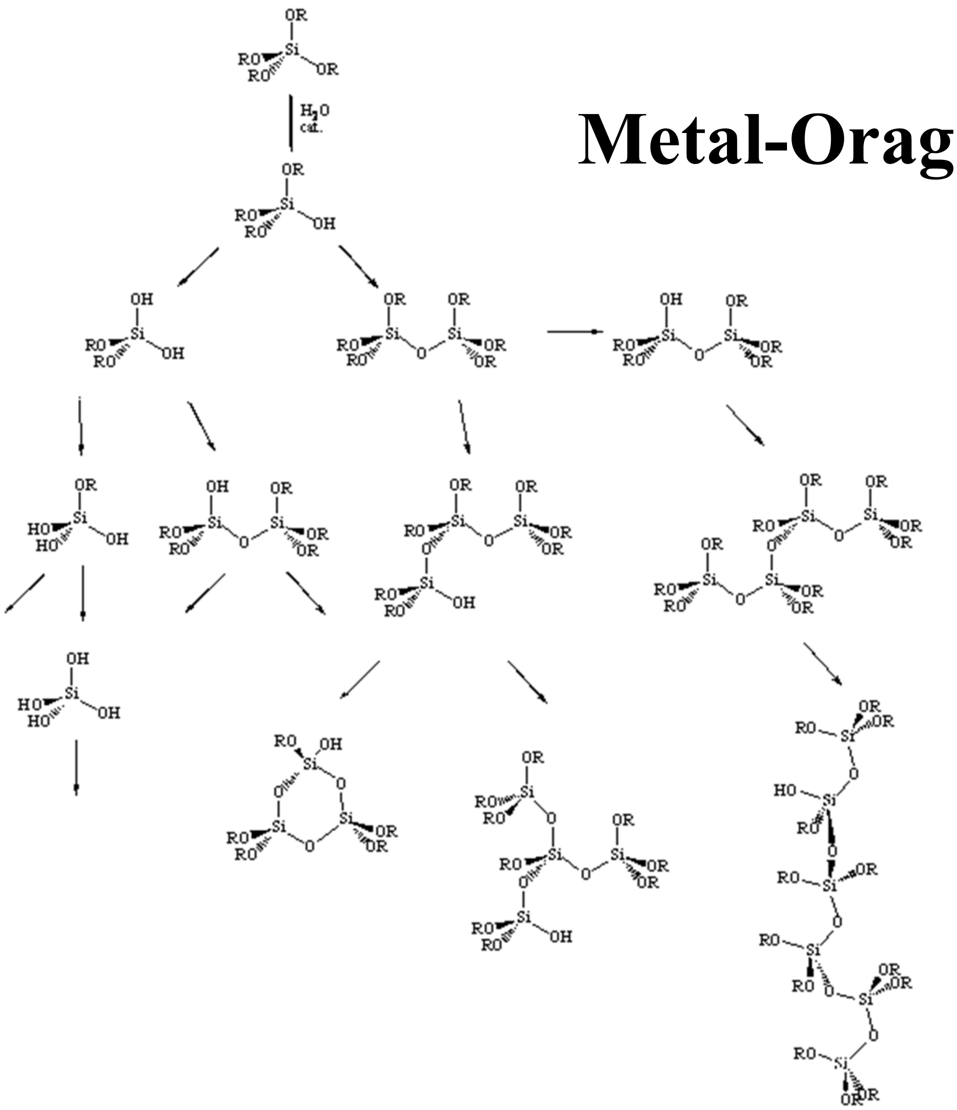
Isotope labelling experiments

$$\equiv\mathrm{Si}-\mathrm{OR} + \mathrm{H}^{18}\mathrm{OH} \rightarrow \equiv\mathrm{Si}-{}^{18}\mathrm{OH} + \mathrm{HOR}.$$



$$\equiv\mathrm{Si}-\mathrm{O}-\underset{\underset{\mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{R} + \mathrm{H}^{18}\mathrm{OH} \rightarrow \equiv\mathrm{Si}-\mathrm{OH} + \mathrm{H}^{18}\mathrm{O}-\underset{\underset{\mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{R}.$$

Metal-Oragnic (Alkoxide) Route



Oligomers formed by hydrolysis-condensation process

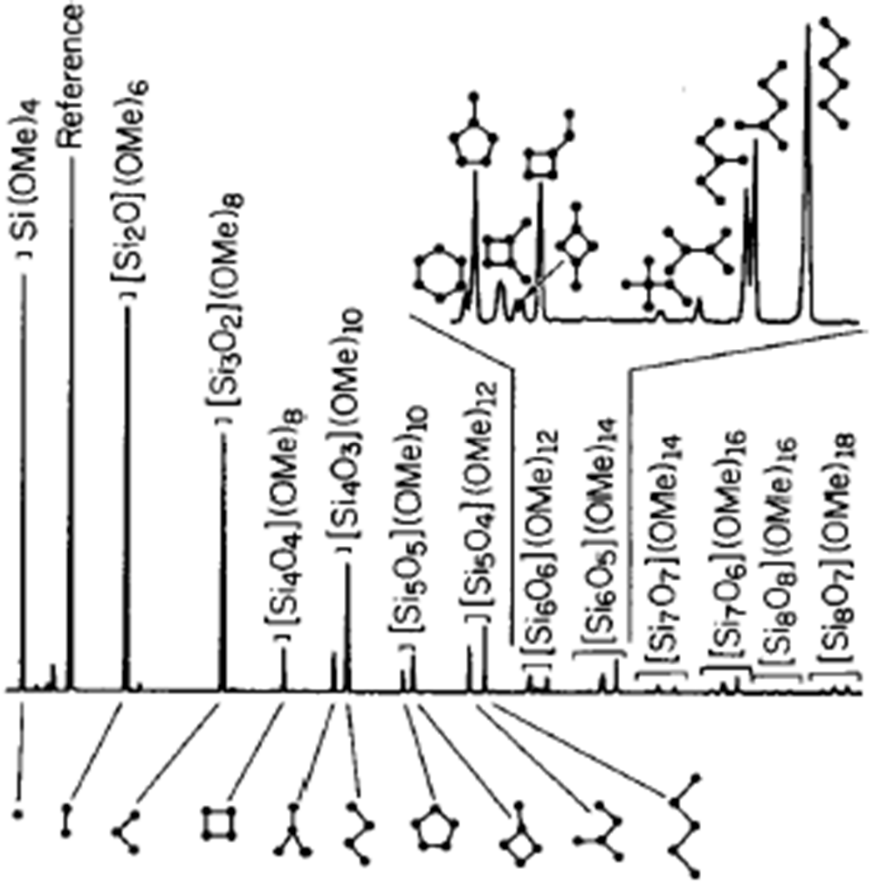
-linear
-branched
-cyclic
-polyhedral

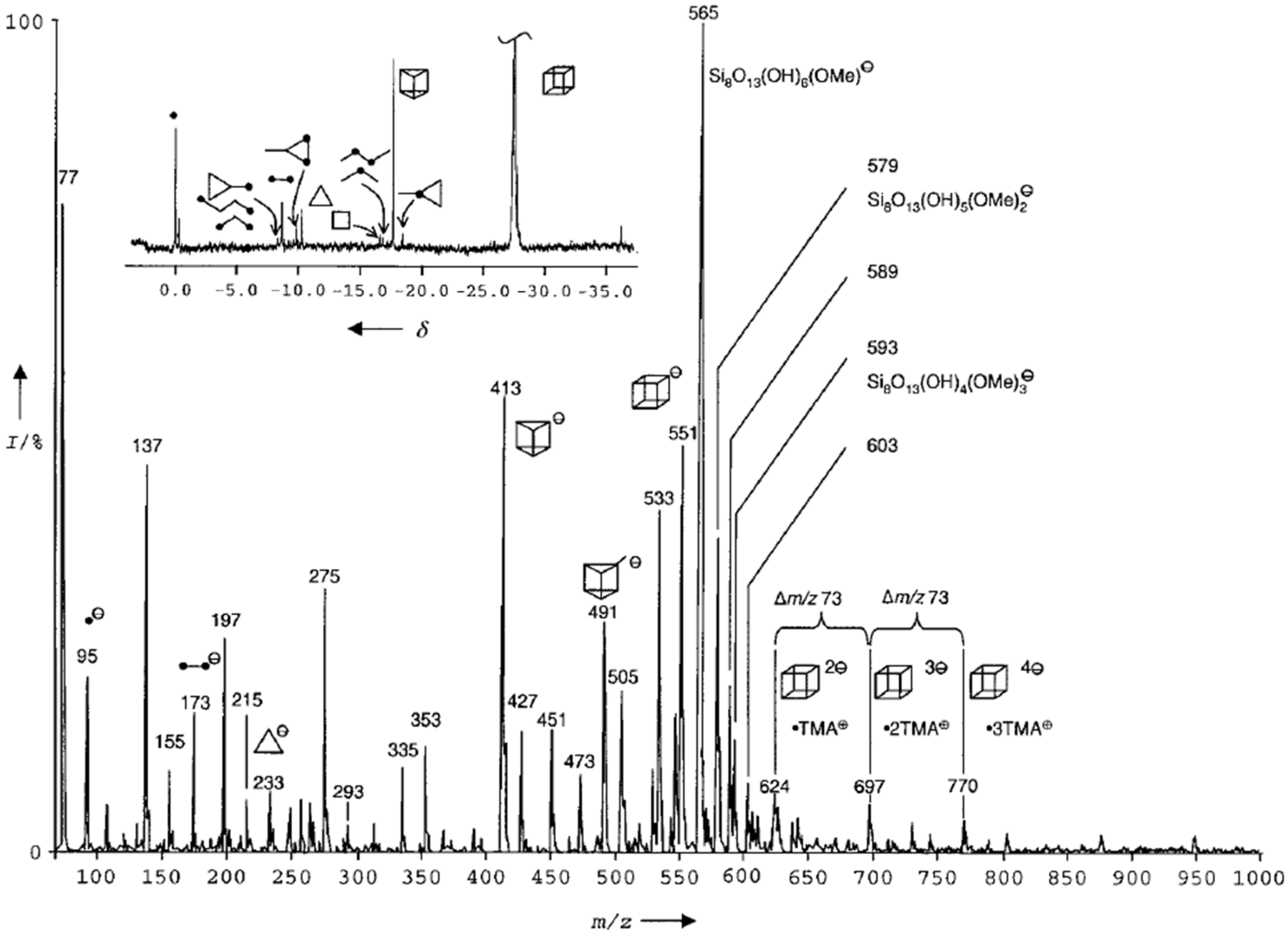
Never goes to pure SiO_2

$$n\ Si(OR)_4 + 2n+(a-b)/2\ H_2O \rightarrow Si_nO_{2n-(a+b)/2}(OH)_a(OR)_b + (4n-b)\ ROH$$

GC of TMOS hydrolysis products

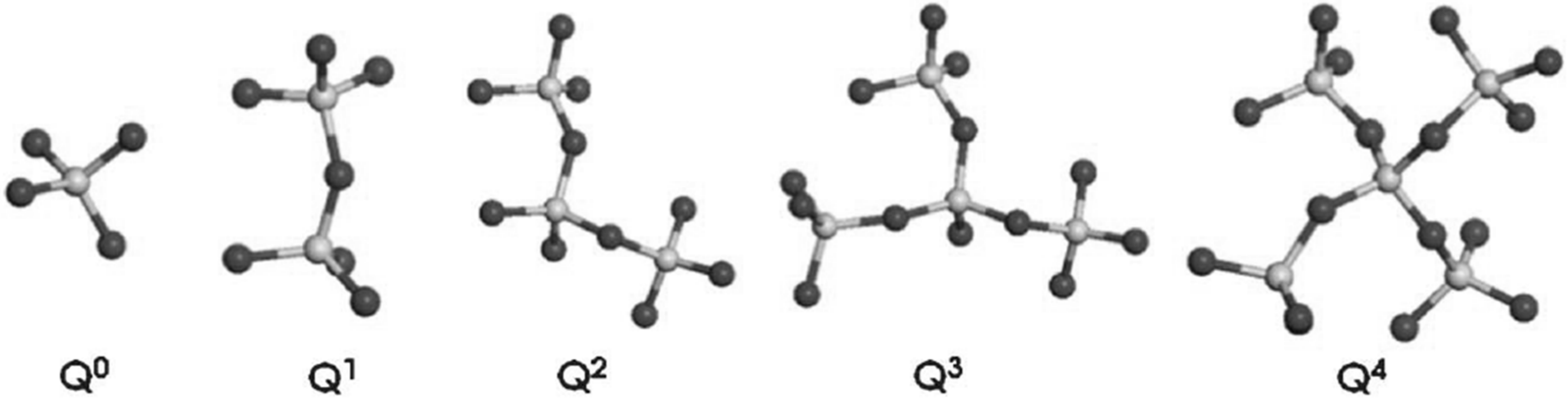
$Si(OMe)_4 + H_2O$ →





Neg. ion ESI-MS and ^{29}Si NMR of silicate aq with TMA ions

Q - notation



The notation of Q^a_b

"Q" stands for the maximum 4 siloxane bonds for each Si
"a" is the actual number of siloxane bonds on each Si
"b" is the number of Si in the unit

$Q^0 = O_4Si$

$Q^1 = O_3SiOSi$

$Q^2 = O_2Si(OSi)_2$

$Q^3 = OSi(OSi)_3$

$Q^4 = Si(OSi)_4$

Silicate anions in aqueous alkaline media (detected by ^{29}Si-NMR)

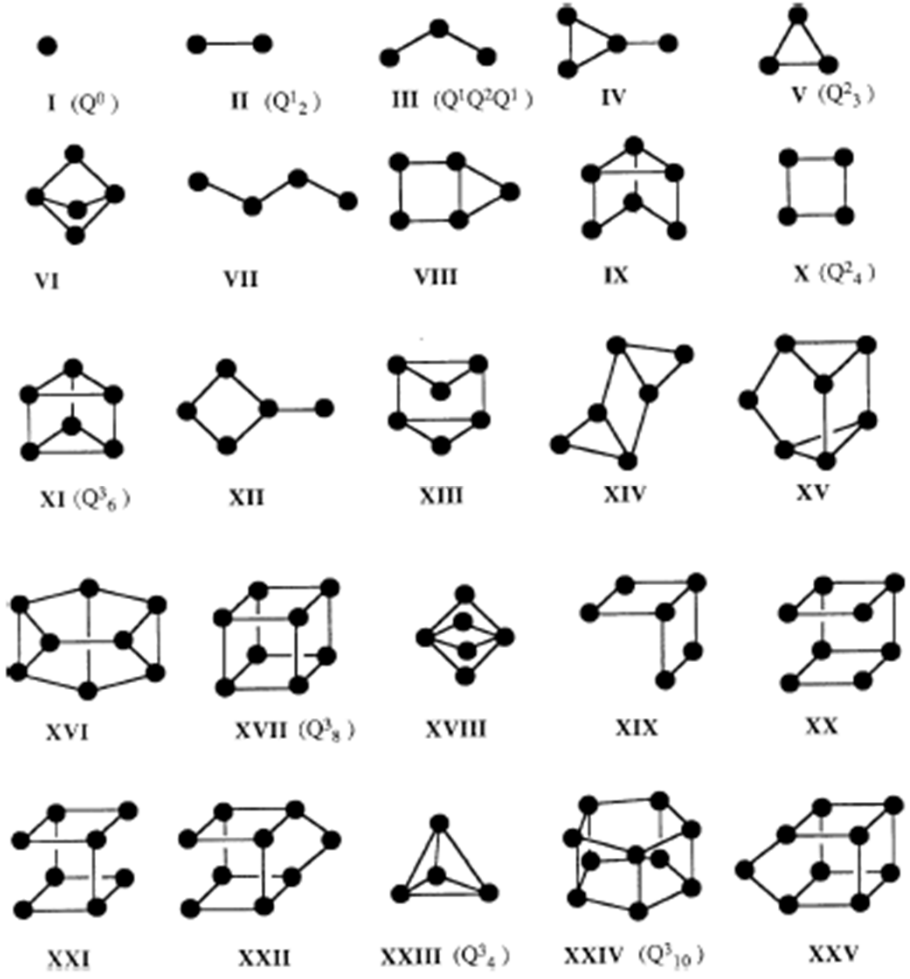
$M = OSiR_3$

$D = O_2SiR_2$

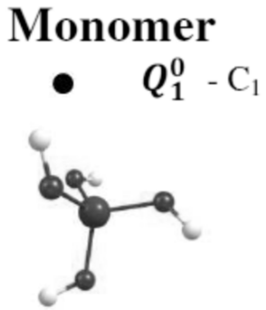
$T = O_3SiR$

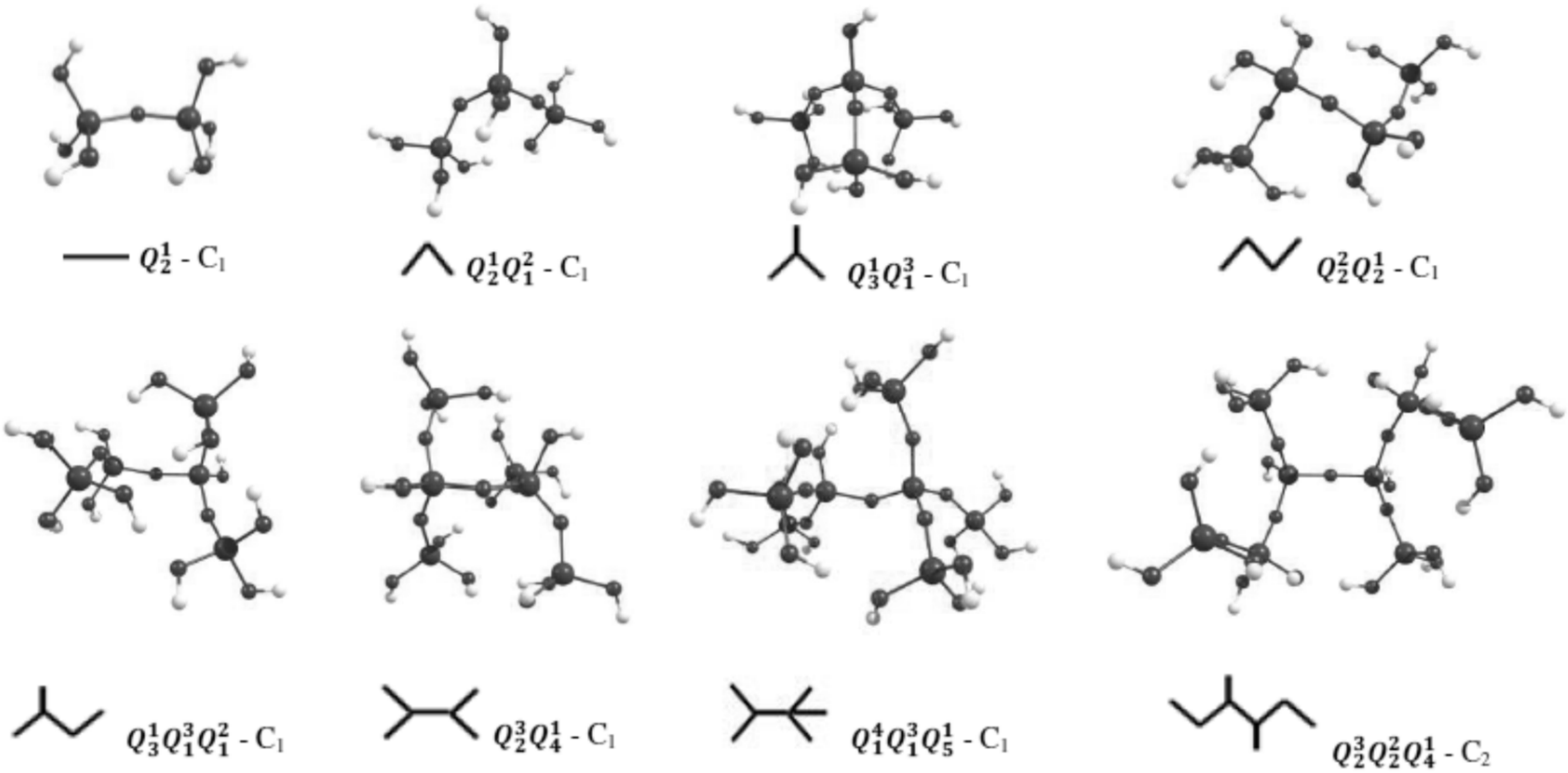
$Q = O_4Si$

$Q^0 = O_4Si$
$Q^1 = O_3SiOSi$
$Q^2 = O_2Si(OSi)_2$
$Q^3 = OSi(OSi)_3$
$Q^4 = Si(OSi)_4$



Silicate anions

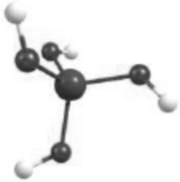


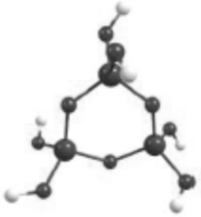


Silicate anions

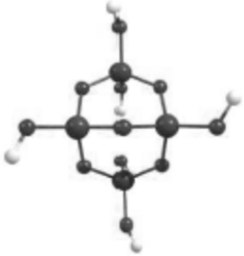
Monomer

● Q_1^0 - C$_1$

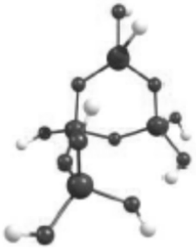




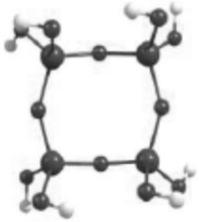
△ Q_3^2 - C$_1$



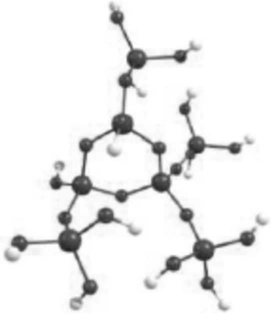
$Q_2^3Q_2^2$ - C$_1$



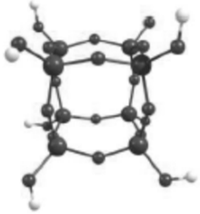
$Q_2^2Q_1^3Q_1^1$ - C$_1$



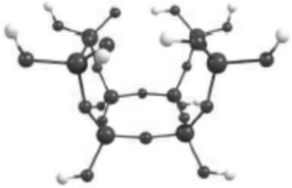
□ Q_4^2 - C$_2$



$Q_1^4Q_2^3Q_4^1$ - C$_1$

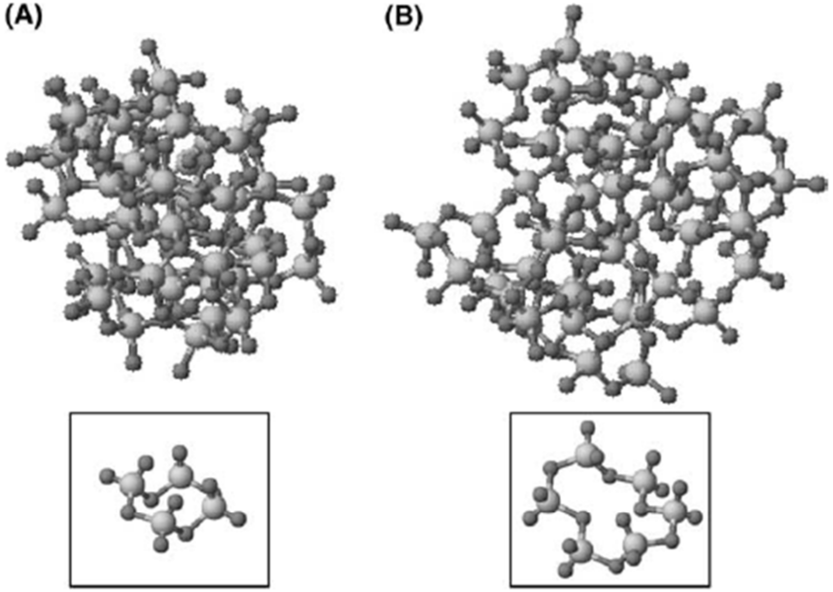


Q_8^3 - O$_h$

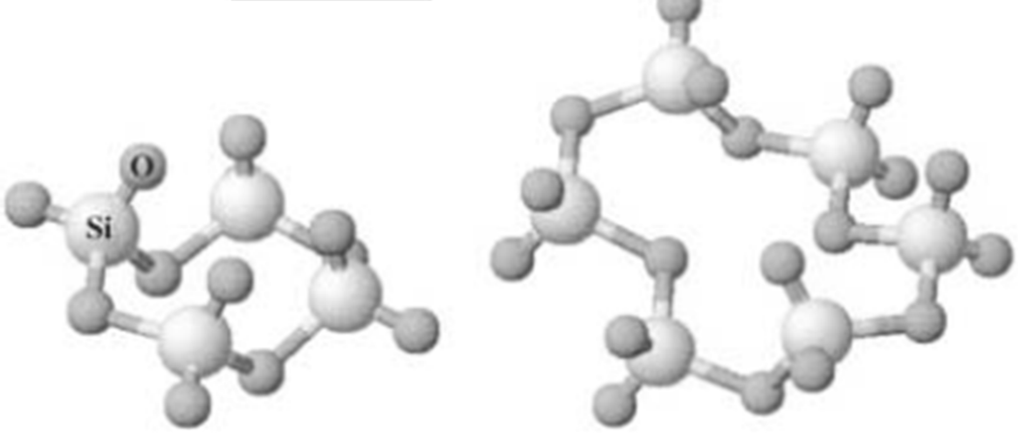


$Q_4^3Q_4^2$ - C$_S$

Oligomers formed by hydrolysis-condensation

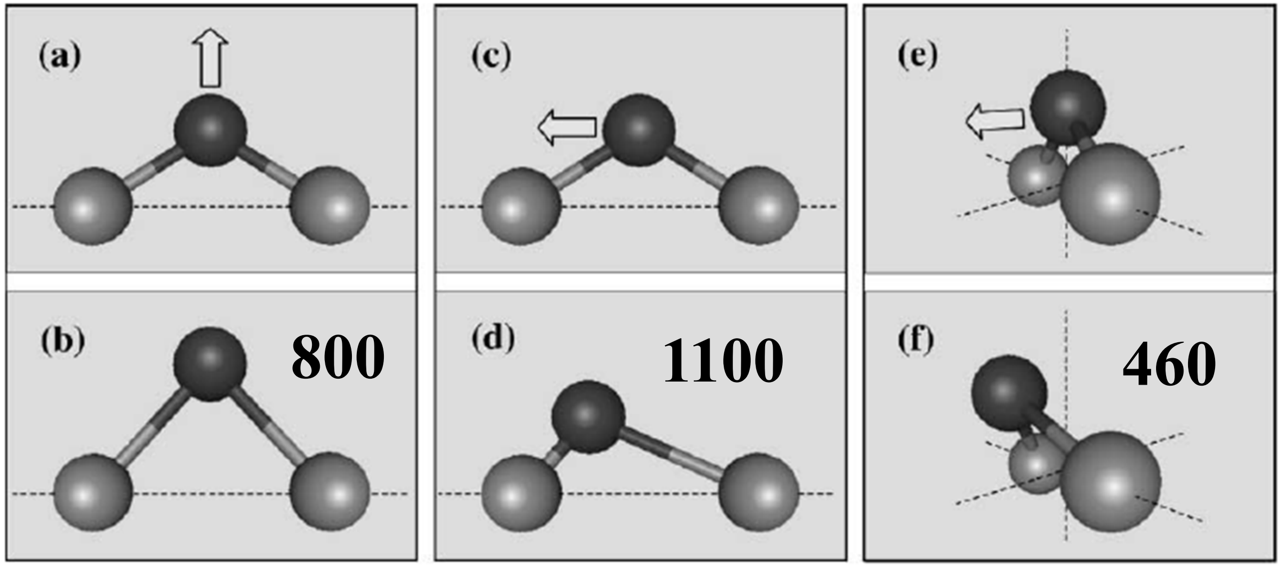


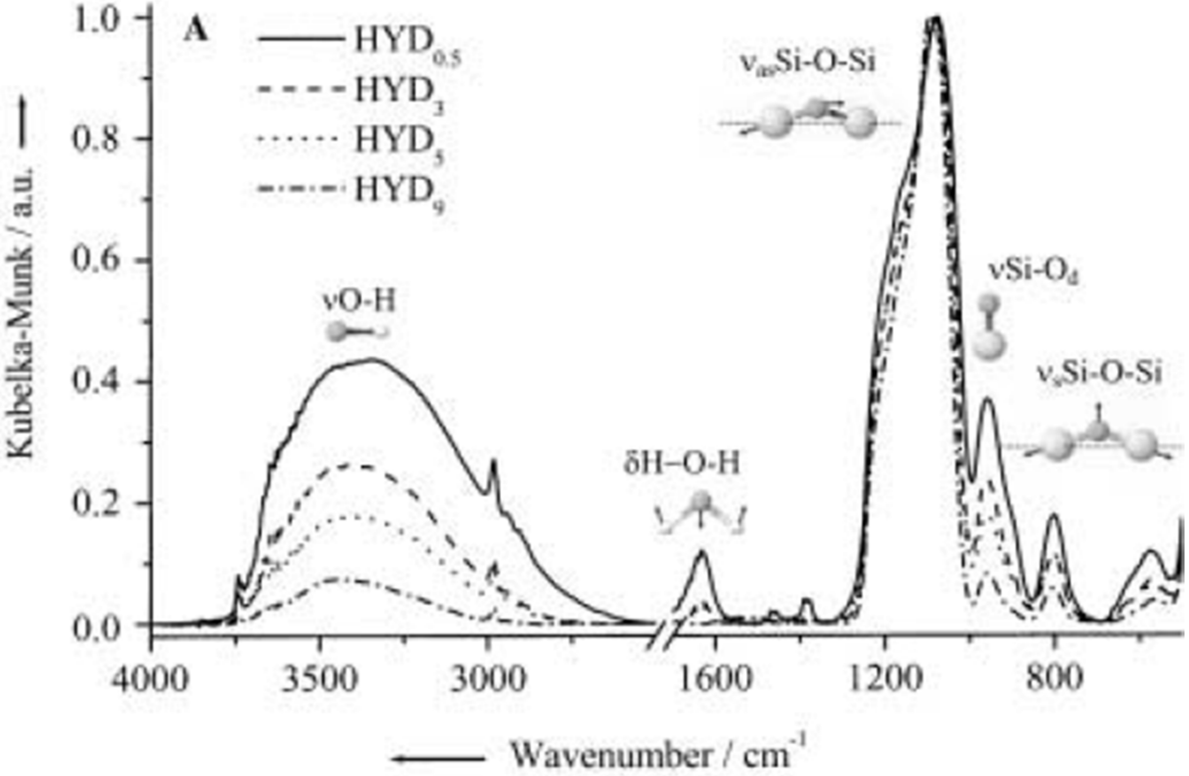
$Si_{50}O_{75}(OH)_{50}$ three-dimensional clusters formed by
(A) four-rings
(B) six-rings



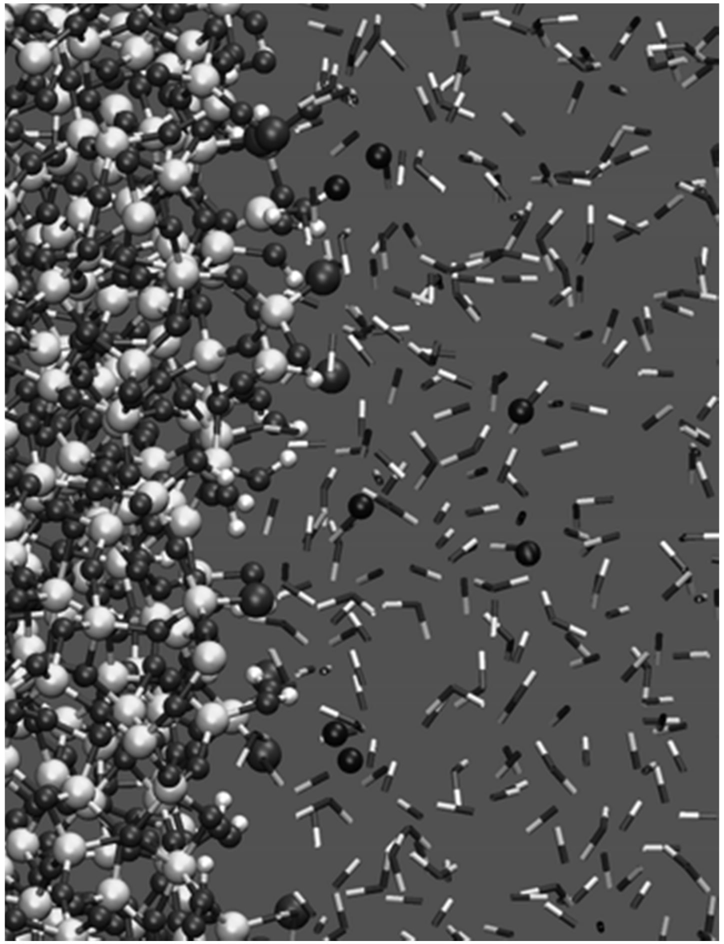
IR spectrum of silica

ν, cm^{-1}





Amorphous silica/water interface



The Electrical Double Layer

The electrical double layer at the interface of silica and a diluted KCl solution

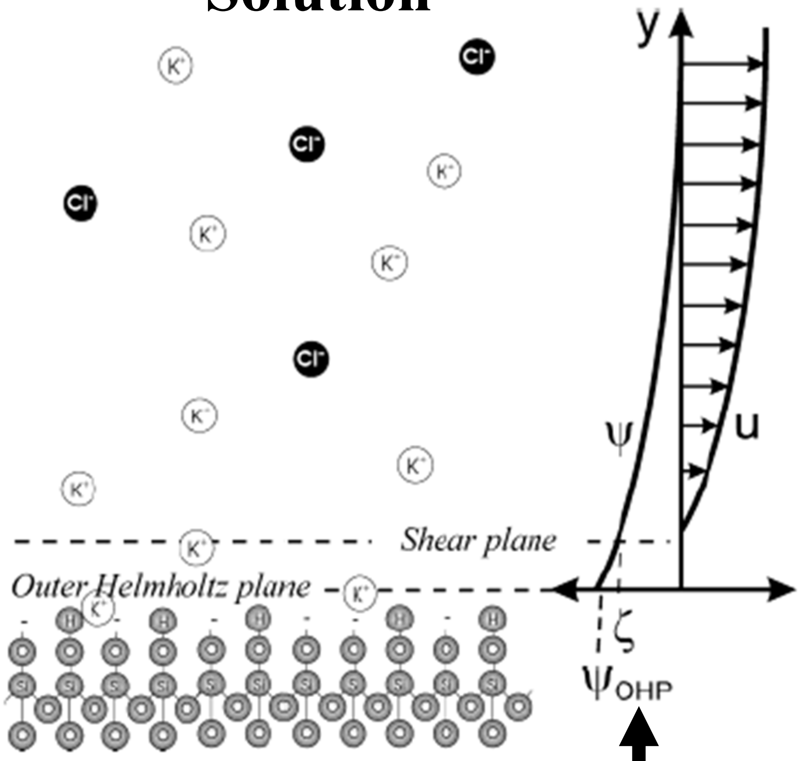
ψ = local potential
OHP = outer Helmholtz plane
***u* = local electroosmotic velocity**

Negative surface charge
stems from deprotonated silanols
Shielding of this surface charge occurs
due to adsorbed ions inside the OHP
and by mobile ions in a diffuse layer

The shear plane = where hydrodynamic motion becomes possible

Zeta = potential at the shear plane

Solution



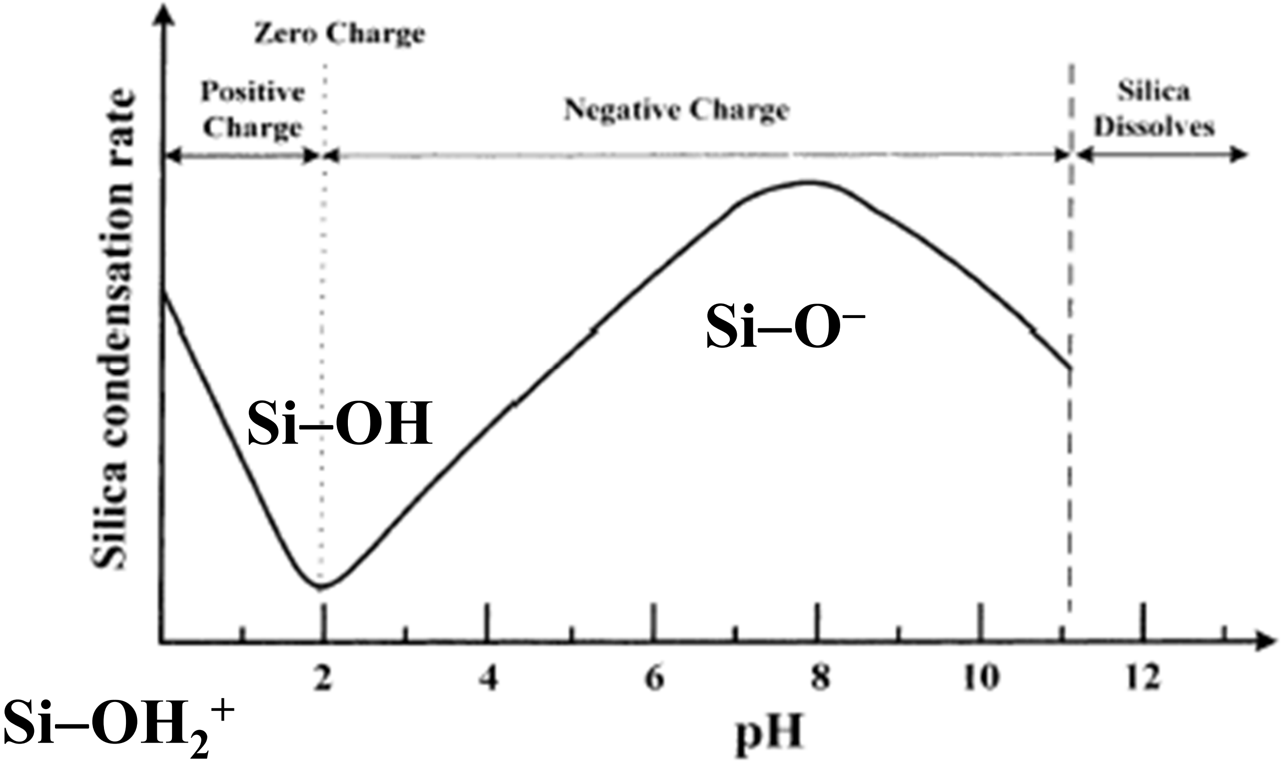
Silica surface

Zeta

Sol-Gel Methods

Isoelectronic point: zero net charge

pH = 2.2 for silica



Sol-Gel Methods

Longest TEOS gel time = the slowest reaction

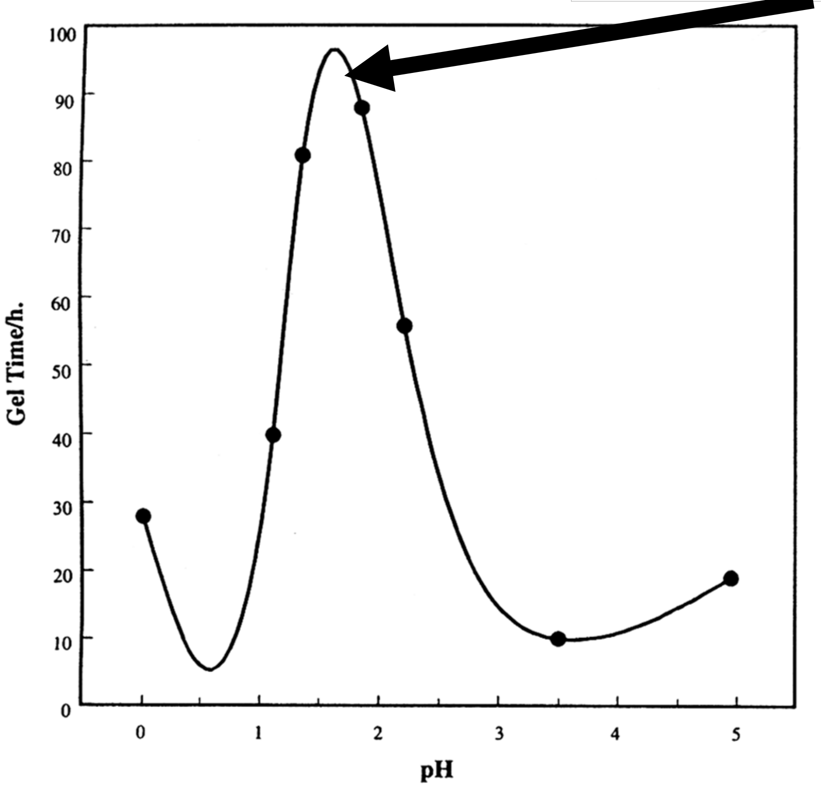
Effects on hydrolysis rate:

pH

substituents

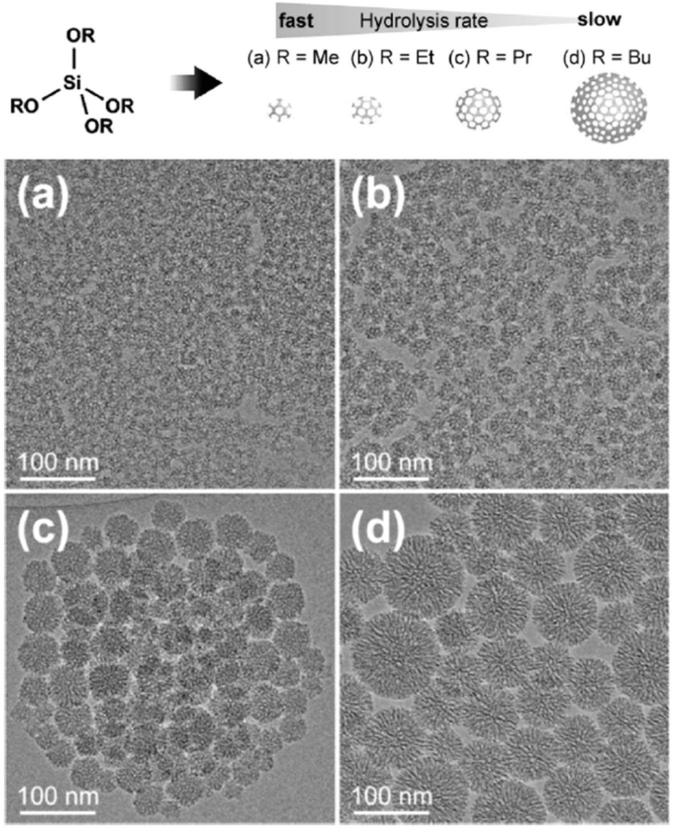
solvent

water



Rate of H^+ catalyzed TEOS hydrolysis (gel time) as a function of pH

Sol-Gel Methods



Precursor substituent effects:

Steric effects: branching and increasing of the chain length LOWERS the hydrolysis rate

$Si(OMe)_4 > Si(OEt)_4 > Si(O^nPr)_4 > Si(O^iPr)_4 > Si(O^nBu)_4$

Inductive effects: electronic stabilization/destabilizatio of the transition state (TS)

Electron density at Si decreases:

$R\rightarrow Si > RO\rightarrow Si > HO–Si > SiO\leftarrow Si$

Partial Charge Model (Livage and Henry)

Electron transfer occurs when atoms combine to give a molecule

Charge transfer causes each atom to acquire

a partial positive or negative charge, δ_i

This transfer mainly depends on the electronegativity difference between atoms

The electronegativity χ_i of an atom varies linearly with its partial charge δ_i

$$\chi_i = \chi^o_i + k\,\delta_i$$

Electron transfer must stop when all electronegativities have the same value

= the mean electronegativity $\bar{\chi}$

Partial Charge Model (Livage and Henry)

The mean electronegativity $\bar{\chi}$ of a molecule
z = the electric charge for ions
k = a constant that depends on the electronegativity scale
(k = 1.36 in Pauling's units)

$$\bar{\chi} = \frac{\sum_i \sqrt{\chi_i} + 1.36z}{\sum_i (1/\chi_i)},$$

The partial charge δ_i on an atom in the molecule

$$\delta_i = \frac{\bar{\chi} - \chi_i}{1.36\sqrt{\chi_i}}.$$

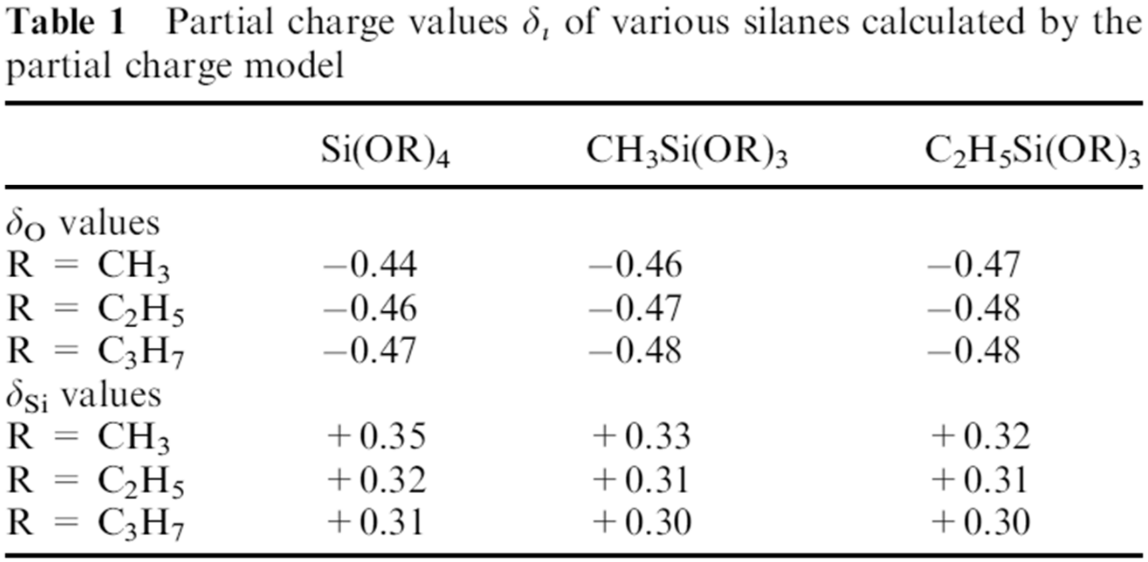


Table 1 Partial charge values δ_ι of various silanes calculated by the partial charge model

	$Si(OR)_4$	$CH_3Si(OR)_3$	$C_2H_5Si(OR)_3$
δ_O values			
R = CH_3	−0.44	−0.46	−0.47
R = C_2H_5	−0.46	−0.47	−0.48
R = C_3H_7	−0.47	−0.48	−0.48
δ_{Si} values			
R = CH_3	+0.35	+0.33	+0.32
R = C_2H_5	+0.32	+0.31	+0.31
R = C_3H_7	+0.31	+0.30	+0.30

Partial Charge Model (Livage and Henry)

Alkoxide	**$Zr(OEt)_4$**	**$Ti(OEt)_4$**	**$Nb(OEt)_5$**	**$Ta(OEt)_5$**	**$VO(OEt)_3$**	**$W(OEt)_6$**	**$Si(OEt)_4$**
δ (M)	**+0.65**	**+0.63**	**+0.53**	**+0.49**	**+0.46**	**+0.43**	**+0.32**

The hydrolysis rate depends on the δ (M):

The more positive partial charge δ_i the faster hydrolysis reaction

$$k_h \approx 5\cdot10^{-9}\ \text{mol}^{-1}\text{s}^{-1}\ \text{for}\ Si(OEt)_4$$

$$k_h \approx 10^{-3}\ \text{mol}^{-1}\text{s}^{-1}\ \text{for}\ Ti(OEt)_4$$

Partial Charge Model

the number of valence electrons n* on the central atom of a radical ·AB

$$n^* = (N - p) + \frac{2m\chi_B}{\chi_A + \chi_B} - \frac{s\chi_A}{\chi_A + \chi_B}$$

N = the number of valence electrons on the free atom A
p = the number of valence electrons supplied by B when forming the A–B bond.
m = the number of bonds between A and B
s = the number of resonance contributions from A^- B+

Group electronegativity χ^g

$$\chi^g = 0.31\left(\frac{n^* + 1}{r_A}\right) + 0.50$$

r_A = the covalent radius of atom A in the radical AB.

Partial Charge Model

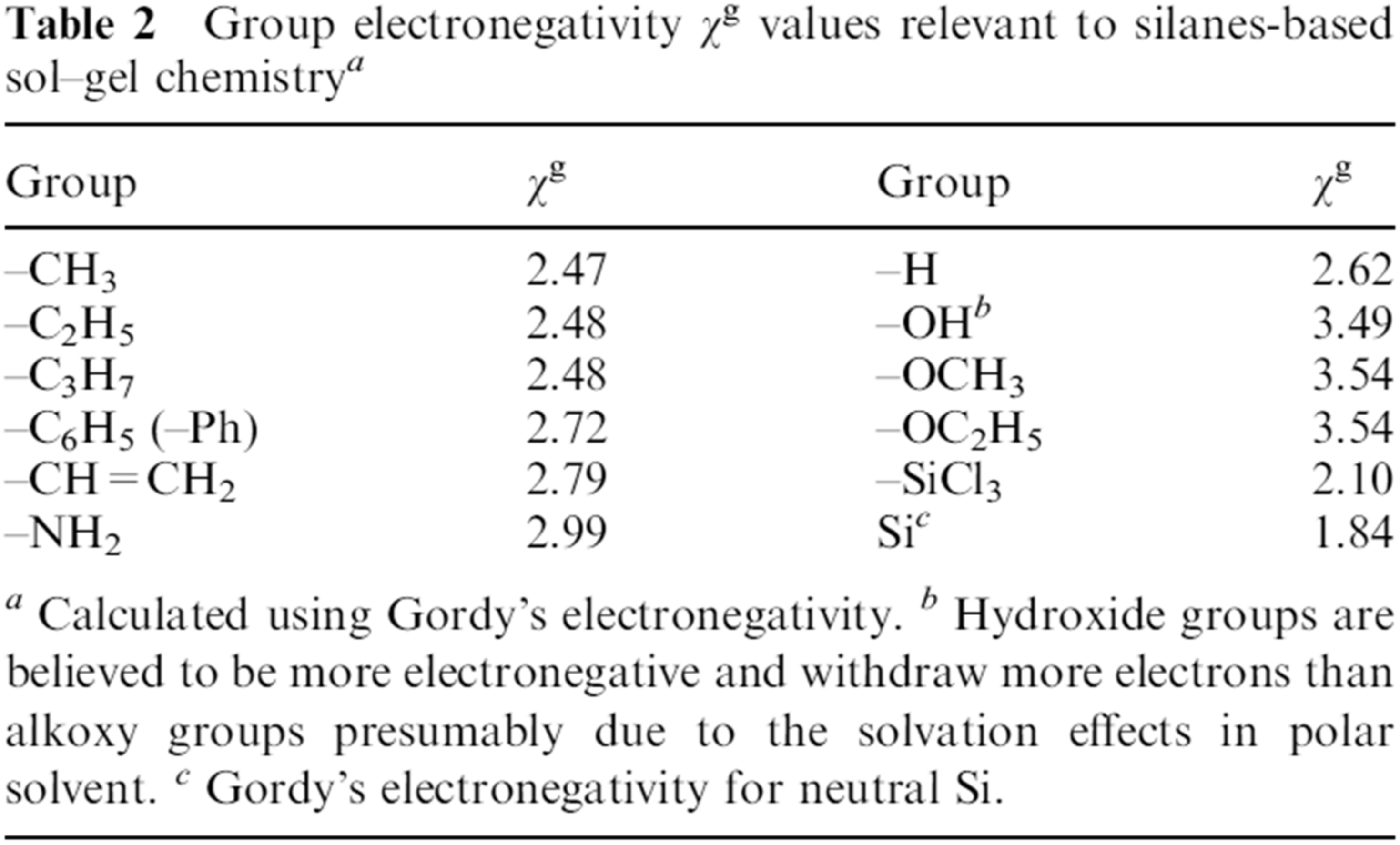


Table 2 Group electronegativity χ^g values relevant to silanes-based sol–gel chemistry[a]

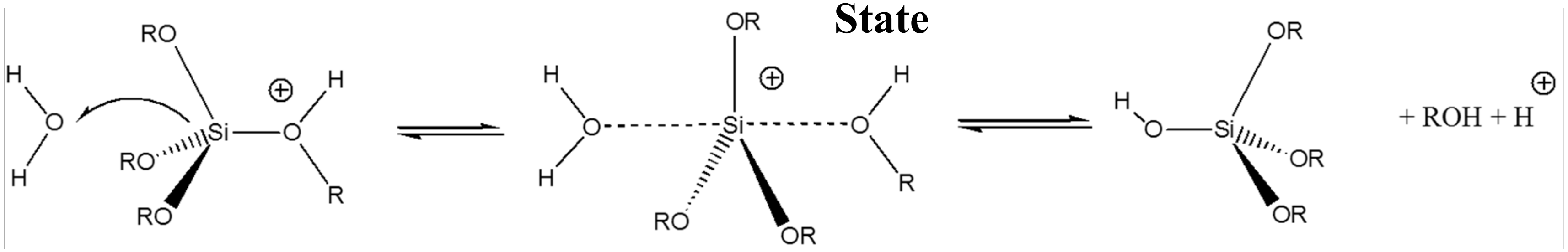
Group	χ^g	Group	χ^g
$-CH_3$	2.47	$-H$	2.62
$-C_2H_5$	2.48	$-OH$[b]	3.49
$-C_3H_7$	2.48	$-OCH_3$	3.54
$-C_6H_5$ (–Ph)	2.72	$-OC_2H_5$	3.54
$-CH=CH_2$	2.79	$-SiCl_3$	2.10
$-NH_2$	2.99	Si[c]	1.84

[a] Calculated using Gordy's electronegativity. [b] Hydroxide groups are believed to be more electronegative and withdraw more electrons than alkoxy groups presumably due to the solvation effects in polar solvent. [c] Gordy's electronegativity for neutral Si.

Hydrolysis

Acid catalysed hydrolysis

Transition State



Acidic conditions:

Hydrolysis reaction rate decreases as more alkoxy groups are hydrolyzed

Electron density at Si decreases:

$R\rightarrow Si > \boxed{RO\rightarrow Si > HO-Si} > SiO\leftarrow Si$

TS (+) is destabilized by increasing number of electron withdrawing OH groups (wrt OR)

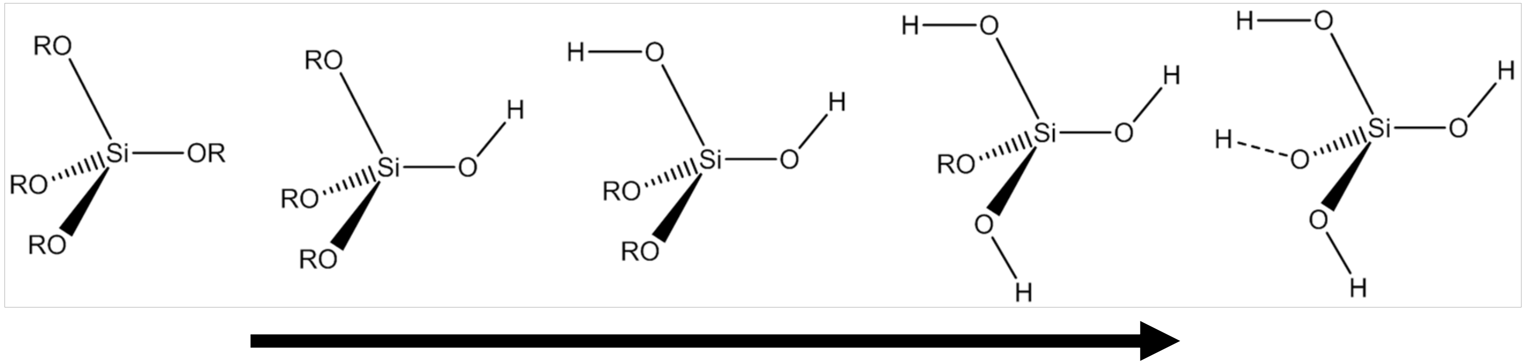
The reaction at terminal Si favored, as there is only one electron withdrawing SiO group

Linear polymer products are favored, leading to fibers

$RSi(OR)_3$ is more reactive than $Si(OR)_4$

Hydrolysis

Acid catalysed hydrolysis



Hydrolysis reaction rate decreases as more alkoxy RO groups are hydrolyzed and replaced with OH groups

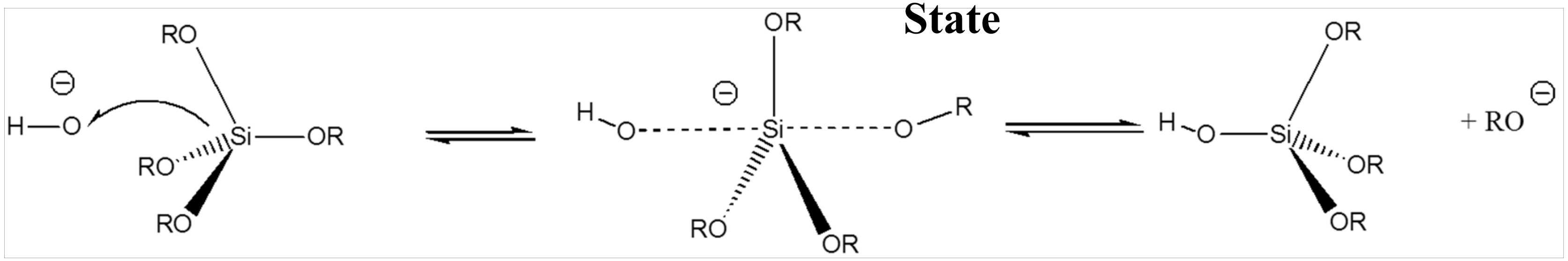
Electron density at Si decreases:

R→Si > RO→Si > HO–Si > SiO←Si

Hydrolysis

Base catalysed hydrolysis

Transition State



Basic conditions:

Hydrolysis reaction rate increases as more alkoxy groups are hydrolyzed

Electron density at Si decreases:

$R\rightarrow Si > \boxed{RO\rightarrow Si > HO\text{–}Si} > SiO\leftarrow Si$

TS (–) is stabilized by increasing number of electron withdrawing OH groups (wrt OR)

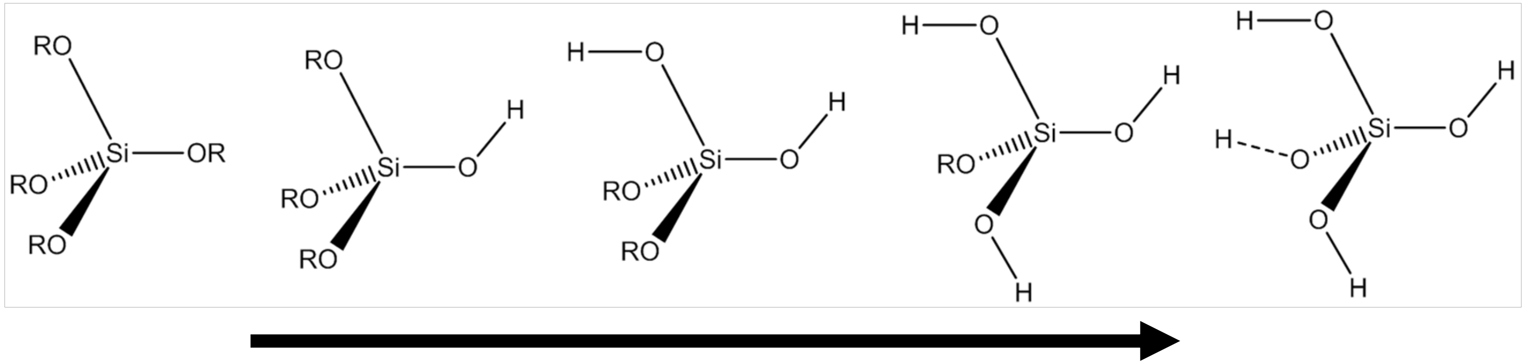
The reaction at central Si favored, as there is more electron withdrawing SiO groups

Branched polymer products are favored, spherical particles, powders

$RSi(OR)_3$ less reactive than $Si(OR)_4$

Hydrolysis

Base catalysed hydrolysis



Hydrolysis reaction rate increases as more alkoxy RO groups are hydrolyzed and replaced with OH groups

Electron density at Si decreases:

R→Si > RO→Si > HO–Si > SiO←Si

Sol-Gel Methods

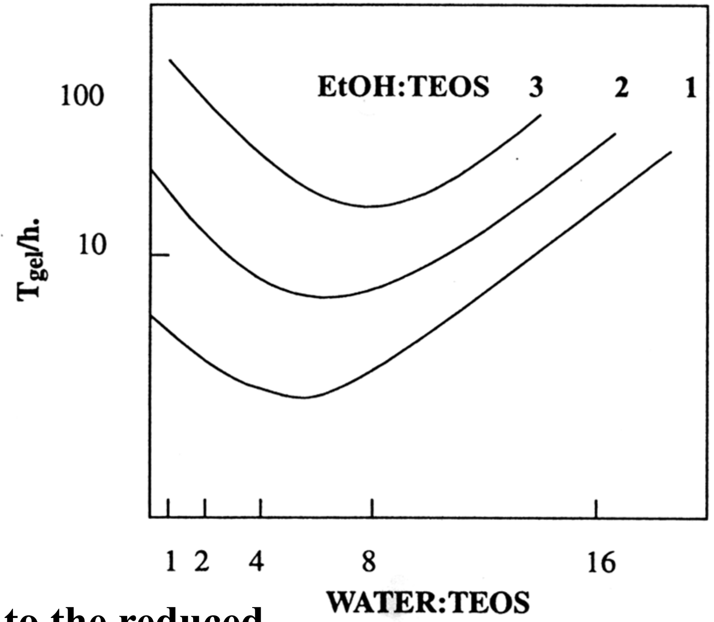
Si-OH becomes more acidic with increasing number of Si-O-Si bonds

Nucleophilic catalysis:

F^- Si-F bonds

HMPA
N-methylimidazol
N,N-dimethylaminopyridin

Sol-Gel Methods



Water-to-Si ratio (k)

stoichiometric ratio for complete hydrolysis k = 4

$Si(OR)_4 + 4 H_2O \rightarrow Si(OH)_4 + 4 ROH$

additional water comes from condensation

$Si\text{-}OH + HO\text{-}Si \rightarrow Si\text{-}O\text{-}Si + H_2O$

Small amount of water (k < 4) = slow hydrolysis due to the reduced reactant concentration
Condensation of incompletely hydrolyzed species

Large amount of water (k > 4) = slow hydrolysis due to the reactant dilution
Condensation of completely hydrolyzed species
Reverse reaction promoted - depolymerization of Si-O-Si

Sol-Gel Methods

Hydrophobic effect

$Si(OR)_4$ are immiscible with water

cosolvent ROH is used to obtain a homogeneous reaction mixture and prevent phase separation

Solvent properties:

polarity, dipole moment, viscosity, protic behavior:

Protic (EtOH) - bind to O–Si

Aprotic (THF) - bind to HO–Si

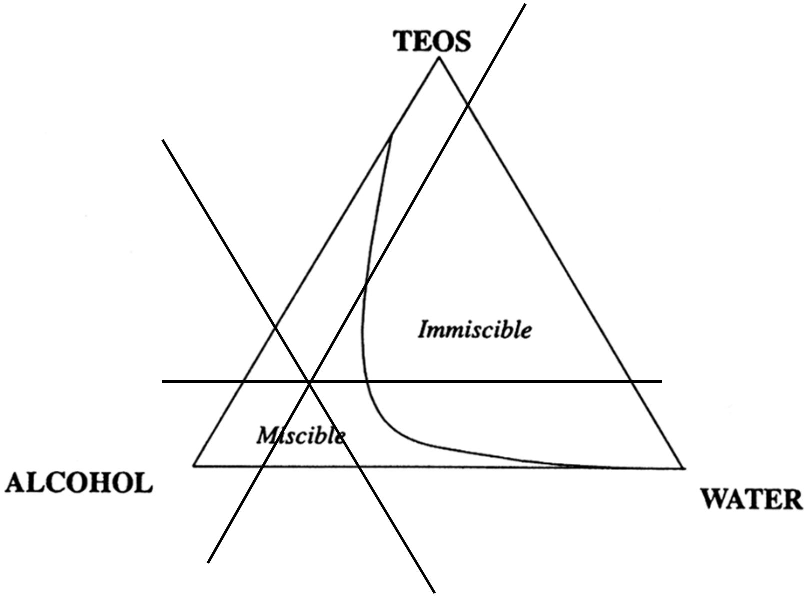
Affect rates

alcohol produced during the reaction

alcohols - transesterification

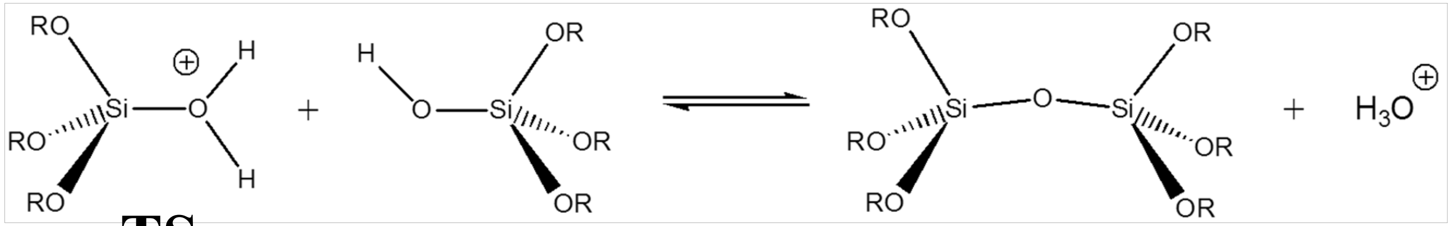
Sonication - homogenization

Solvents affect drying



Condensation

Acid catalysed condensation
fast protonation, slow condensation



TS

Positively charged transition state, fastest condensation for
$(RO)_3SiOH > (RO)_2Si(OH)_2 > ROSi(OH)_3 > Si(OH)_4$

TS (+) is destabilized by increasing number of electron withdrawing OH groups

Hydrolysis fastest in the first step, i.e. the formation of $(RO)_3SiOH$

Condensation for this species also fastest, the formation of linear chains

Condensation

Base catalysed condensation

fast deprotonation, slow condensation

TS

Negatively charged transition state, fastest condensation for $(RO)_3SiOH < (RO)_2Si(OH)_2 < ROSi(OH)_3 < Si(OH)_4$

TS (–) is stabilized by increasing number of electron withdrawing OH groups

Hydrolysis speeds up with more OH, i.e. the formation of $Si(OH)_4$

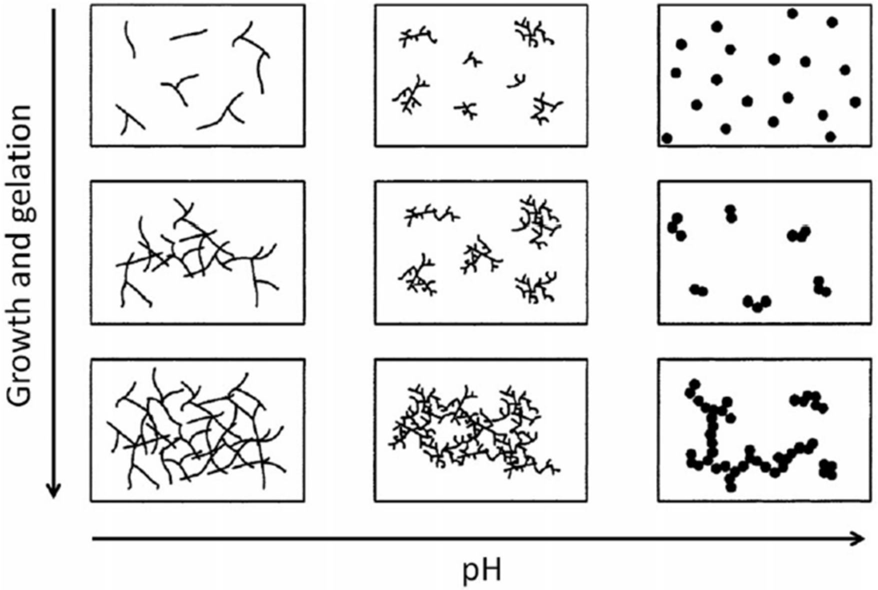
Condensation for the fully hydrolysed species fastest, the formation of highly crosslinked particles

Acid Catalysed Condensation

- For k > 4 : complete hydrolysis at early stage
- Reaction limited cluster aggregation (RLCA)
- Q^0 or terminal groups Q^1 on chains
- Irreversible reactions in acidic pH
- Condensation to linear chains or weakly branched

- For k < 4 : incomplete hydrolysis at early stage
- Unhydrolysed chains, highly concentrated solution without gelling
- Spinnable to fibers
- Small primary particles
- Microporosity, Type I isotherms

pH ~ 2

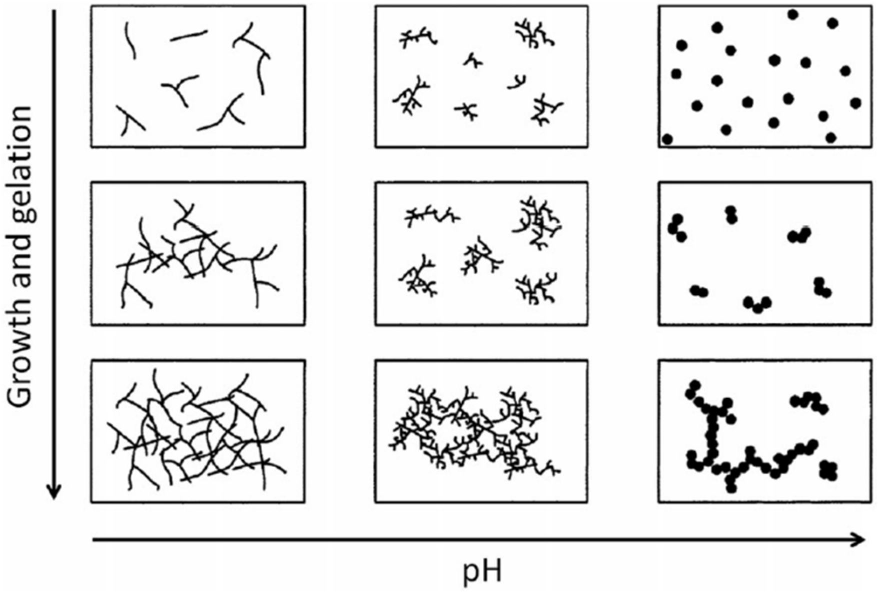


Base Catalysed Condensation

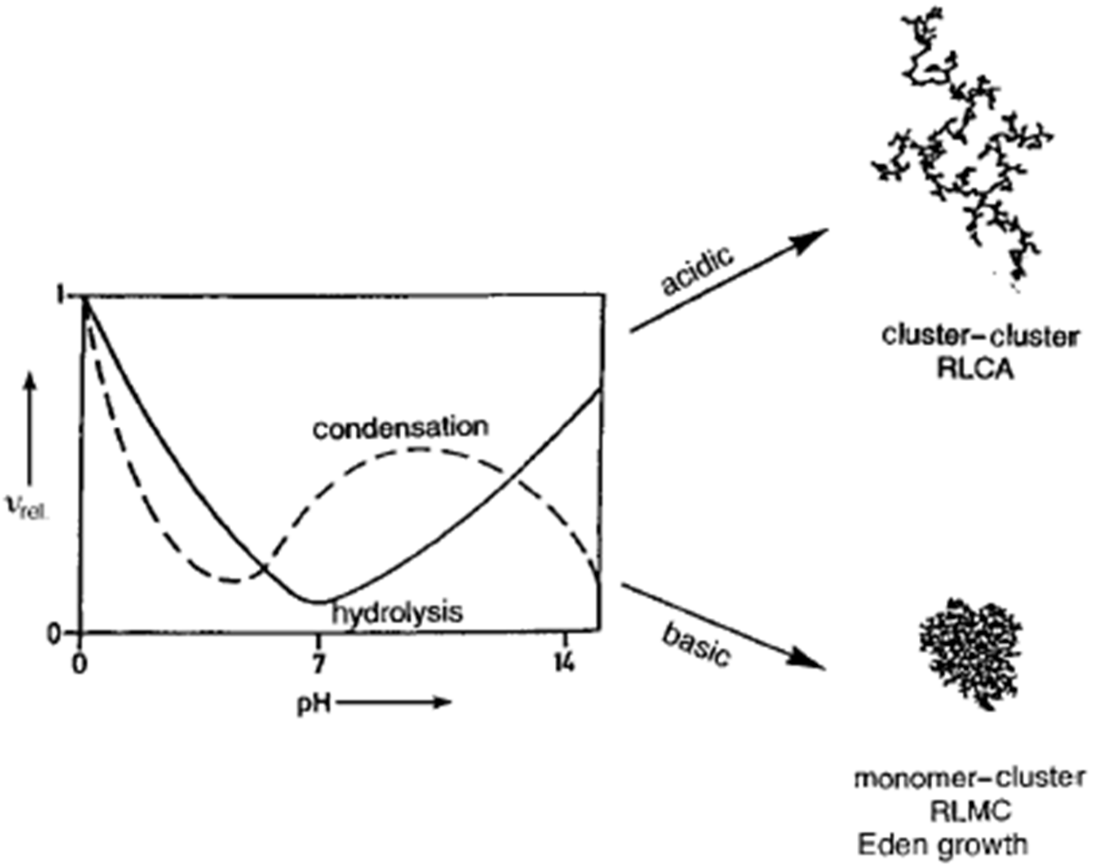
- **For k > 4 : complete hydrolysis at early stage**
- **Reversible reactions in basic pH**
- **Chains cleaved at Q^1, source of Q^0**
- **Condensation to highly crosslinked particles**
- **Reaction limited monomer-cluster growth (RLMC)**
- **Compact nonfractal structure**

- **For k < 4 : incompletely hydrolysed species incorporated**
- **Fractal uniformly porous structure**
- **Large primary particles**
- **Mesoporosity, Type IV isotherms**

pH > 7



Reaction limited cluster aggregation (RLCA)



Acid catalysed

Base catalysed

Reaction limited monomer-cluster growth (RLMC) or Eden growth

Hydrolysis - Condensation Kinetics

$Si(OR)_x(OH)_y(OSi)_z$

$$Si(OR)_4 \xrightarrow{\text{Hydrolysis}} Si(OH)_4$$

400	310	220	130	040
	301	211	121	031
		202	112	022
			103	013
x y z				004

$$Si(OH)_4 \xrightarrow{\text{Condensation}} Si(OSi)_4$$

$x + y + z = 4$

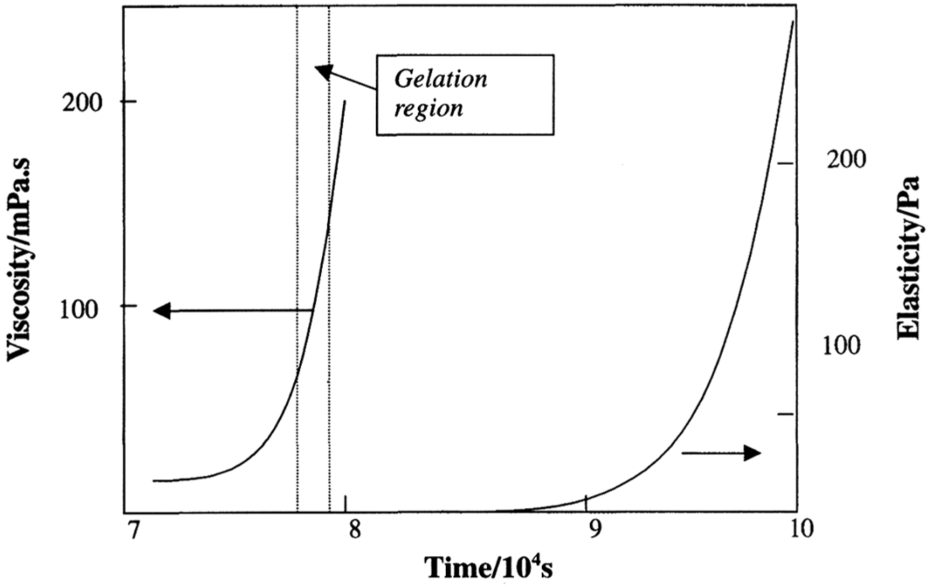
Gelation = Sol-to-Gel Transition

Gel point **- a spannig cluster reaches across the container,**

sol particles, oligomers and monomer still present

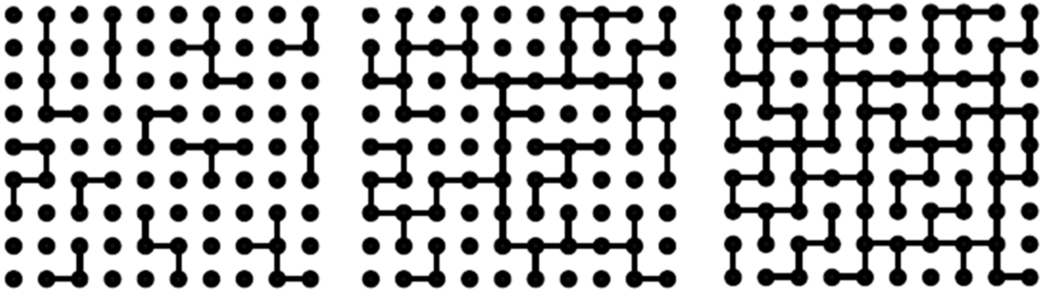
a sudden viscosity increase at the gel point

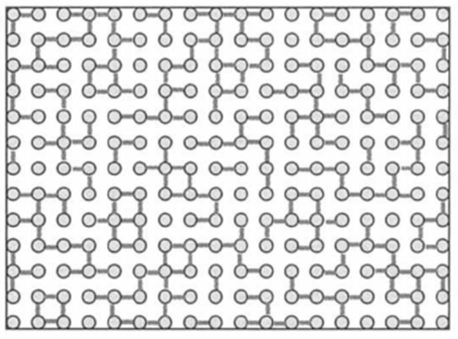
further crosslinking - increase in elasticity



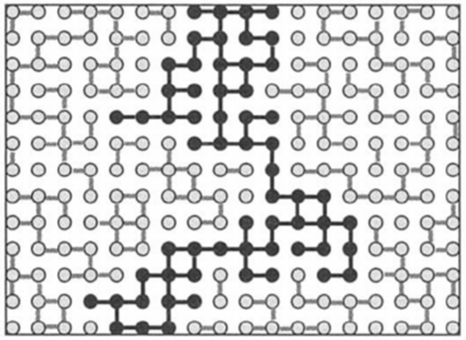
Bond Percolation

p = the fraction of created links

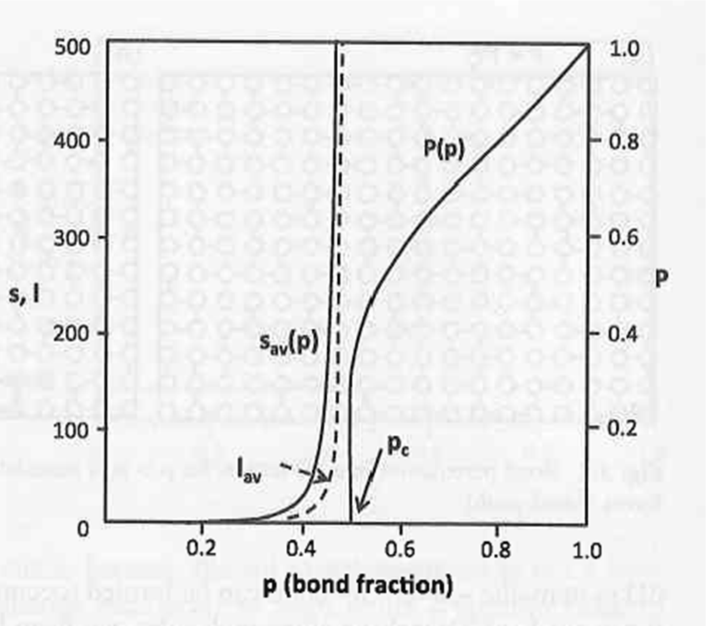




$p < p_c$



$p > p_c$

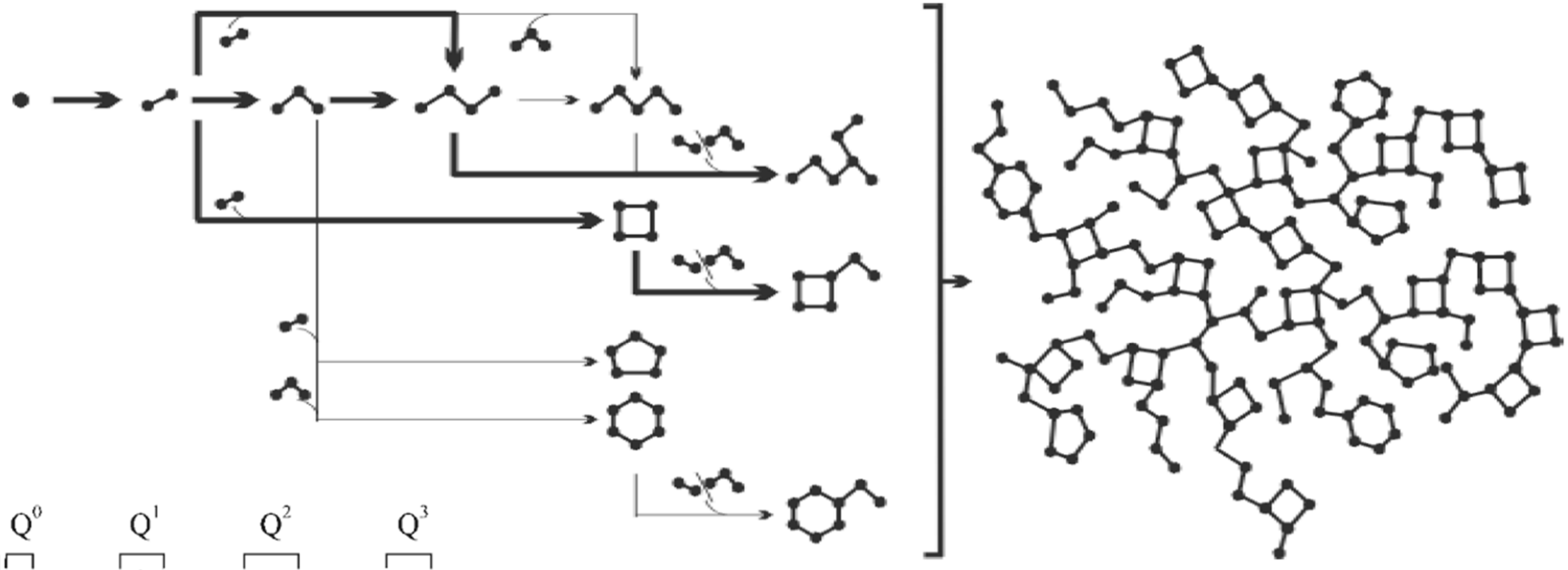


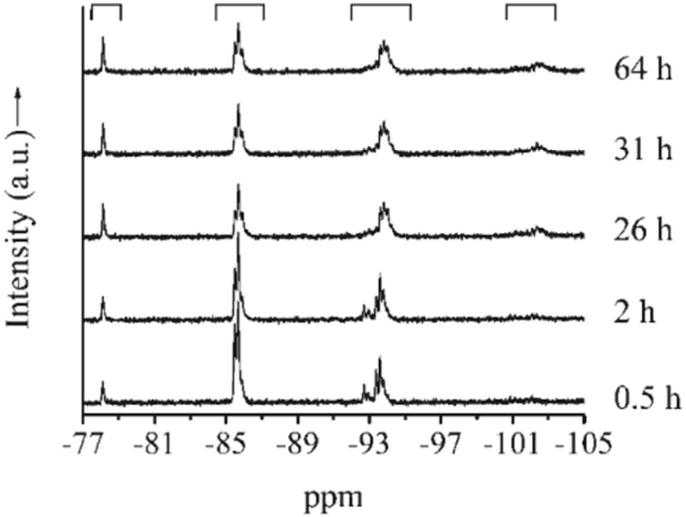
s_{av}(p) = average cluster size

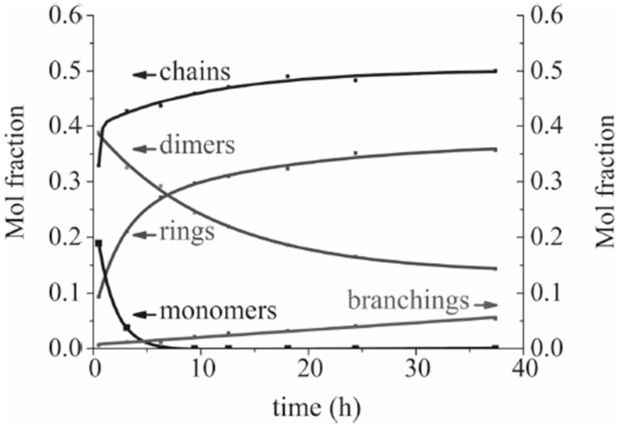
l_{av}(p) = average spanning length

P(p) = percolation probability = a bond is added to a spanning cluster

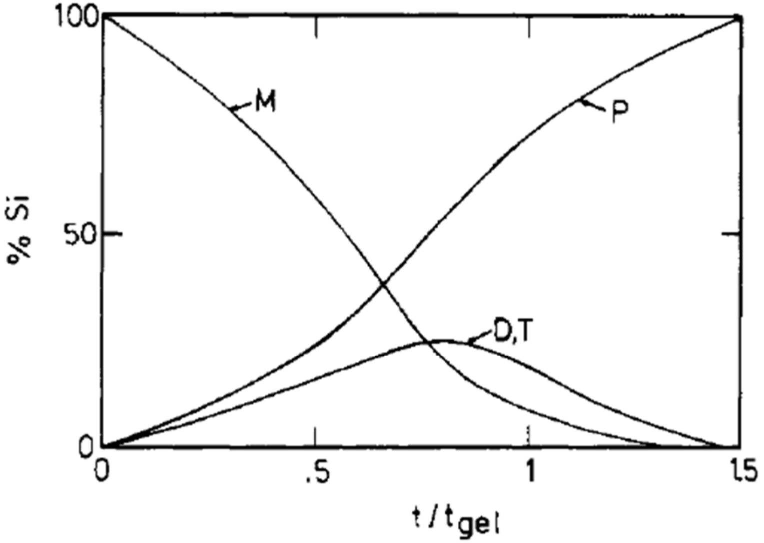
Sol-to-Gel Transition

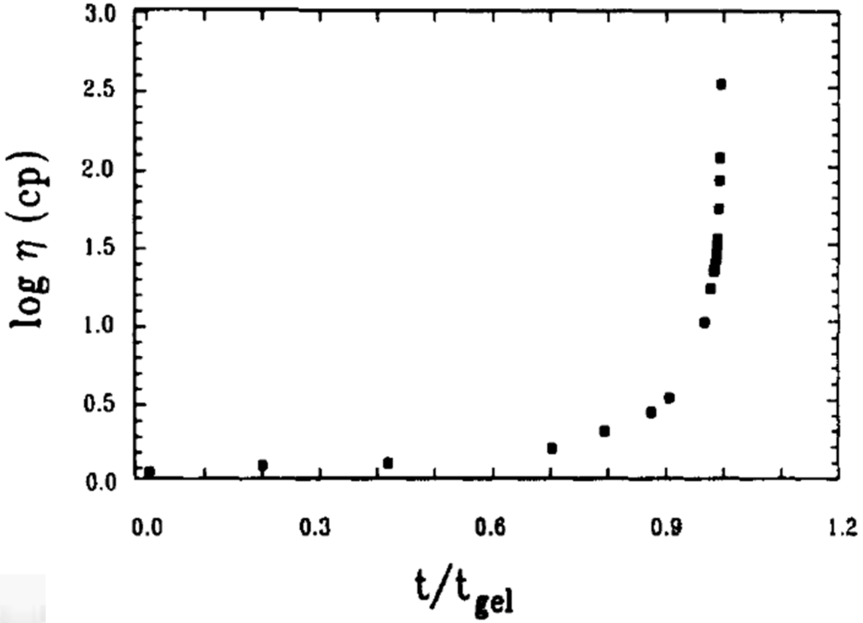


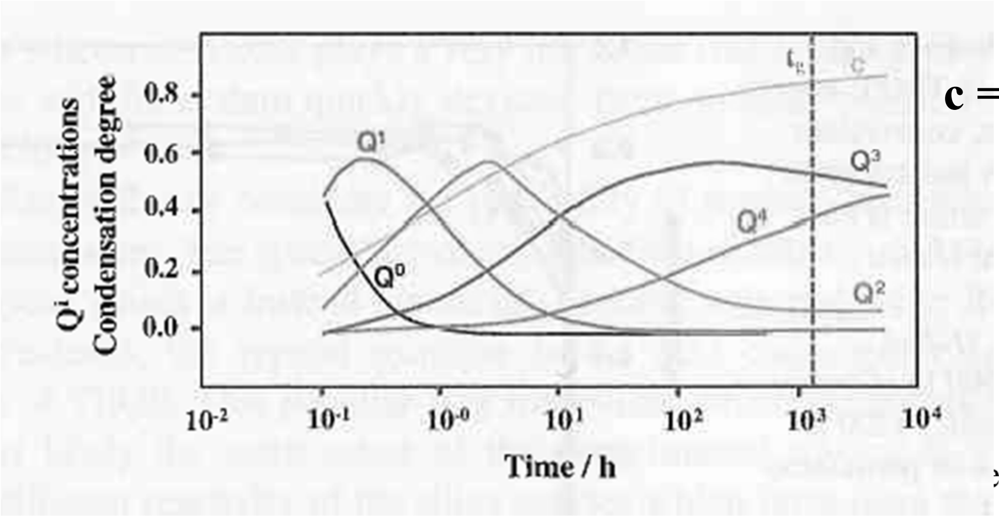




Sol-to-Gel Transition

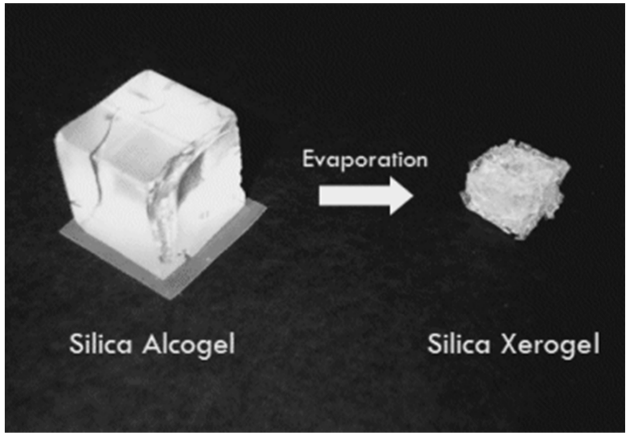






c = condensation degree, max 83 %

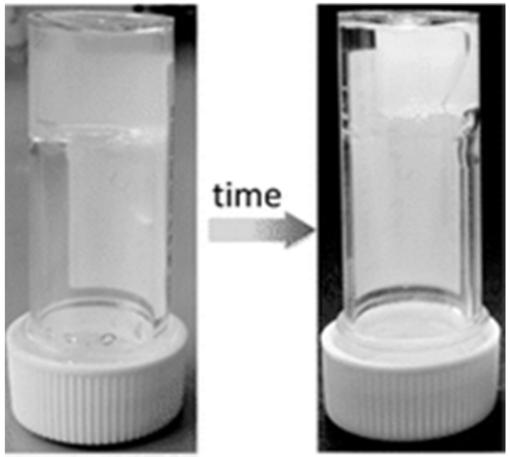
Ageing of Gels



Ageing

Crosslinking
condensation of the OH surface groups, stiffening and shrinkage

Syneresis
shrinkage causes expulsion of liquid from the pores



Coarsening
materials dissolve from the convex surfaces and deposits at the concave surfaces: necks

Rippening
Smaller particles have higher solubility thean larger ones

Phase separation
Fast gelation, different miscibility, isolated regions of unreacted precursor, inclusions of different structure, opaque, phase separation

Drying of Gels

1. The constant rate period
the gel is still flexible and shrinks as liquid evaporates

2. The critical point
the gel becomes stiff and resists further shrinkage and deformation by surface tension, the liquid begins to recede (meniscus with a contact angle θ) into the pores (radius r), surface tension γ creates large capillary pressures P_c, stress, cracking

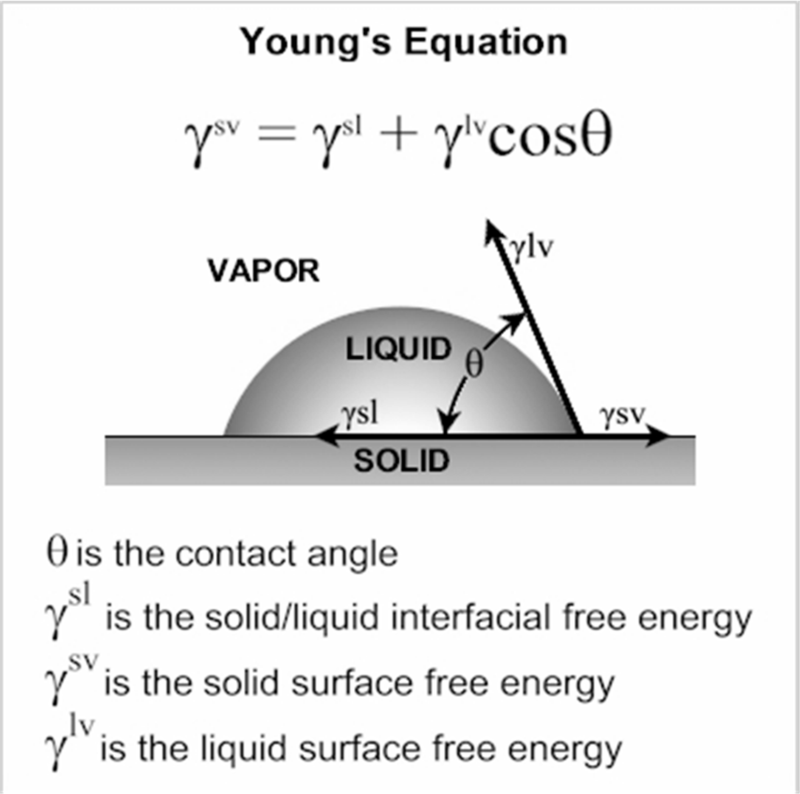
$$P_c = \frac{2\gamma \cos\theta}{r}$$

3. The first falling-rate period
a thin liquid film remains on the pore walls, flows to the surface and evaporates, the menisci first recede into the largest pores only, as these empty, the vapor pressure drops and smaller pores begin to empty

4. The second falling-rate period
liquid film on the walls is broken, further liquid transport by evaporation

Drying of Gels

$$P_c = \frac{-2\gamma_{LV}\cos\theta}{r}$$



Young's Equation

$$\gamma^{sv} = \gamma^{sl} + \gamma^{lv}\cos\theta$$

θ is the contact angle

γ^{sl} is the solid/liquid interfacial free energy

γ^{sv} is the solid surface free energy

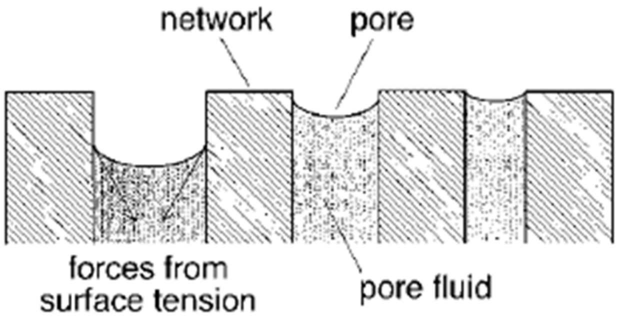
γ^{lv} is the liquid surface free energy

$$P_c = 2\gamma/r$$

Wetting surface: $\cos\theta = 1$
Water: $\gamma = 72.75$ mN/m
n-Pentan: $\gamma = 16.0$ mN/m
Pore: $r = 2$ nm

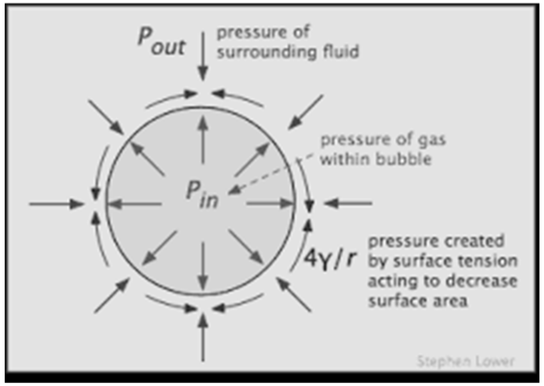
$$P_c = 73 \text{ MPa}$$

Drying of Gels



$$P_c = \frac{2\gamma\cos\theta}{r}$$

$$\ln\frac{p}{p_0} = \frac{2\gamma V_\mathrm{m}}{rRT},$$



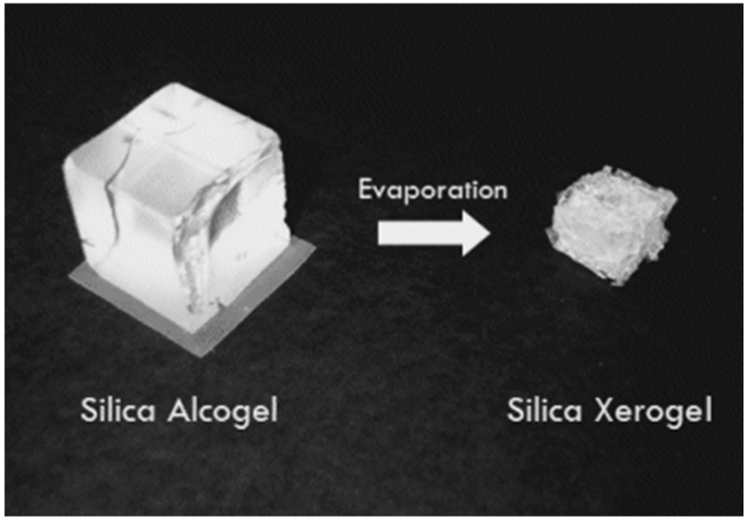
Drying Methods

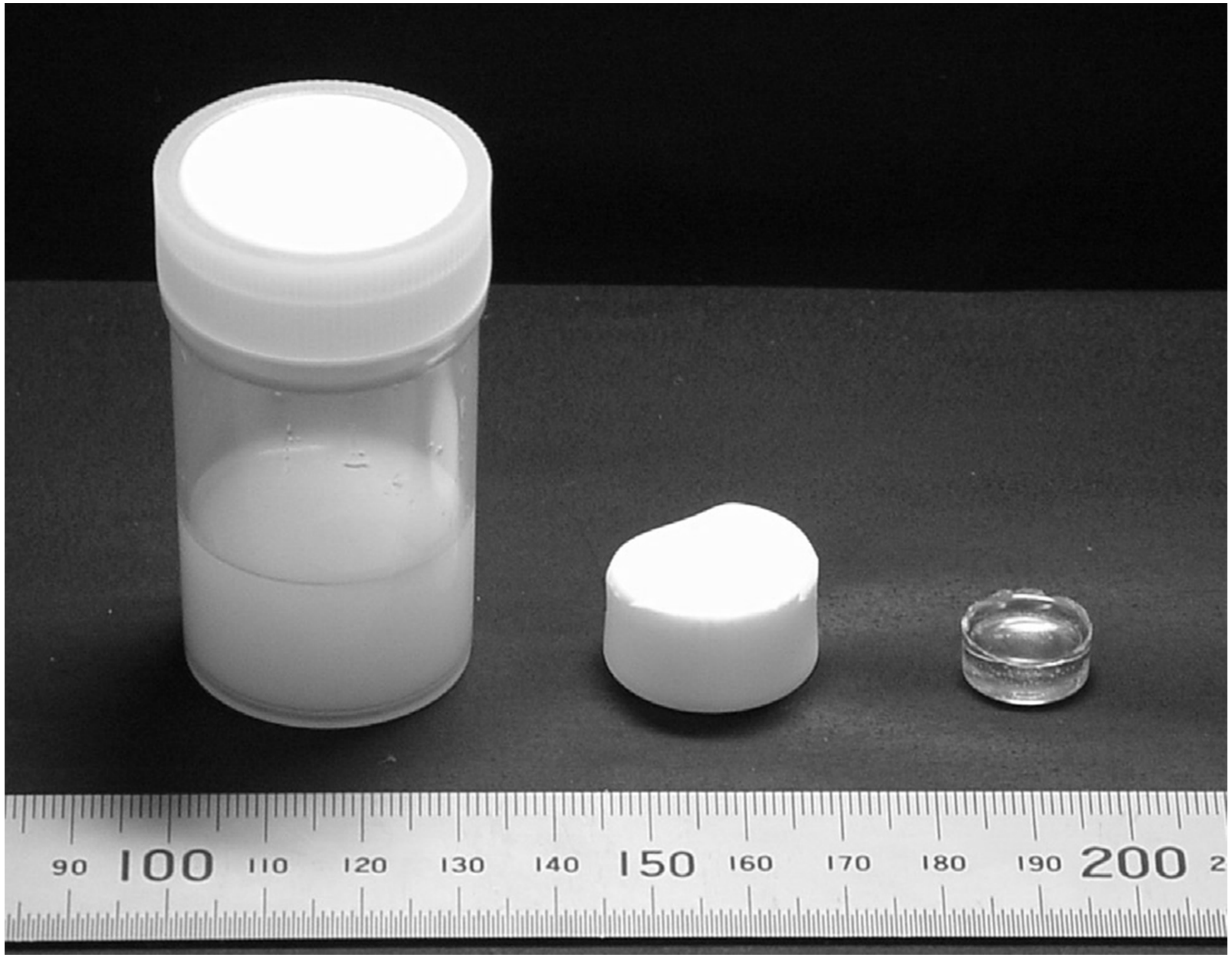
To avoid cracking:

$$P_c = \frac{2\gamma\cos\theta}{r}$$

- **No meniscus**
- **Decrease surface tension**
- **Increase wetting angle (isopropanol)**
- **Increase pore size**
- **Make a stiff gel**

1. **Supercritical drying**
2. **Freeze-drying**
3. **Drying control chemical additives**
4. **Ageing**
5. **Large pore gels**





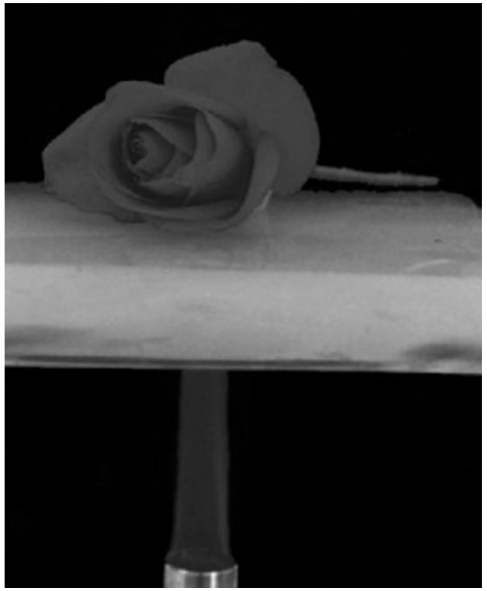
25 mmol (5.2 g) of tetraethoxysilane (TEOS)
TEOS:H_2O:HNO_3:ammonium acetate molar ratio of the solution is 1 : 10 : 0.002 : 0.02

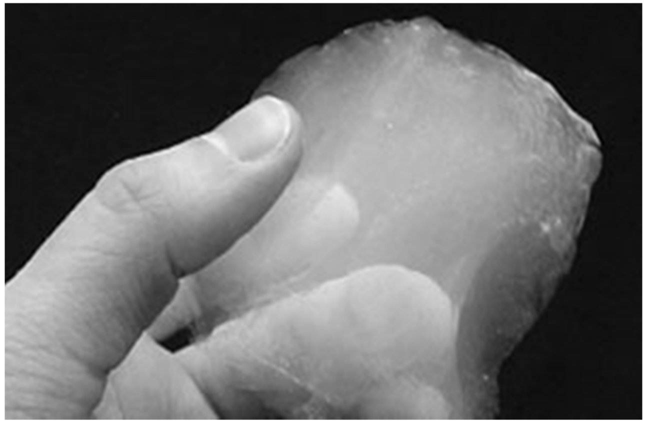
Aerogels

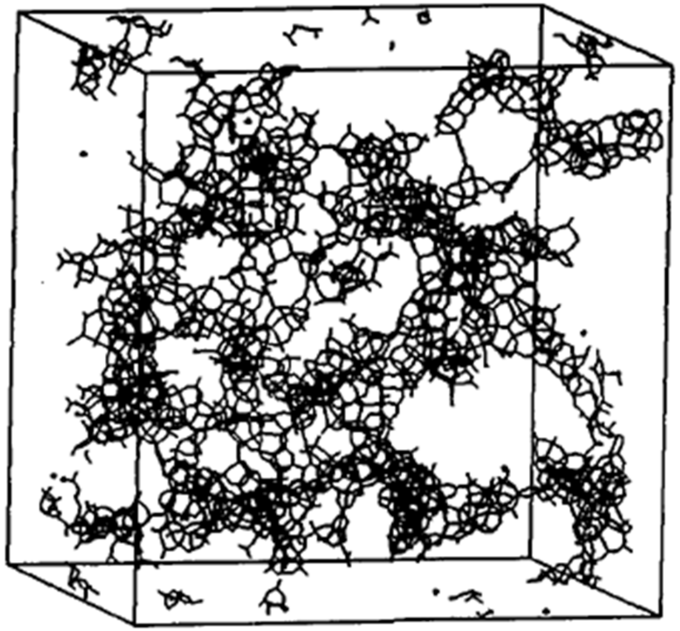
1931 Steven S. Kistler J. Phys. Chem. 34, 52, 1932

Aerogels = materials in which the typical structure of the pores and the network is largely maintained while the pore liquid of a gel is replaced by air

The record low density solid material - 10 mg/cm^3
density of air 1.2 mg/cm^3



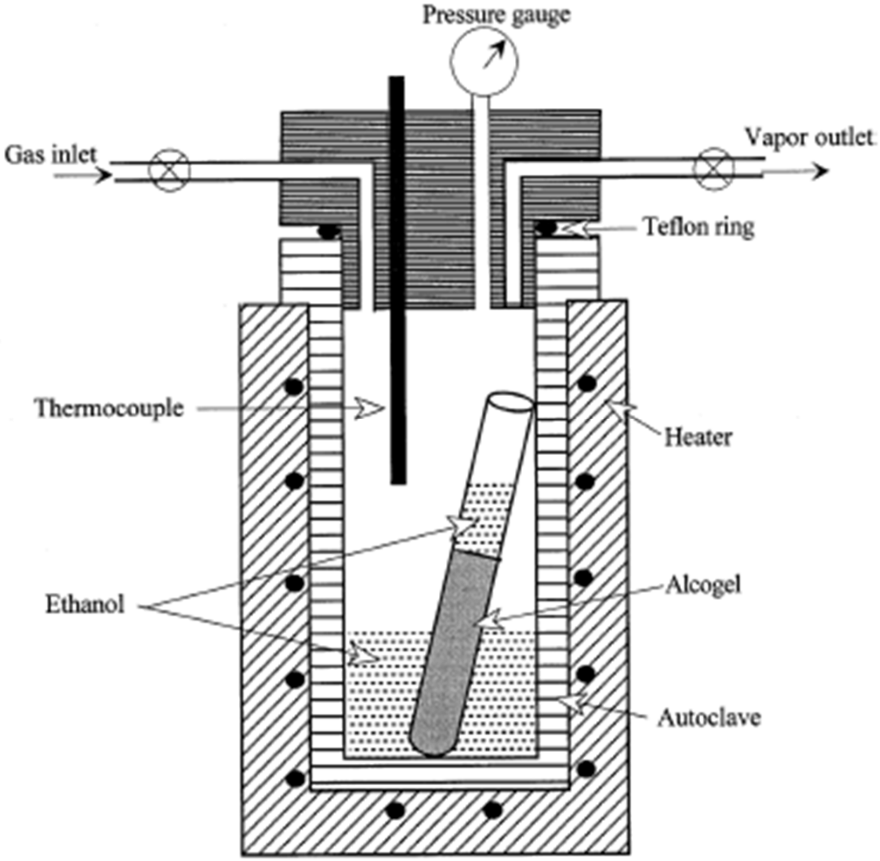




Aerogels - Supercritical Drying

Silica aerogel

- **Byproduct, salt, water washing**
- **Water replacement with acetone**
- **Replacement of acetone with CO_2 (l)**
- **Supercritical drying**



Aerogels - Supercritical Drying

Silica aerogel

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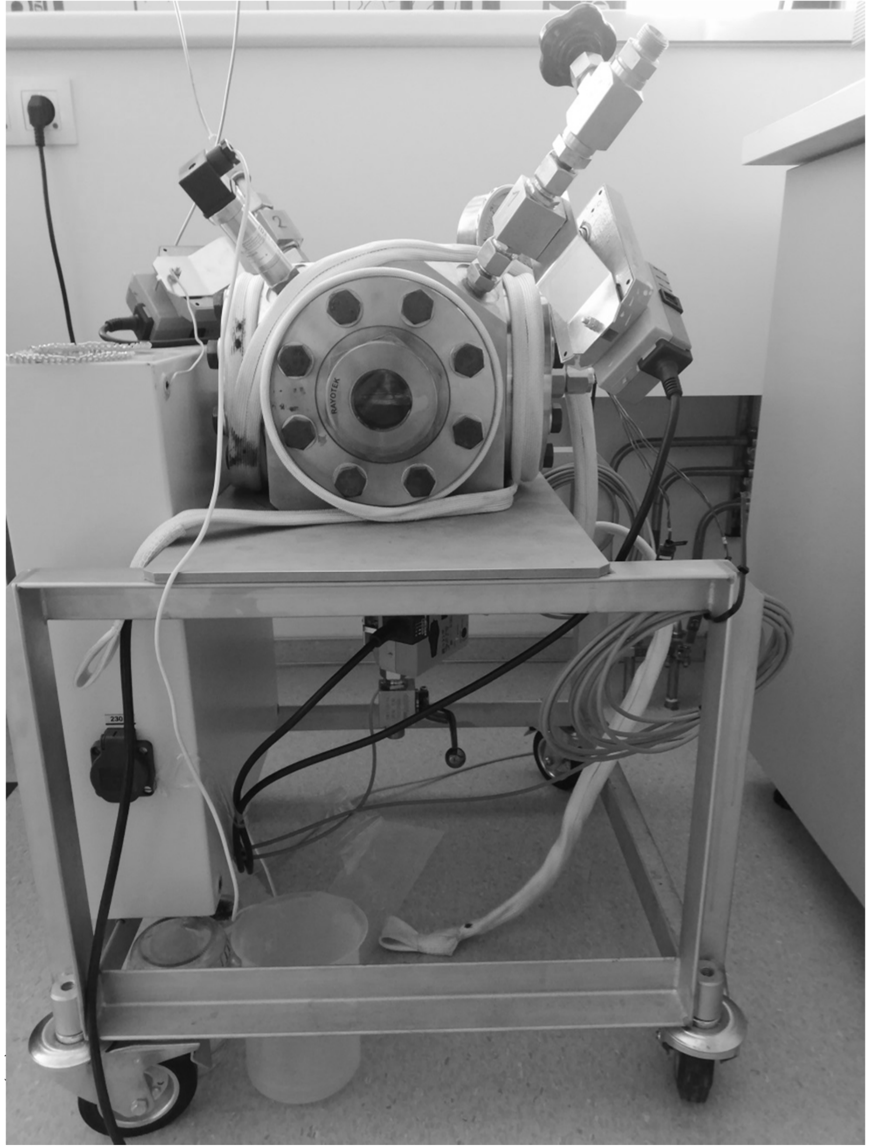
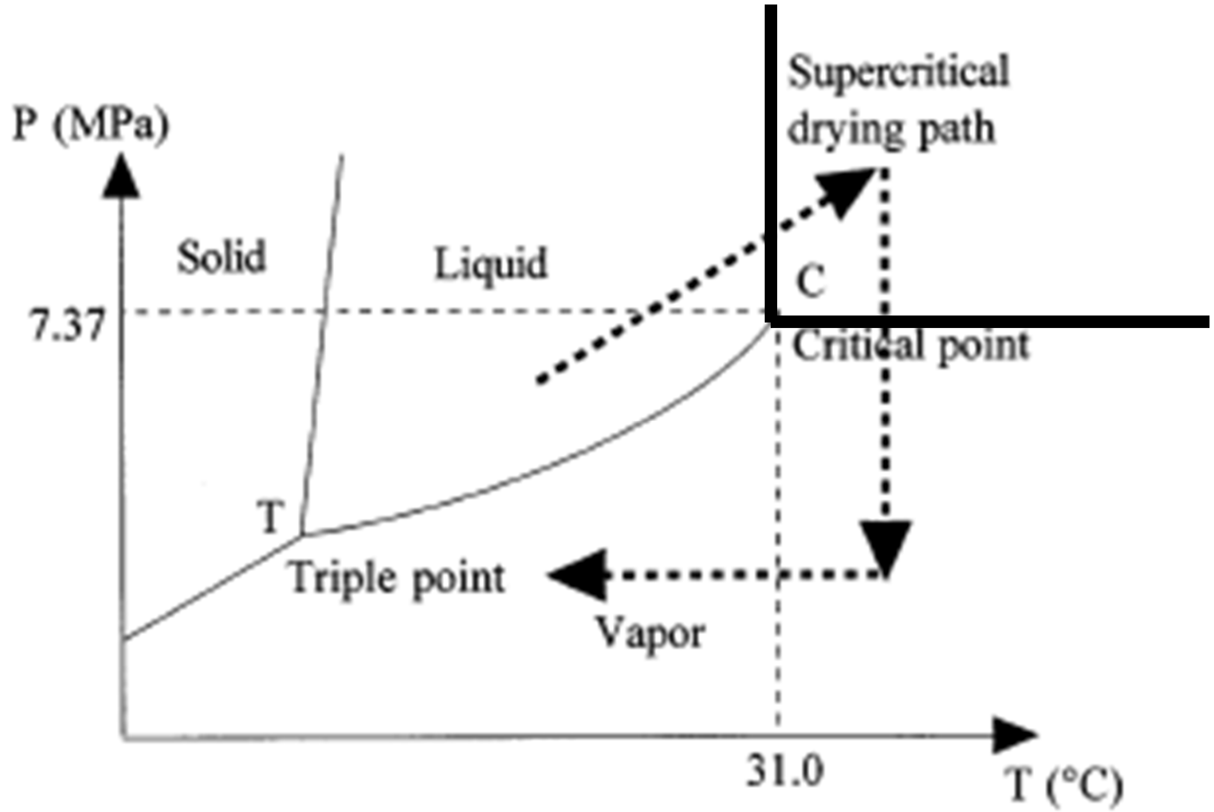
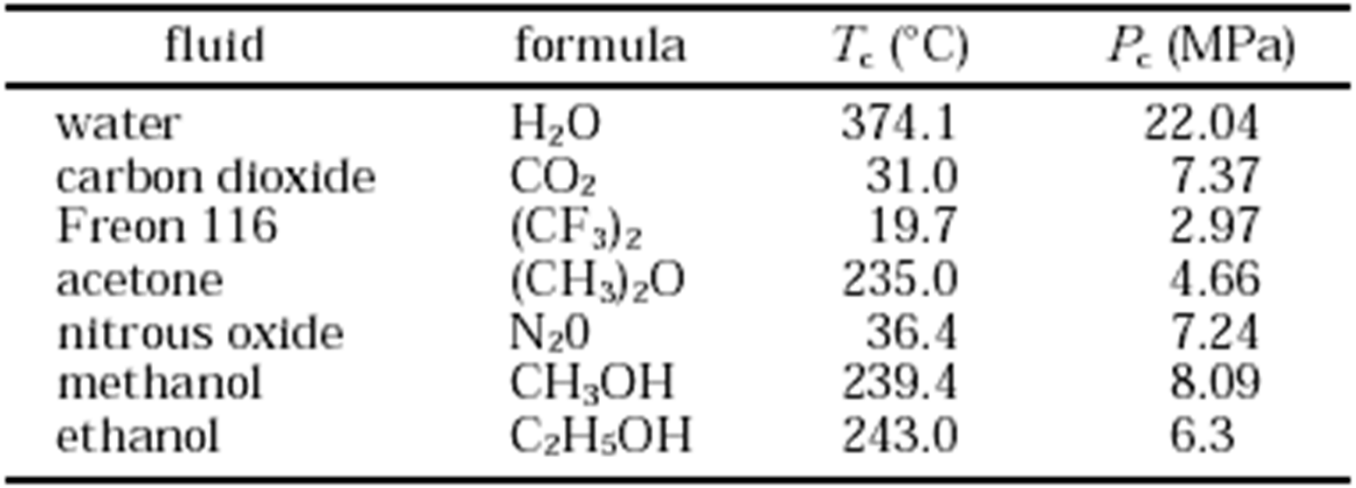


Supercritical Drying

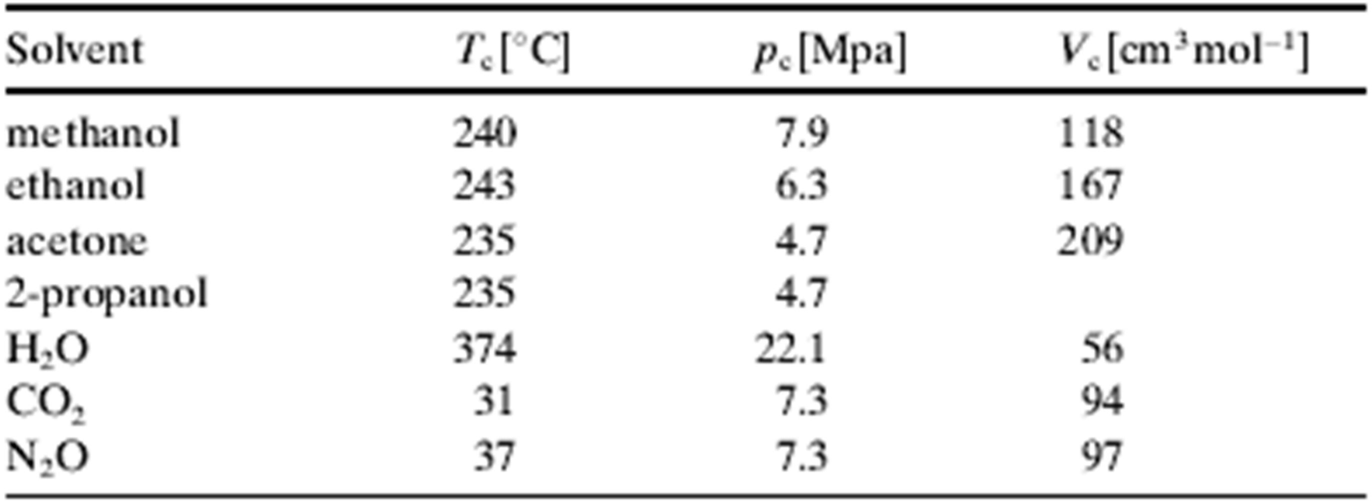


Cold supercritical drying path in the Pressure (P) Temperature (T) phase diagram of CO_2

Supercritical Drying



fluid	formula	T_c (°C)	P_c (MPa)
water	H_2O	374.1	22.04
carbon dioxide	CO_2	31.0	7.37
Freon 116	$(CF_3)_2$	19.7	2.97
acetone	$(CH_3)_2O$	235.0	4.66
nitrous oxide	N_20	36.4	7.24
methanol	CH_3OH	239.4	8.09
ethanol	C_2H_5OH	243.0	6.3



Solvent	T_c [°C]	p_c [Mpa]	V_c [$cm^3 mol^{-1}$]
methanol	240	7.9	118
ethanol	243	6.3	167
acetone	235	4.7	209
2-propanol	235	4.7	
H_2O	374	22.1	56
CO_2	31	7.3	94
N_2O	37	7.3	97

Sintering

Common ceramic and metallurgic manufacturing process

Thermal sintering
A powder is first pressed into a highly porous pellets
50-60% of the maximum theoretical density = green pellet
heating, the pellet densifies, reducing surface area and surface energy of individual particles without reaching melting point, sintering time - several hours to several days

Other methods of sintering:

- two-phase sintering
- microwave sintering
- spark-plasma sintering
- oxidative sintering

Control of sintering
sintering parameters: temperature, pressure, time, atmosphere

Sintering

Sintering - self-diffusion of atoms in the crystal lattice

Atoms diffuse randomly through the lattice by moving into adjacent vacant lattice sites = vacancies

A vacant lattice site increases the energy of the lattice

Atoms on the surface of particles have higher energies than the atoms in the particle interiors

Energy is lower if the particle is in contact with another particle of the same material than if it is in contact with the atmosphere or a different material

The lattice sites that increase the contact area between particles are preferred = around the edges of the contact area

Sintering

When atoms move out of the bulk and to the contact area - vacancies are created within the bulk

The overall energy change - the difference of the energy reduced by increasing the surface area and the energy increased by creating a vacancy = the sintering stress

The magnitude of the sintering stress depends on the contact angle between the particles = the dihedral angle

Sharper contact angles reduce the overall energy, as the contact area increases the dihedral angle widens

Eventually it reaches a wide enough angle that the sintering stress is zero and sintering ceases = the equilibrium dihedral angle

Sintering

Sintering stress

$$\sigma = \frac{\gamma}{R}$$

σ [MPa]	R [nm]
300	10
3	1000

γ is constant (e.g. 1,5 $J.m^{-2}$)

σ – sintering stress [Pa]

γ – surface energy [$J.m^{-2}$]

R – diameter [m]

Densification rate:

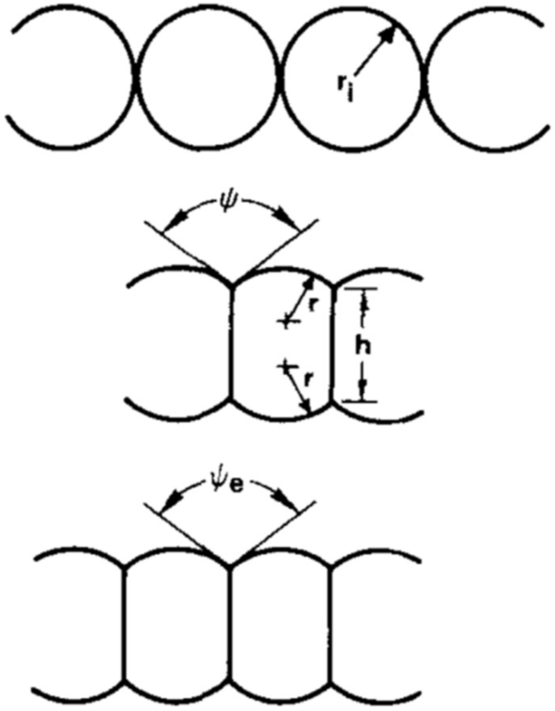
$$-\frac{dL}{Ldt} = \frac{\gamma\Omega}{kT}\left(\frac{\delta D_b \Gamma_b}{d^4} + \frac{D_\nu \Gamma_\nu}{d^3}\right)$$

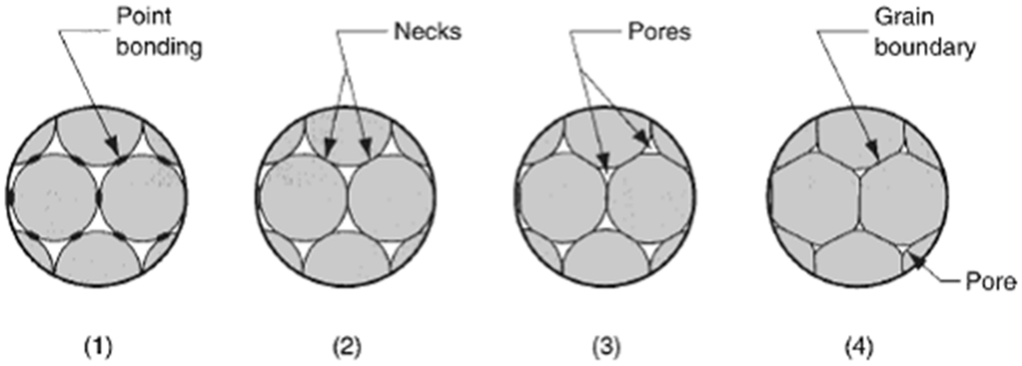
d – grain size

D/Γ/Ω – constants for diffusion/density functions/atomic volume

Decreace of particle diameter leads to much higher densification rate

Sintering


r_i
ψ
r
h
r
ψe

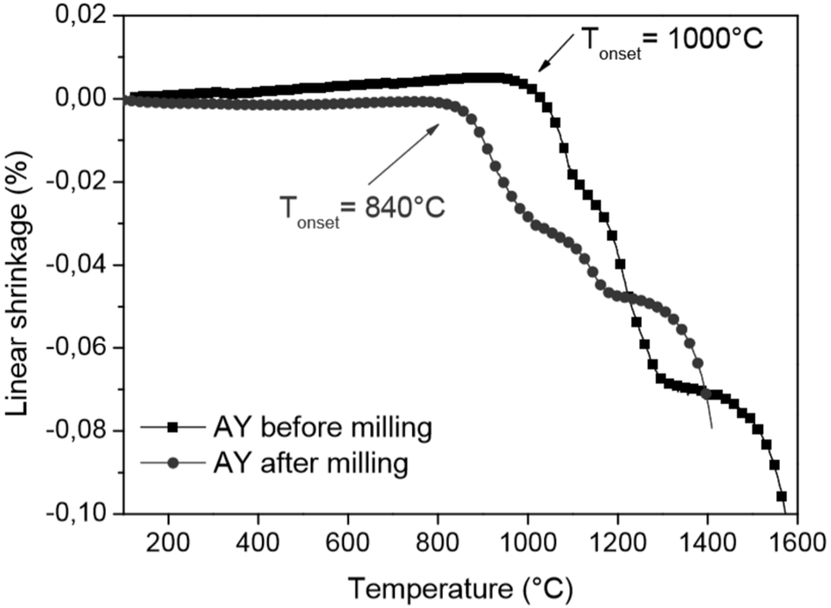

Point bonding
Necks
Pores
Grain boundary
Pore
(1)
(2)
(3)
(4)

Sintering

Larger agglomerates = higher sintering temperature

Agglomerates 3μm

Agglomerates 0.5μm



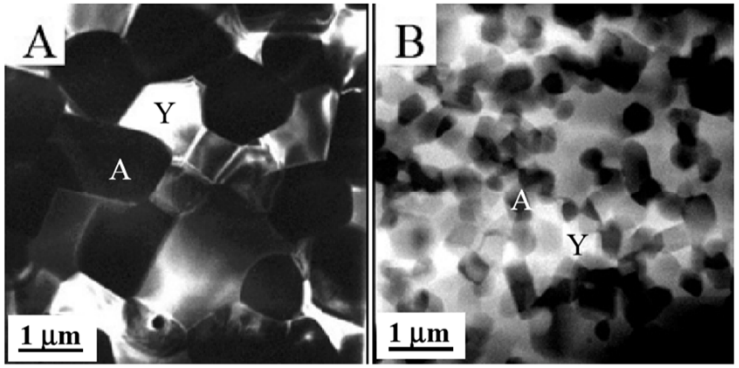


Figure 5. Transmission Electron Microscopy (TEM) images of AY materials. (**a**) Un-milled powder, sintered ad 1600 °C/3 h; (**b**) Milled powder sintered at 1420 °C/3 h. Characters A and Y refer to α-Al_2O_3 (black grains) and YAG (white grains), respectively.

Sintering

Because of the limit on the dihedral angle, it is possible for sintering to reach equilibrium with pores still present in the material

The rate at which sintering occurs is controlled by the diffusion rate and sintering stress

The diffusion rate is affected by the defect concentration and temperature

More defects mean more atoms can diffuse simultaneously, while higher temperatures allow individual atoms to diffuse faster = sintering is done at high temperature

Sintering

Stage I.
the powder particles increase their contact areas through the formation of necks, it ends once neck growth ceases to be the major mechanism

Stage II.
the overall density increases as the pores decrease in size, the contact areas grow into planes called grain boundaries, the pores become more columnar in shape as they shrink into tunnel systems on grain boundaries and triple junctions

Stage III.
begins when pores become closed off to the surface, grain boundary motion begins as the lattice continues to decrease its overall energy by decreasing the surface area between grains, large grains grow at the expense of smaller grains

Sintering

Grain boundaries move - pick up vacancies, impurity atoms, and even small pores. These small pores can come in contact with one another as grains are eliminated = grain boundary sweeping

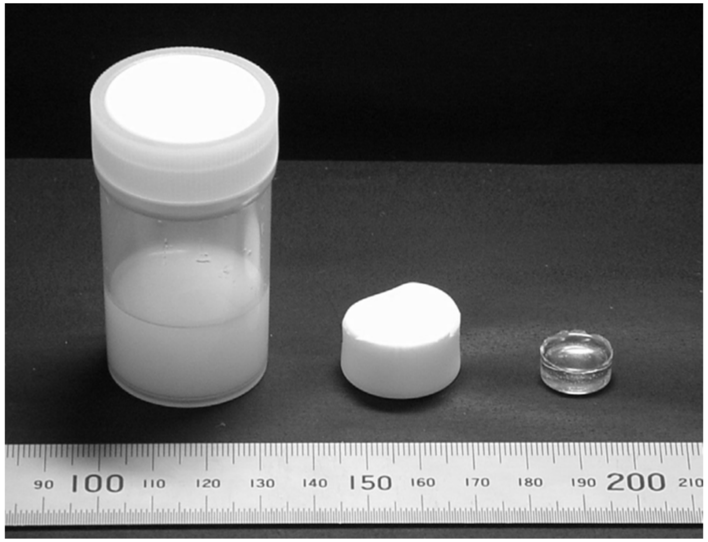
Reduction in the number of pores, defect concentration in regions near moving grain boundaries

In the final stage of sintering, atmospheric pressure becomes important. The pores are closed off from the surface - gas is trapped in the pores. As the pores decrease in volume the pressure inside the pore increases, pushing back against further pore shrinkage

If the temperature is raised suddenly, reverse sintering = the pores increase in volume

The gas will diffuse into the solid lattice, relieving pressure and allowing sintering to continue - the rate of sintering depends on the gas solubility

Densification



Densification

Stage I. Below 200 °C, weight loss, no shrinkage

pore surface liquid desorption

Stage II. 150 - 700 °C, both weight loss and shrinkage

loss of organics - weight loss
further condensation - weight loss and shrinkage
structural relaxation - shrinkage

Stage III. Above 500 °C, no more weight loss, shrinkage only

close to glass transition temperature, viscous flow, rapid densification, large reduction of surface area, reduction of interfacial energy, termodynamically favored

Mechanical Properties

$$\sigma_{yp} = \sigma_o + \frac{k}{\sqrt{d}}$$

- **τ – yield stress**
- **H – microhardness**
- **d – average grain size**

$$H = H_0 + \frac{k}{\sqrt{d}}$$

Smaller grains – higher yield stress and hardness!

Mechanical Properties

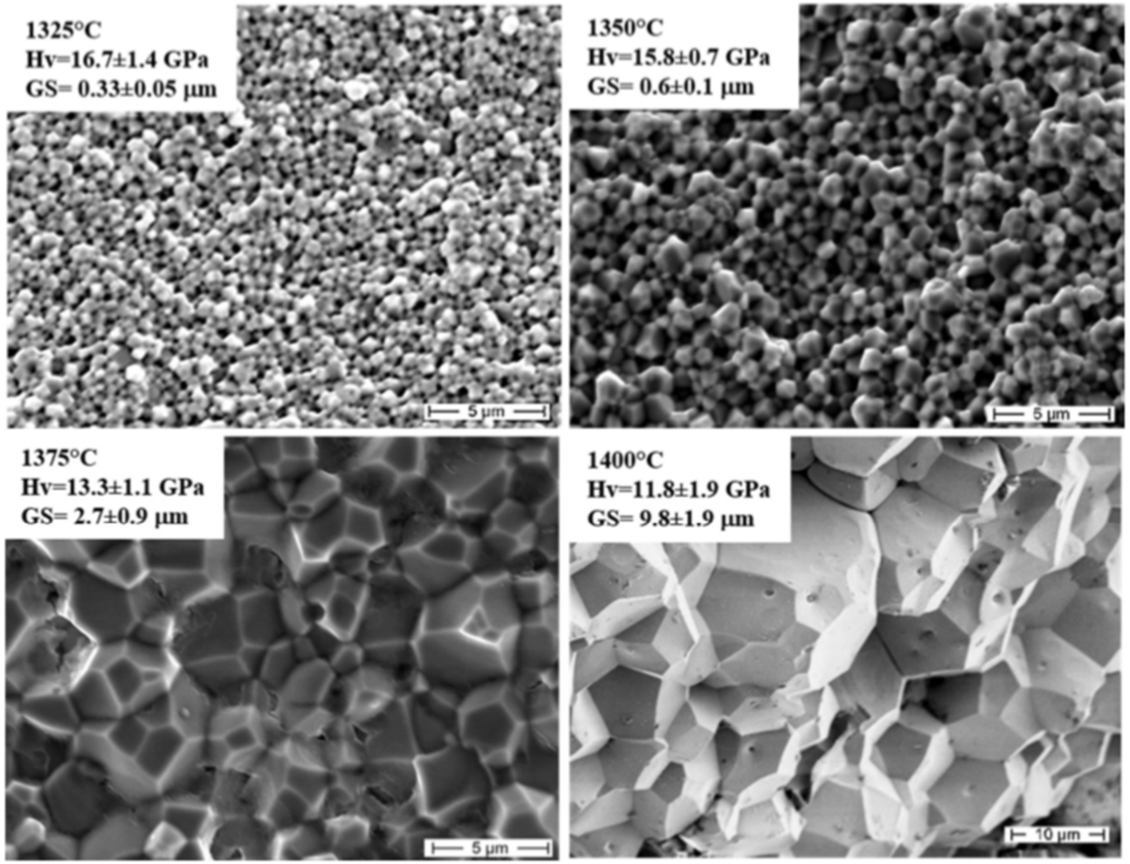
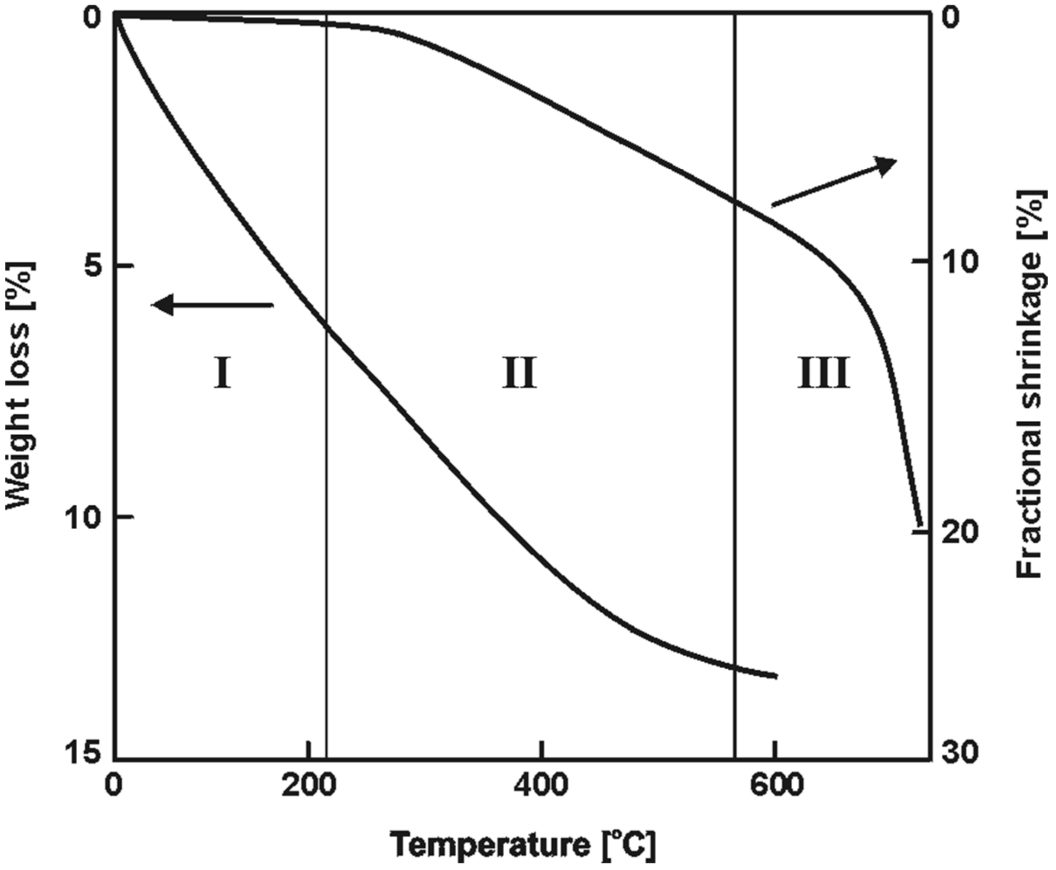
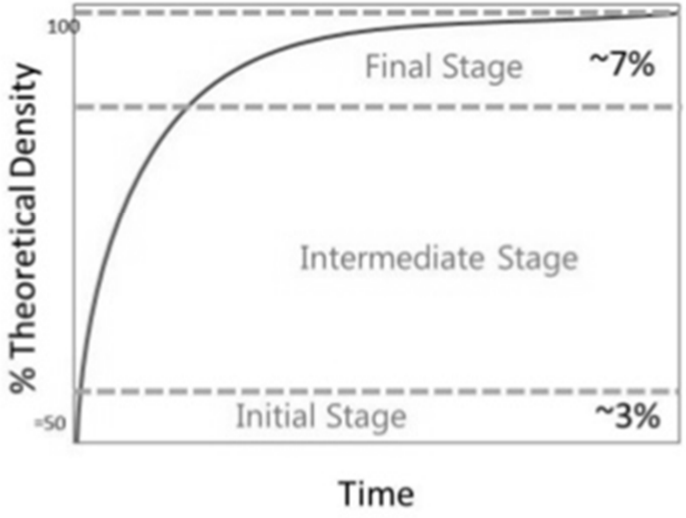


Figure 6. Field Emission Scanning Electron Microscopy (FESEM) micrographs of $Y_3Al_5O_{12}$ (YAG) sintered by Spark Plasma Sintering (SPS) at increasing temperatures (Hv = average Vickers hardness; GS = average grain size) [41].

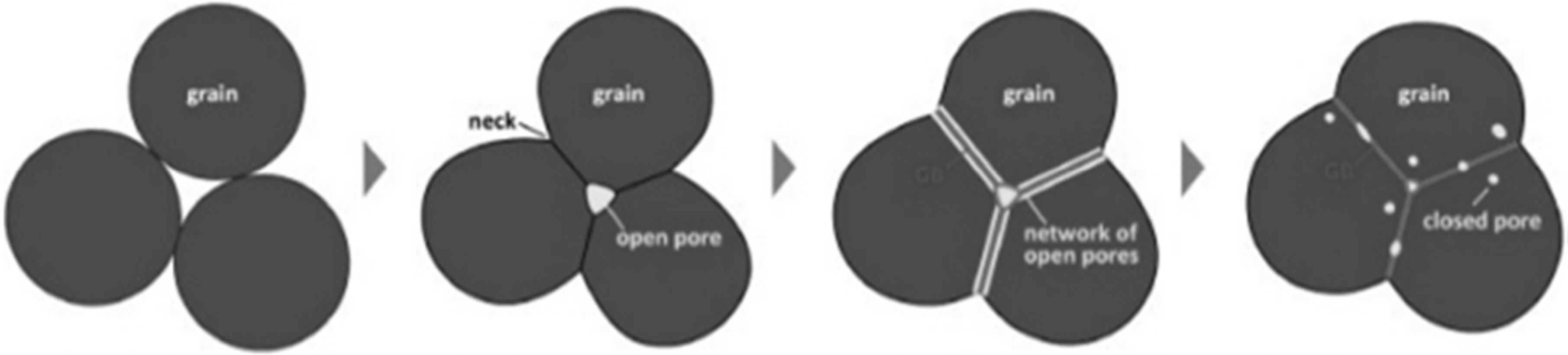
Densification - Sintering



Generalized Sintering Curve



Stages of Sintering



Stage I: before sintering

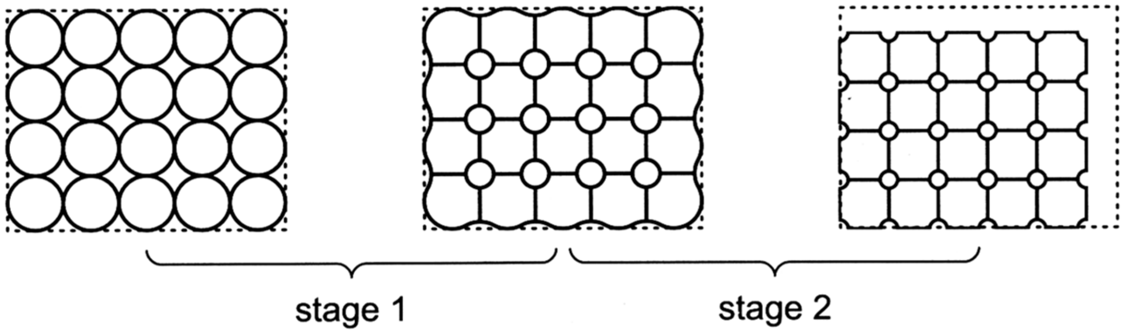
Stage II: formation of necks

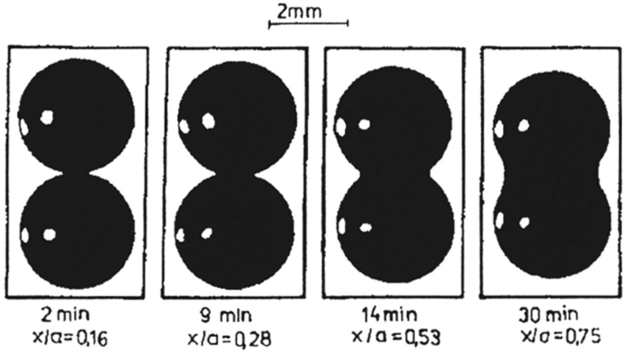
Stage III: evolution of necks and GBs and elimination of pores

Stage IV: isolation of pores

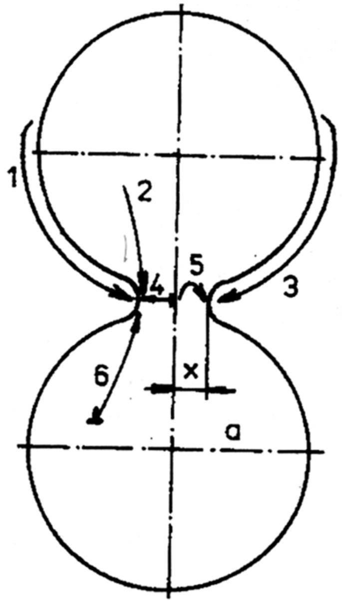
Densification - Sintering

Densification





Sintering mechanisms



Sintering mechanisms - solid, liquid, gas phase

1. Evaporation-condensation and dissolution-precipitation

2. Volume diffusion

3. Surface diffusion

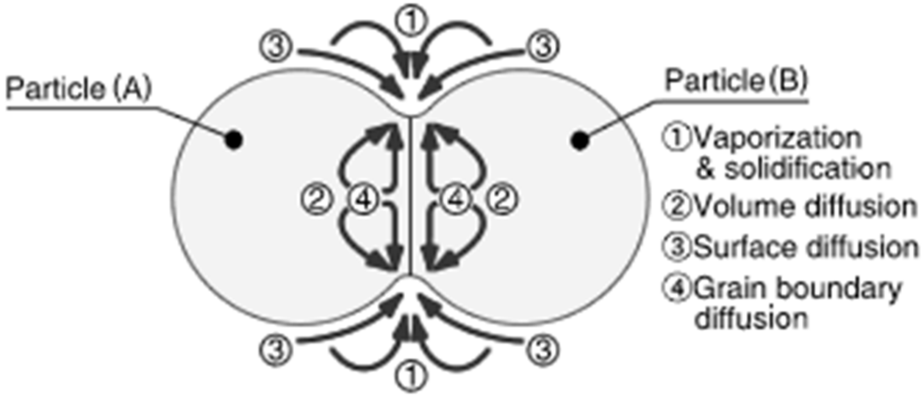
4. Grain boundary diffusion

5. Volume diffusion from grain boundaries

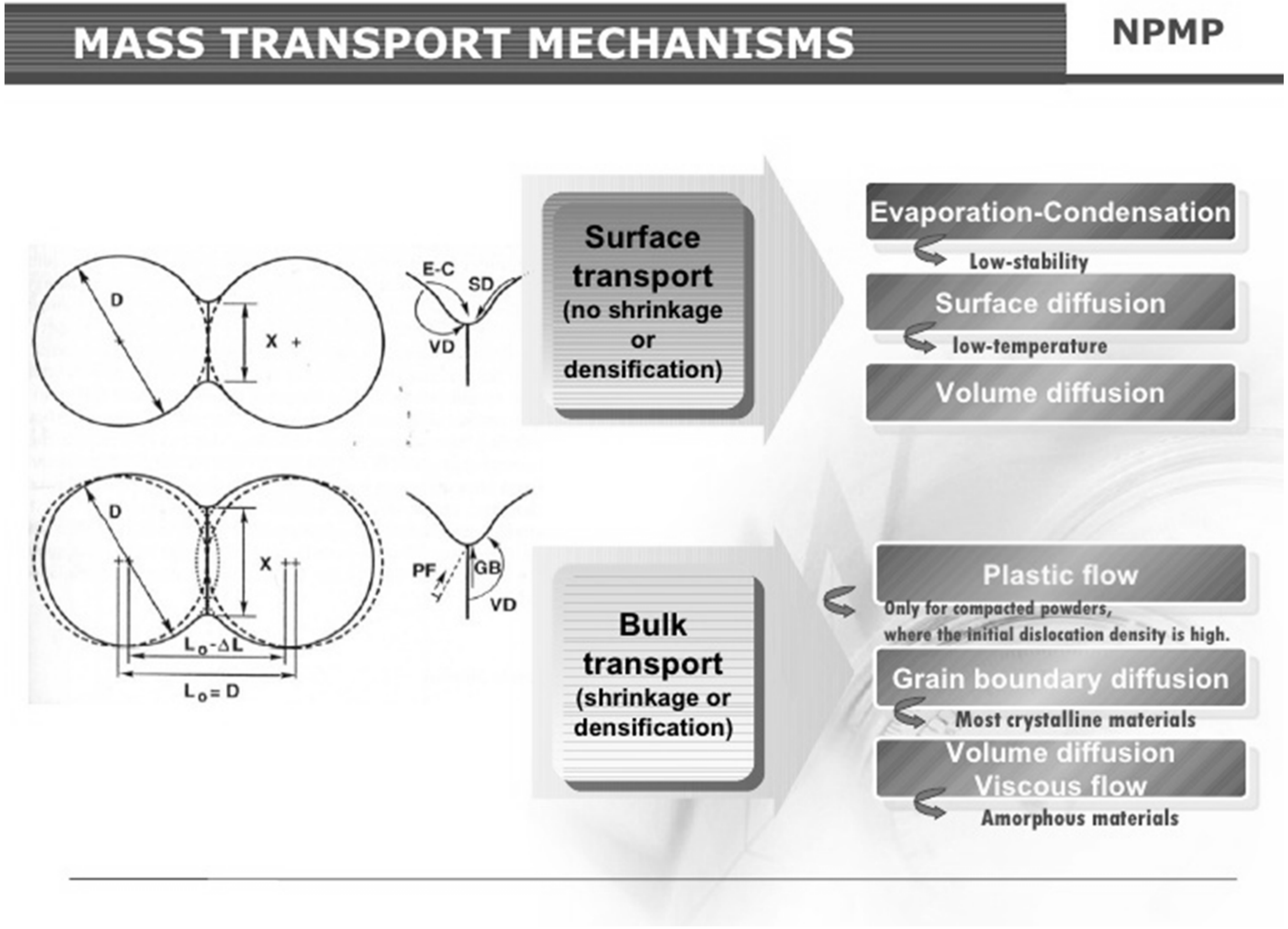
6. Volume diffusion from dislocations – plastic flow

Volume diffusion from dislocations vacancies

Viscous flow



Sintering Mechanisms



MASS TRANSPORT MECHANISMS

NPMP

Surface transport (no shrinkage or densification)

- Evaporation-Condensation
  - Low-stability
- Surface diffusion
  - low-temperature
- Volume diffusion

Bulk transport (shrinkage or densification)

- Plastic flow
  - Only for compacted powders, where the initial dislocation density is high.
- Grain boundary diffusion
  - Most crystalline materials
- Volume diffusion
  Viscous flow
  - Amorphous materials

Sintering Mechanisms

Vapor Pressure over a Curved Surface

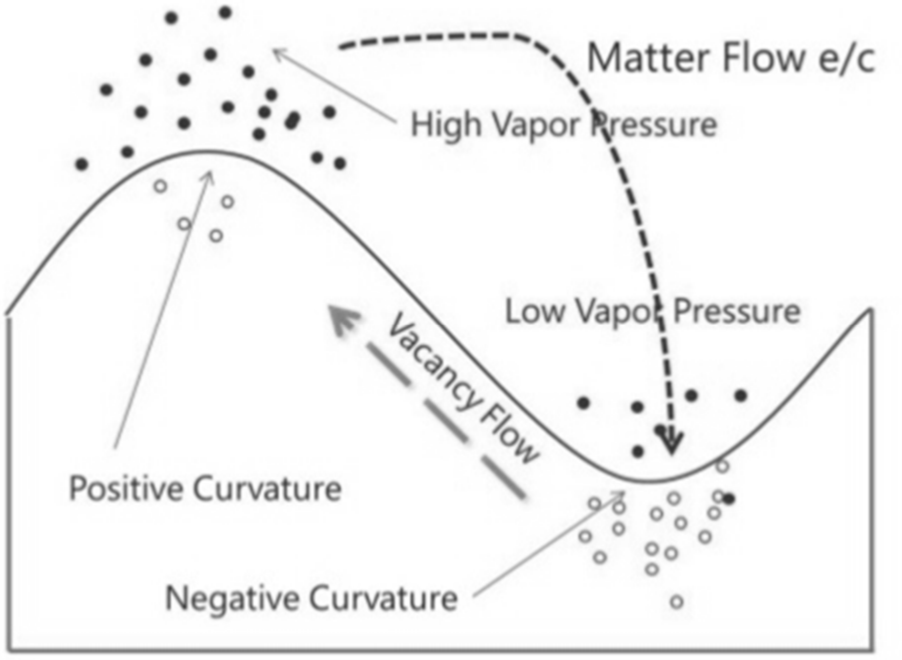


Figure : Curvature in solids, and their effect on vapor pressure

Sintering Mechanisms

Curvature

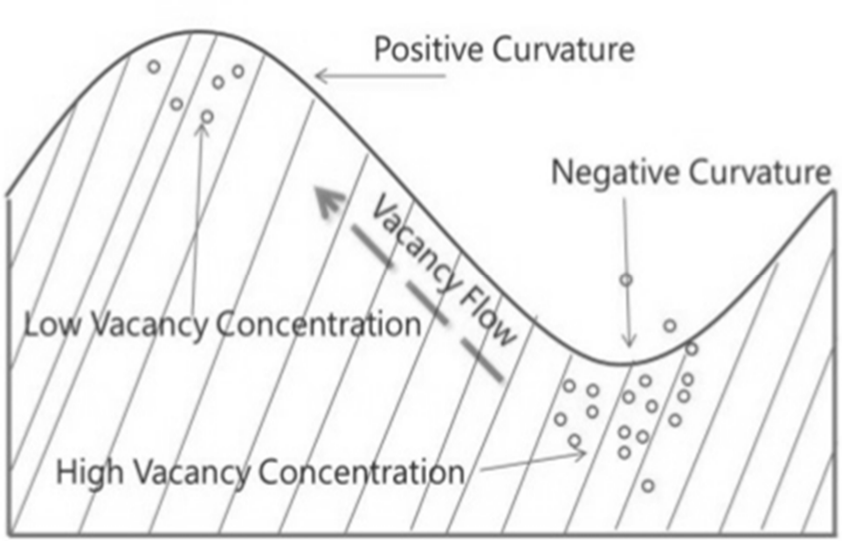
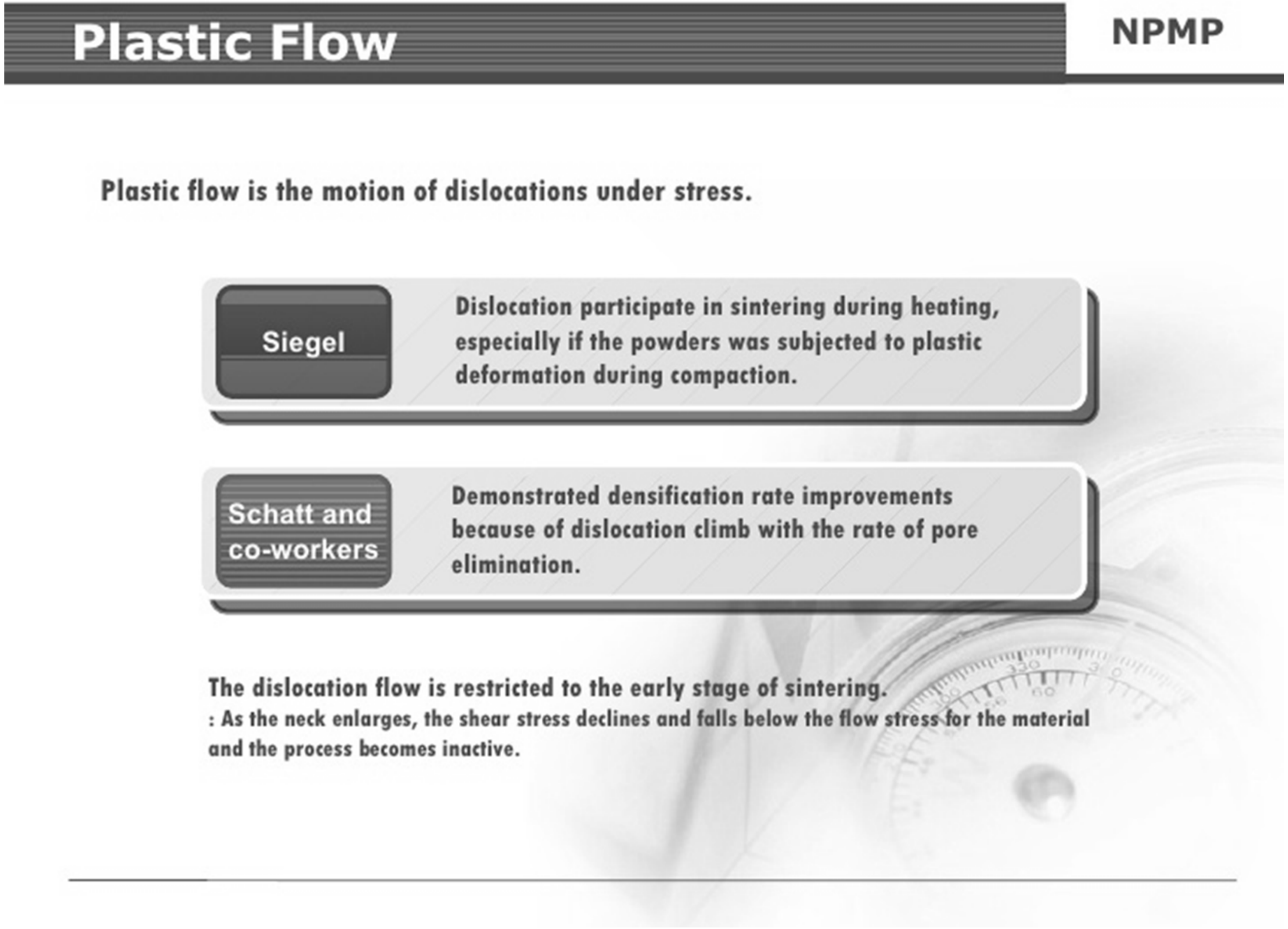


Figure : Curvature in solids, and their effect of vacancy concentration

Sintering Mechanisms



Plastic Flow

NPMP

Plastic flow is the motion of dislocations under stress.

Siegel

Dislocation participate in sintering during heating, especially if the powders was subjected to plastic deformation during compaction.

Schatt and co-workers

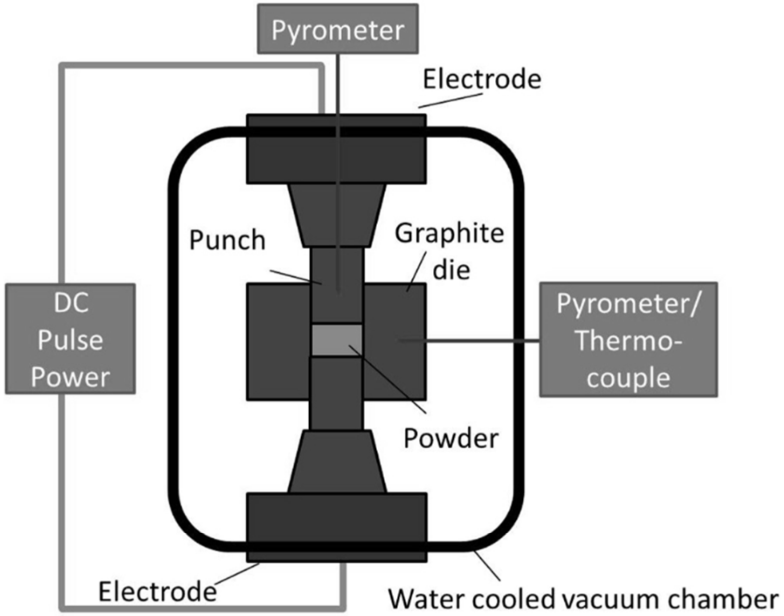
Demonstrated densification rate improvements because of dislocation climb with the rate of pore elimination.

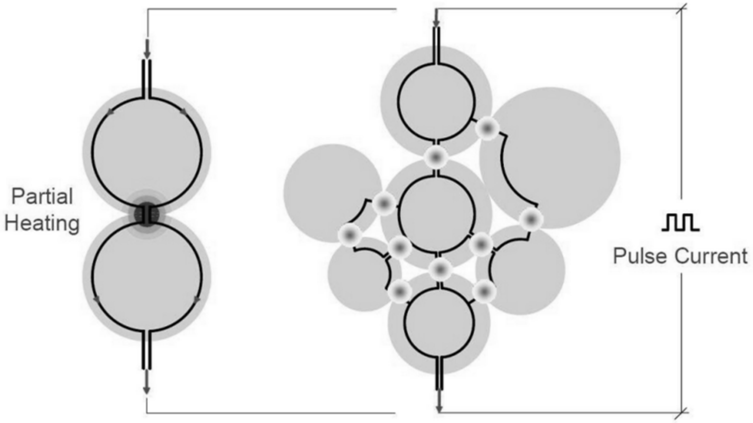
The dislocation flow is restricted to the early stage of sintering.

: As the neck enlarges, the shear stress declines and falls below the flow stress for the material and the process becomes inactive.

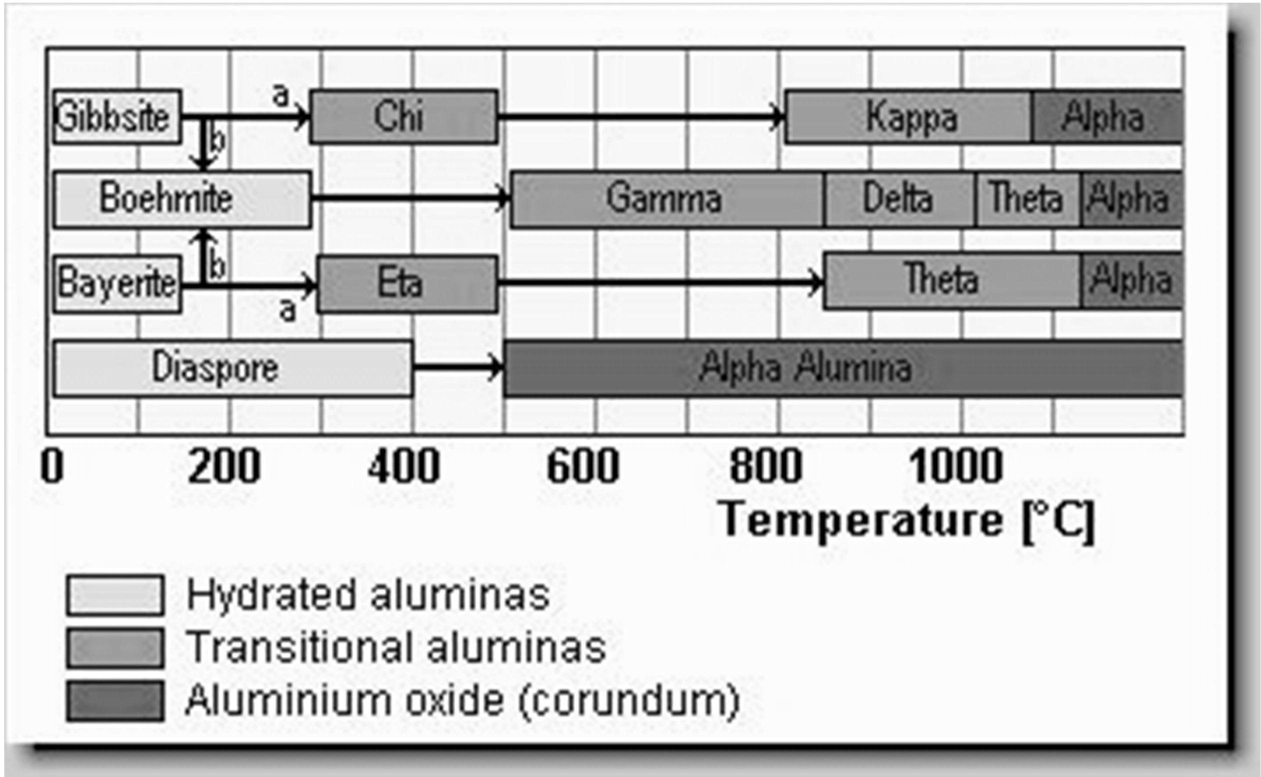
SPS/FAST – Spark Plasma Sintering

- **Field assisted sintering technique**
- **No spark, No plasma**
- **Pulsed electric current sintering**
- **High pressure – limitation by high temperature fracture strength**
- **graphite 100-150 MPa, WC or SiC – 1GPa**
- **High temperature – up to 2400 °C**
- **Joule heating – resistence - at contact points**
- **Up to 10 V, 10 kA**
- **Extreme heating rates: 1000 K/min**





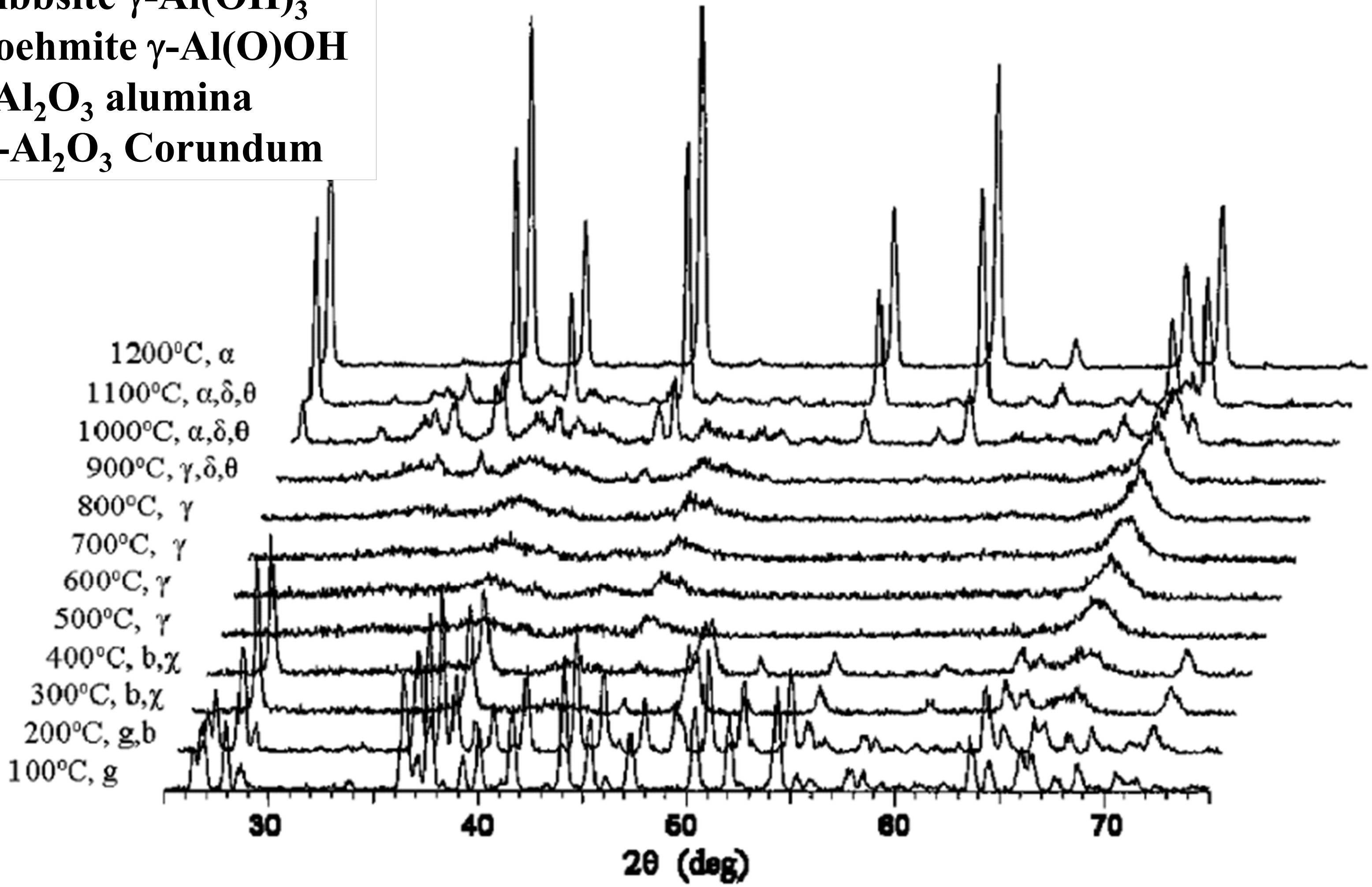
Dehydration sequence of hydrated alumina in air



**Path (b) is favored by moisture, alkalinity, and coarse particle size (100µm)
path (a) by fine crystal size (<10µm)**

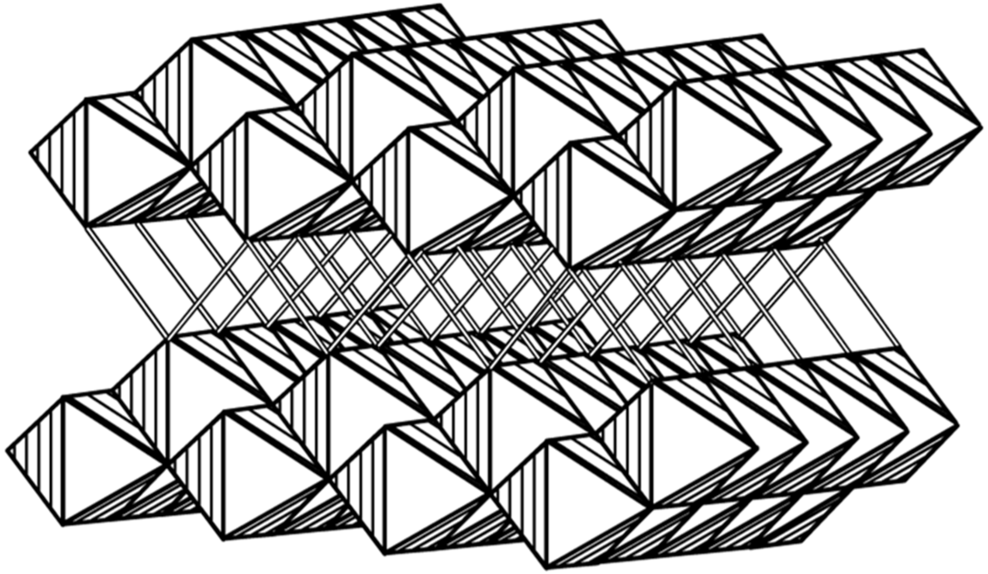
HT-XRD of the phase transitions

g = Gibbsite γ-$Al(OH)_3$
b = Boehmite γ-Al(O)OH
γ = γ-Al_2O_3 alumina
α = α-Al_2O_3 Corundum

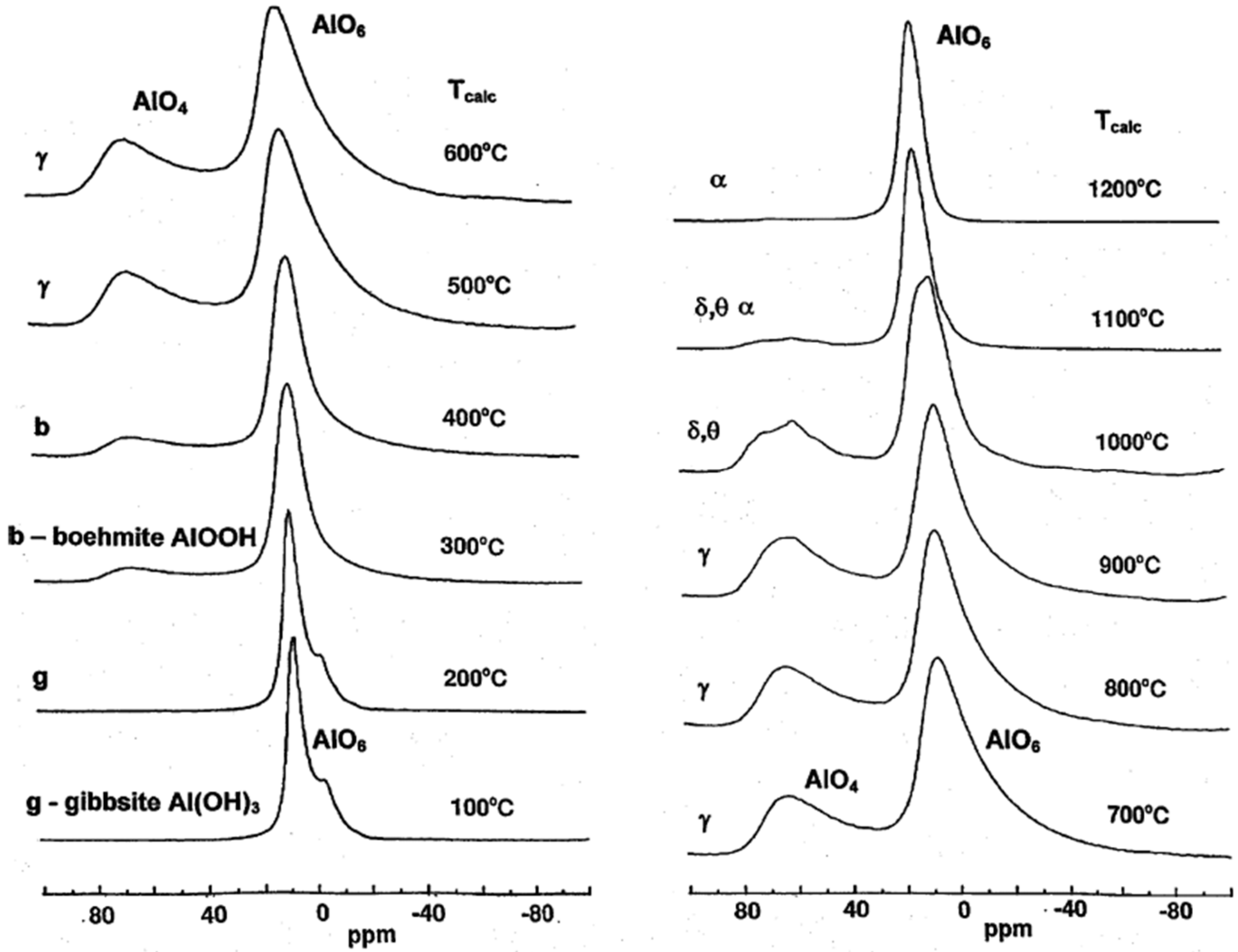


Gibbsite to Boehmite to Gamma

Gibbsite γ-$Al(OH)_3$ to Boehmite γ-$Al(O)OH$ to γ-Al_2O_3 alumina (defect spinel) CCP

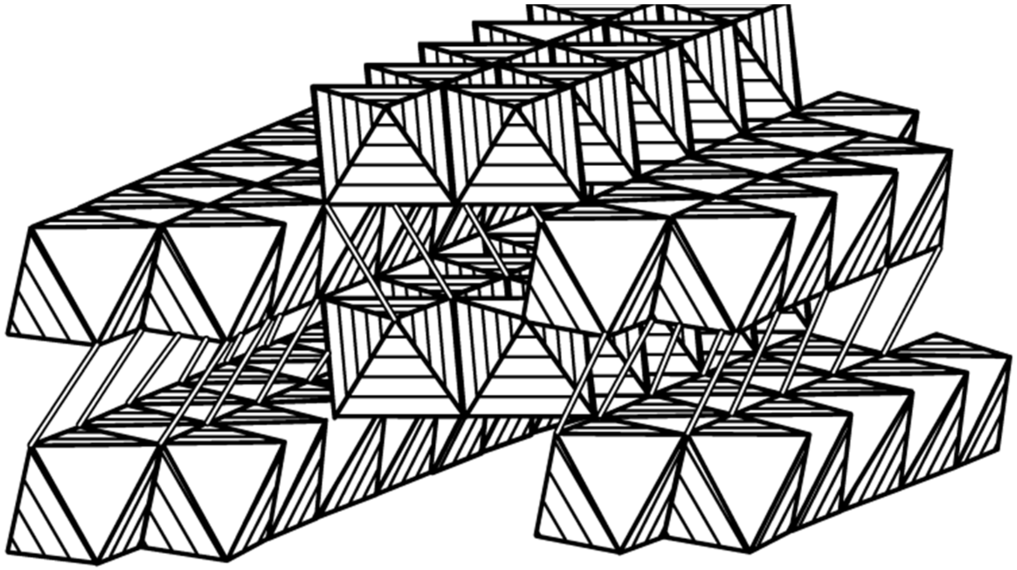


^{27}Al Solid-State NMR spectra

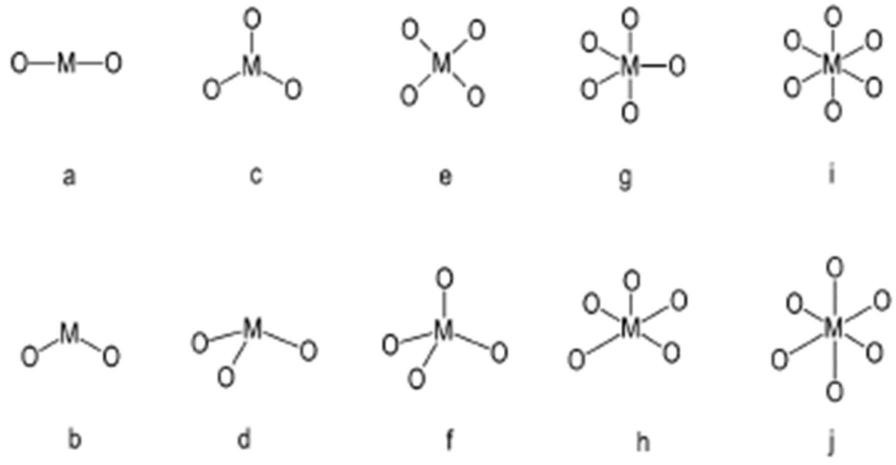


Bayerite to Diaspore to Corundum

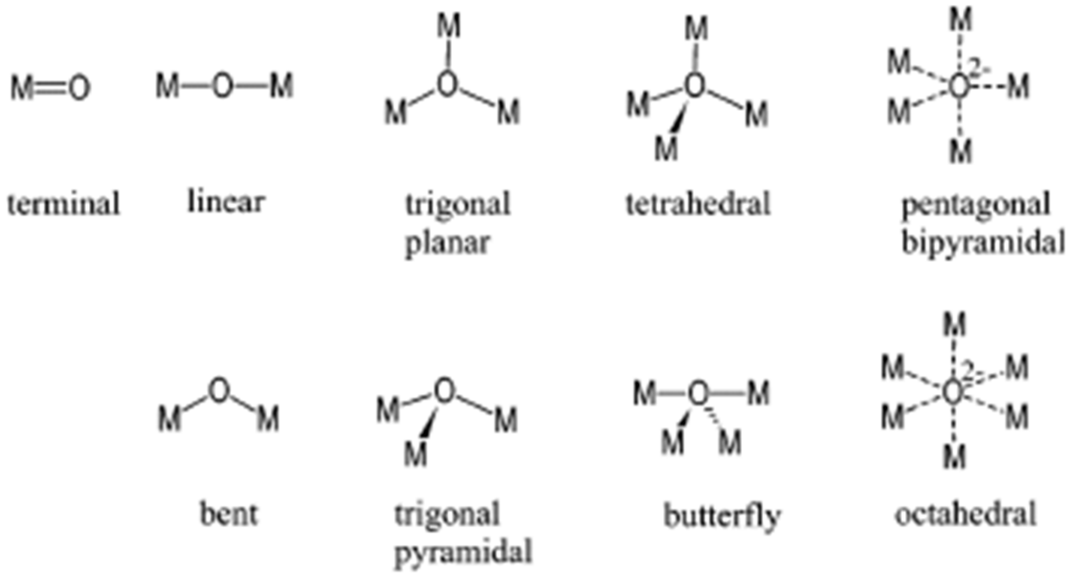
Bayerite α-Al(OH)$_3$ to Diaspore α-Al(O)OH to α-Al$_2$O$_3$ Corundum HCP

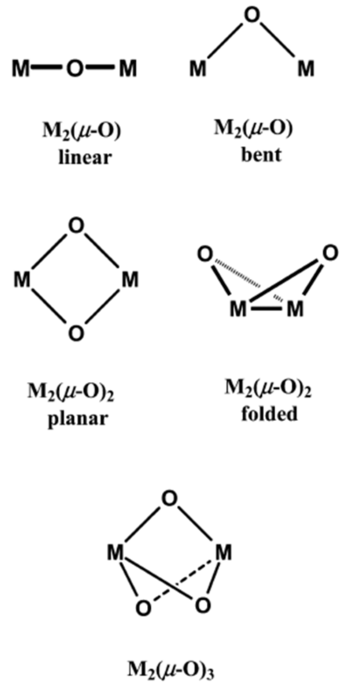


Metal Coordination

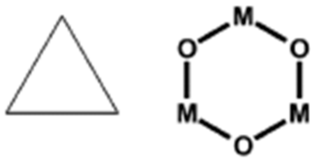


Oxygen Coordination

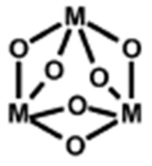




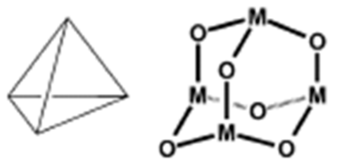
Metal-Oxide Clusters



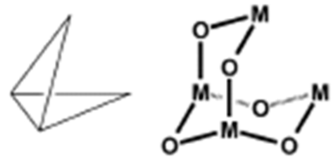
$M_3(\mu\text{-}O)_3$



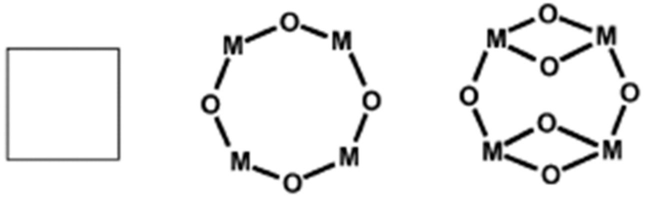
$M_3(\mu\text{-}O)_6$



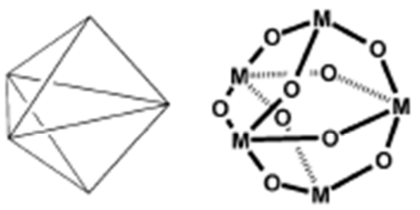
$M_4(\mu\text{-}O)_6$



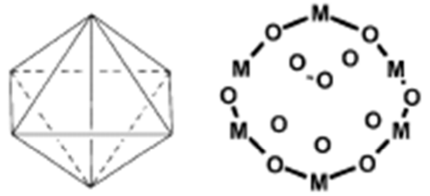
$M_4(\mu\text{-}O)_5$



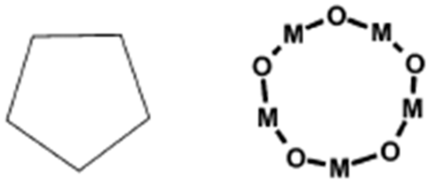
$M_4(\mu\text{-}O)_6$



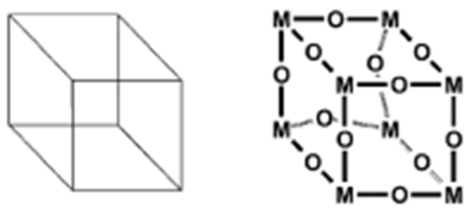
$M_5(\mu\text{-}O)_9$



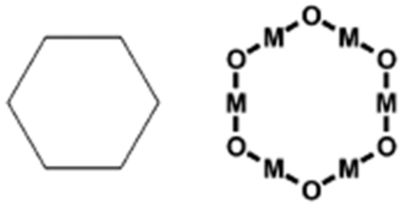
$M_6(\mu\text{-}O)_{12}$



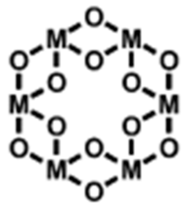
$M_5(\mu\text{-}O)_5$



$M_8(\mu\text{-}O)_{16}$

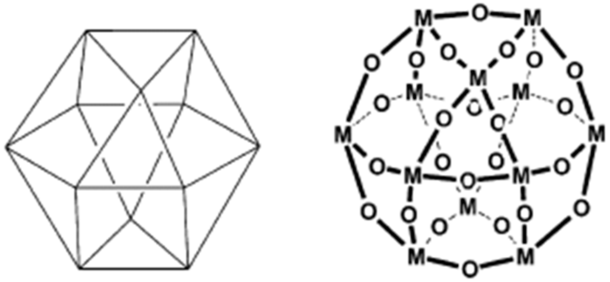


$M_6(\mu\text{-}O)_6$

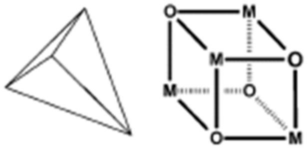


$M_6(\mu\text{-}O)_{12}$

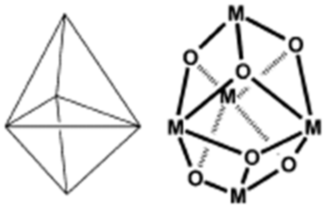
Metal-Oxide Clusters



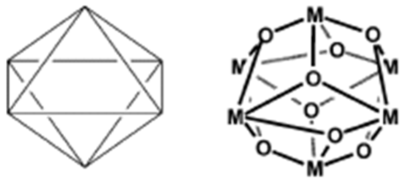
$M_{12}O_{24}$



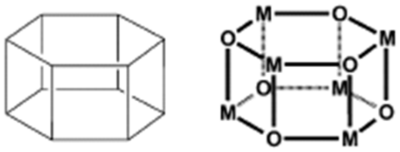
$M_4(\mu_3\text{-}O)_4$



$M_5(\mu_3\text{-}O)_6$



$M_6(\mu_3\text{-}O)_8$



$M_6(\mu_3\text{-}O)_6$