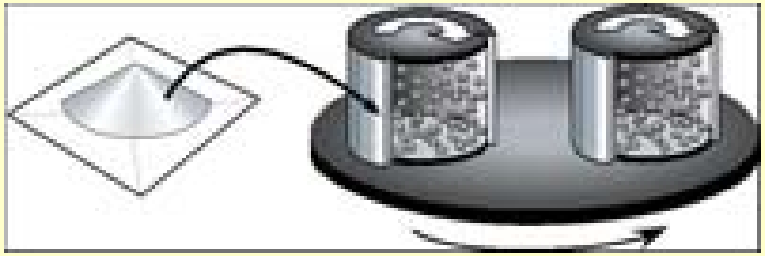
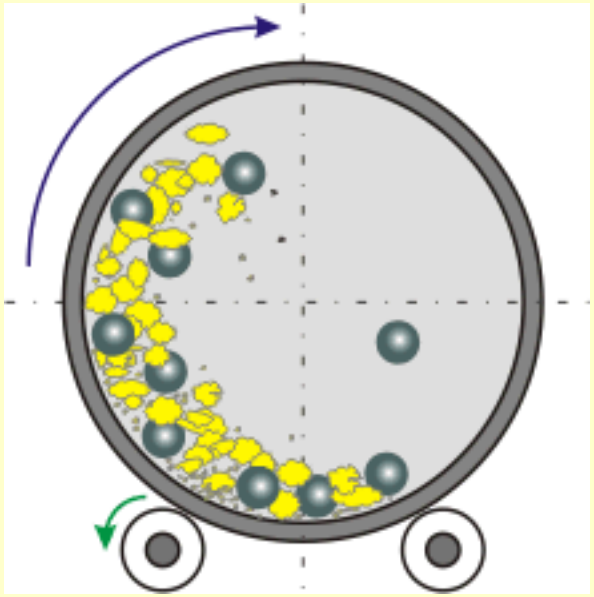
Mechanochemical Synthesis

Reaction Setup





- Precursor powder mixing
- High-energy ball-milling for several hours
- Ball-to-powder ratio (20:1)
- Vial (250 ml) and balls (d = 10-20 mm)
- WC, stainless steel, zirconia
- 250 rotations per minute
- Controlled atmosphere

Mechanochemical Synthesis

- Particles repeatedly subjected to deformation, cold welding, and fracture, homogenization on an atomic scale
- On impact, high energy concentrated in a small spot, stress 200 MPa, duration of microseconds
- Fragmentation, atomically clean surface exposed
- Balance between fragmentation and coalescence
- Grain size ~10 nm
- Amorphization, product nucleation and crystallization

Mechanochemical Synthesis

Phase Transitions (to denser structures)

Oxide	Before	V, Å^3	After	V, Å^3
GeO_2	quartz	40.3	rutile	27.6
TiO_2	anatase	34.1	rutile	31.2
ZrO_2	baddaleyite	35.2	fluorite	32.8

V = volume per formula unit

Mechanical Alloying

$Ni + Nb \rightarrow Nb_{40}Ni_{60}$ amorphous

Mechanochemical Synthesis

Preparation of mixed oxides

Al_2O_3(corundum) + SiO_2 (xerogel) → mullite $Al_6Si_2O_{13}$
Al_2O_3 + La_2O_3 → $LaAlO_3$ 120 min
La_2O_3 + Mn_2O_3 → $LaMnO_3$ room temp., 180 min

SnO + B_2O_3 + P_2O_5 + Li_2O → $(Li_2O)_2(Sn_2BPO_6)_4$
in dry N_2, anodic material for lithium batteries

Preparation of chalcogenides

Fe (powder 4 μm) + S (50 μm) → FeS in Argon
$ZnCl_2$ + Na_2S → ZnS + 2 NaCl
$CdCl_2$ + Na_2S → CdS + 2 NaCl

Mechanochemical Synthesis

Preparation of carbides, borides, nitrides, silicides

Nb + C (graphite) → NbC (Fe impurities from abrasion)
Nb + C + Cu + Fe → NbC/Cu/Fe cermet

Ti + N_2 → TiN 60 h
Ti + C → TiC 35 h
Ti + 2 B → TiB_2 15 h

TiO_2 + 2 Mg + C → TiC + 2 MgO (MgO removed by HCl)

WO_3 + 3 Mg + C → α-W + 3 MgO + C explosive

α-W + 3 MgO + C → WC 50 h, 4-20 nm
(MgO removed by HCl)

Polymer Pyrolysis

Preparation of:
powders, monoliths, fibers, films, impregnation (PIP)

SiC fibers

- **polymer synthesis**

$$Me_2SiCl_2 + Li \rightarrow [Me_2Si]_6 + LiCl \xrightarrow{400\ ^\circ C} [\text{-}SiMe_2\text{-}]_n$$

soluble preceramic polymer

$$Me_2SiCl_2 + MePhSiCl_2 + Na \rightarrow [\text{-}SiMe_2\text{-}SiMePh\text{-}]_n$$

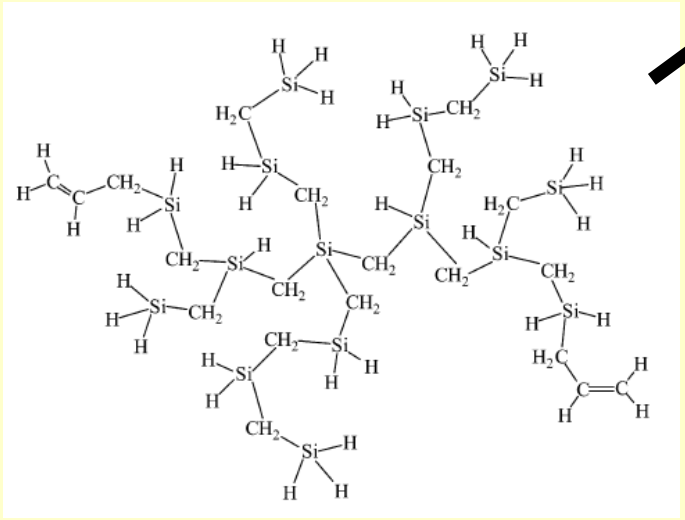
- **melt spinning or drawing from solution gives continuous polymer fiber**
- **curing in O_2, heat to 400 - 500 °C, thermoset, crosslinking to prevent melting**
- **pyrolysis at 1000 - 1500 °C to polyxtalline β-SiC fiber**

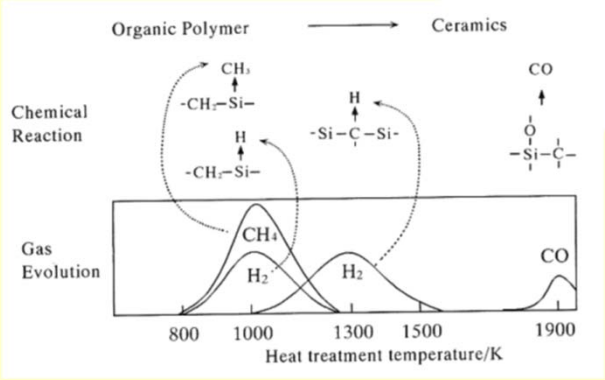
Polymer Pyrolysis

$Cl\text{-}CH_2\text{-}SiCl_3$

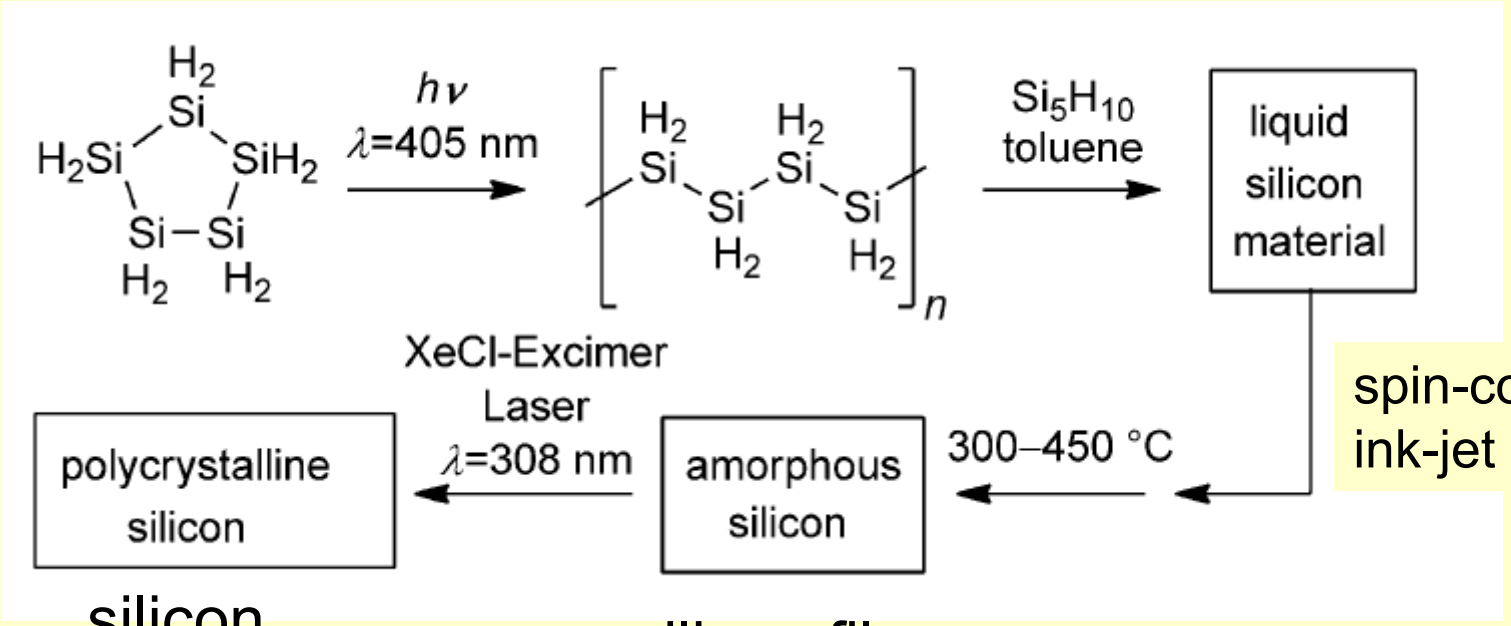
Mg in Et_2O

$LiAlH_4$





Polymer Pyrolysis

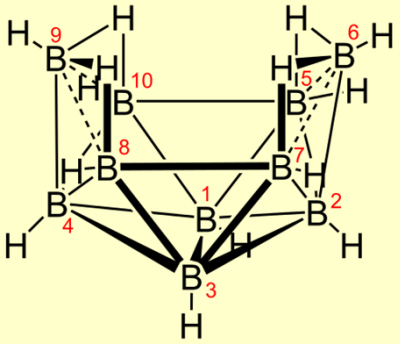


silicon films

silicon
thin-film
transistors

Nature **440**, 783-786 (6 April 2006) doi:10.1038/nature04613

Polymer Pyrolysis



BN

$$B_{10}H_{14} + en \rightarrow \text{polymer} \xrightarrow{1300\ K,\ NH_3} \text{BN powder}$$

AlN

$$Al \rightarrow Al(NHR)_3 \quad \text{anodic dissolution, } CH_3CN,\ RNH_2,\ R_4N^+$$

$$Al(NHR)_3 \rightarrow Al_2(NR)_3 \quad \text{polymeric gel}$$

$$Al_2(NR)_3 \text{ polymeric gel} \xrightarrow{1100\ K,\ NH_3} \text{AlN powder}$$

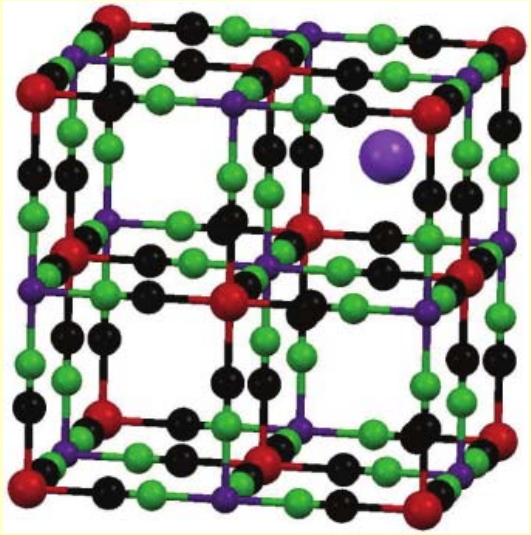
Thermolysis of Organometallic Coordination Polymers

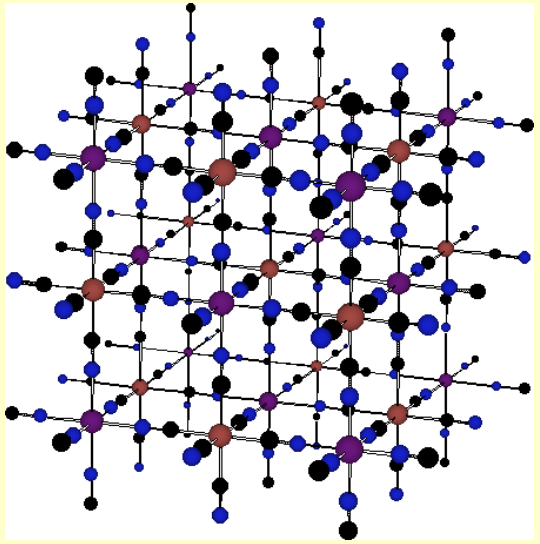
Prussian blue

$(Me_3Sn)_nM(CN)_6$ n = 3,4; M = Fe, Co, Ru

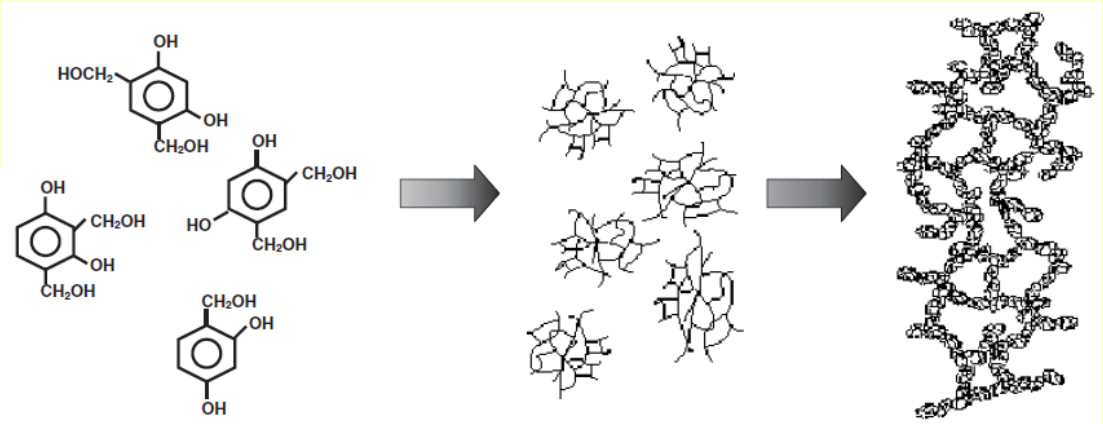
thermolysis in Ar or H_2 gives intermetallics $FeSn_2$, $CoSn_2$, Ru_3Sn_7

thermolysis in air gives oxides Fe_2O_3/SnO_2, Co_2SnO_4, RuO_2

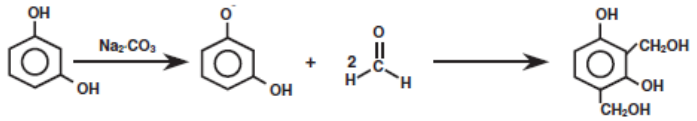




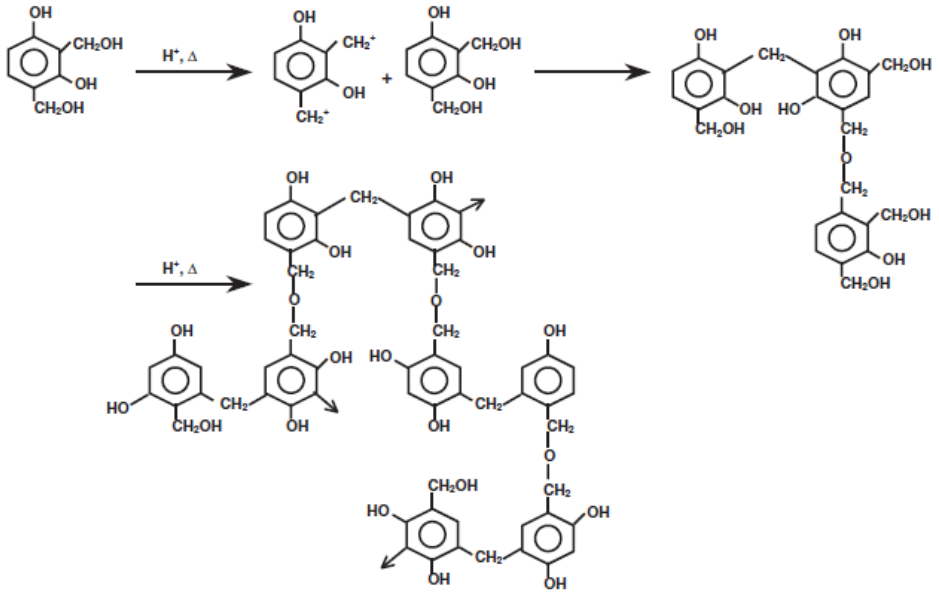
Resorcinol-Formaldehyde Polymers

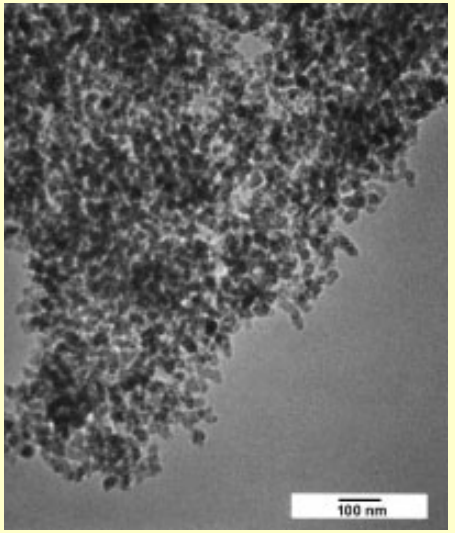


1. Addition Reaction



2. Condensation Reaction





TEM of carbon xerogel carbonized at 1200 °C

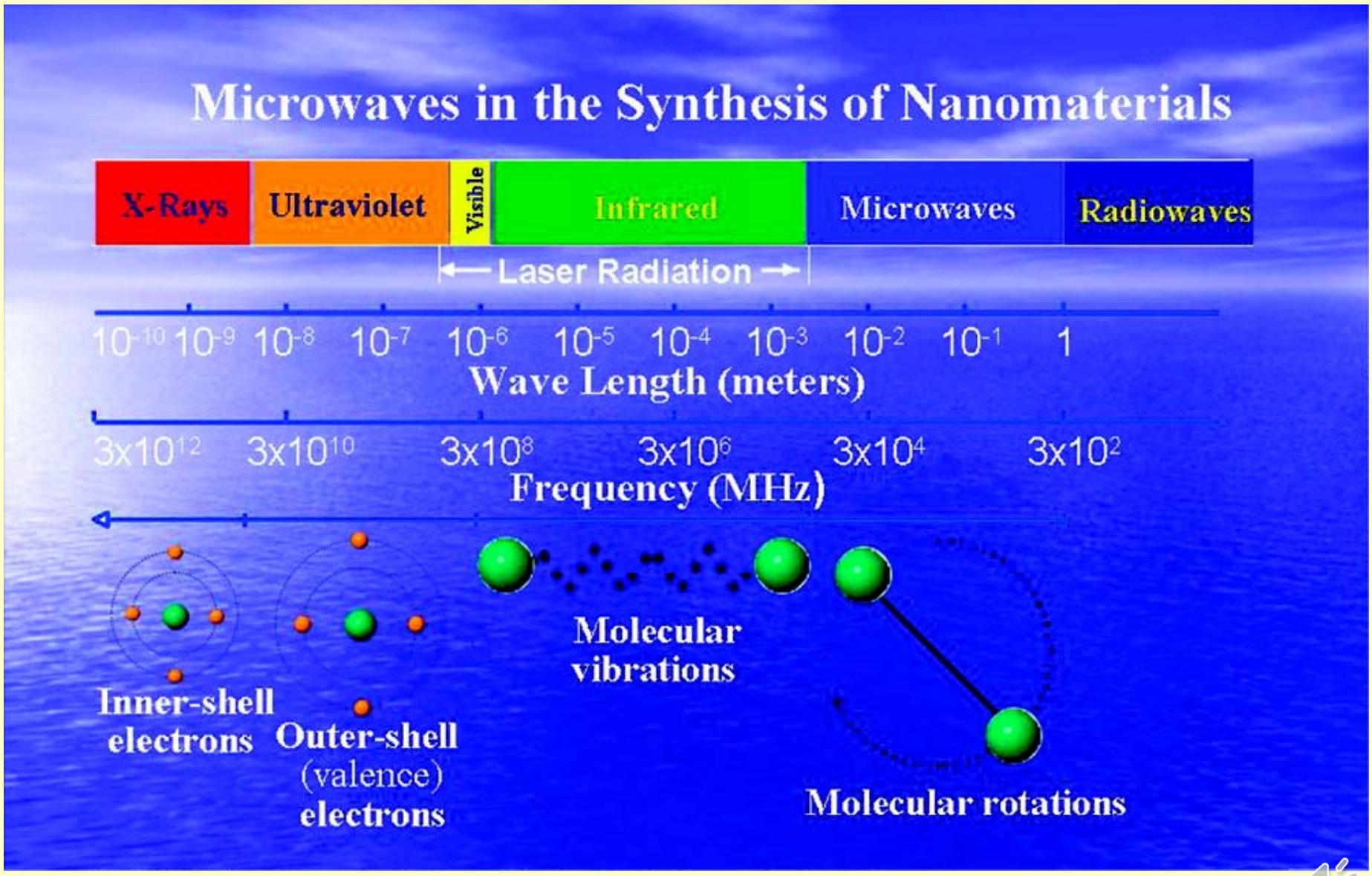
Microwave-Assisted Synthesis

Microwave radiation = electromagnetic radiation
Microwaves: λ = 1 mm to 1m, ν = 0.3 to 300 GHz
Microwave ovens 2.45 GHz, λ = 12.24 cm

All kitchen microwave ovens and all microwave reactors for chemical synthesis operate at a frequency of 2.45 GHz to avoid interference with telecommunication and cellular phone frequencies

Power up to 1 kW, pulses, magnetron, microwaveguide, microwave cavity

Microwaves in the Synthesis of Nanomaterials



Microwave-Assisted Synthesis

The energy of the microwave photon in this frequency region is too low (10^{-5} eV) to break chemical bonds
lower than the energy of Brownian motion at 298 K

Microwaves cannot induce chemical reactions

Microwave-enhanced chemistry

The heating of materials by "microwave dielectric heating" effects = the ability of a material (solvent or reagent) to absorb microwave energy and convert it into heat

Microwave-Assisted Synthesis

Dielectric heating

Electric dipole reorientation in the applied alternating field

The dipoles or ions aligning in the applied electric field applied field oscillates, the dipole or ion field attempts to realign itself with the alternating electric field

Energy is lost in the form of heat through molecular friction and dielectric loss

If the dipole does not have enough time to realign, or reorients too quickly with the applied field, no heating occurs

Microwave-Assisted Synthesis

Resistive heating
polarization current, a reorientation phase lag

Joule heating
ionic current, ionic conduction, ions drift in the applied field

Electronic transport
metal powders, semimetallic and semiconducting materials

Rotational excitation: weak bonds (interlayer bonds in graphite and other layer materials)

Eddy currents: metal powders, alternating magnetic fields

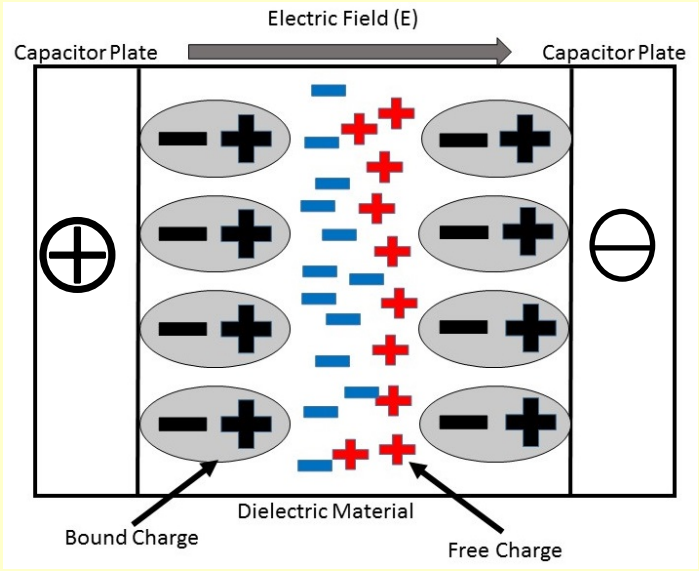
Microwave absorption = f (frequency, temperature)
Thermal runaway = increased dielectric loss at higher T

Dielectric Properties

Dipolar polarization, P
Dipole moment per volume

$$P = \varepsilon_0(\varepsilon_r - 1)E$$

E = external electric field (V)
ε_0 = permittivity of free space
ε_r = relative permittivity of a material



ε^* permittivity is a complex quantity: $\varepsilon^* = \varepsilon_0\varepsilon_r$ $\varepsilon^* = \varepsilon' + i\varepsilon''$

ε' = time-independent polarizability of a material in the presence of an external electric field

ε'' = time-dependent component of the permittivity, quantifies the efficiency with which electromagnetic energy is converted to heat

Dielectric Properties

The ability of a substance to convert electromagnetic energy into heat at a given frequency and temperature

Loss factor tanδ $\tan\delta = \varepsilon''/\varepsilon'$

ε" is the dielectric loss, the efficiency of radiation-to-heat conversion

ε' is the dielectric constant, the ability of molecules to be polarized by the electric field

A high tanδ value is required for efficient absorption and for rapid heating

Loss Factors (tanδ) of different solvents (2.45 GHz, 20 ºC)

Solvent	tanδ	Solvent	tanδ
ethylene glycol	1.350	DMF	0.161
ethanol	0.941	1,2-dichloroethane	0.127
DMSO	0.825	water	0.123
2-propanol	0.799	chlorobenzene	0.101
formic acid	0.722	chloroform	0.091
methanol	0.659	acetonitrile	0.062
nitrobenzene	0.589	ethyl acetate	0.059
1-butanol	0.571	acetone	0.054
2-butanol	0.447	tetrahydrofuran	0.047
1,2-dichlorobenzene	0.280	dichloromethane	0.042
NMP	0.275	toluene	0.040
acetic acid	0.174	hexane	0.020

Microwave absorbing properties

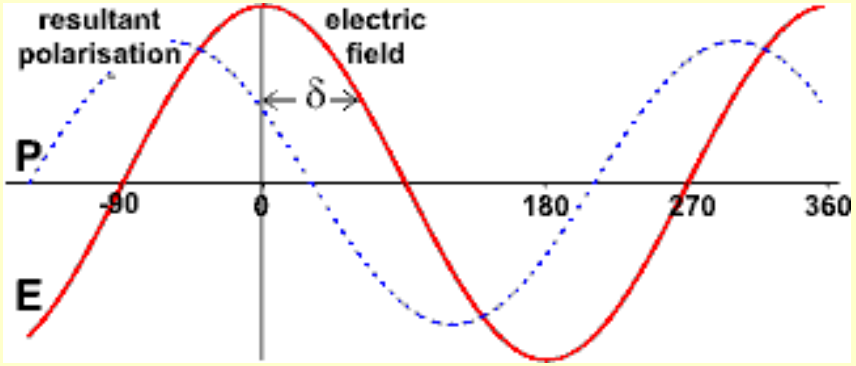
high	tanδ > 0.5
medium	tanδ 0.1–0.5
low	tanδ < 0.1

Dielectric Heating

The applied field potential E of electromagnetic radiation

$$E = E_{max}.\cos(\omega t)$$

E_{max} = the amplitude of the potential (V)
ω = the angular frequency (rad s^{-1})
τ = time (s)



If the polarization lags behind the field by the phase (δ, radians, phase lag) then the polarization (P, coulombs) varies as

$$P = P_{max}.\cos(\omega\tau - \delta)$$

P_{max} is the maximum value of the polarization

Dielectric Heating

The current (I, A) varies as $I = (dP/dt) = -\omega P_{max} \sin(\omega t - \delta)$

The power (*P*, watts) given out as heat is the average value of (current x potential)
***P* is zero if there is no lag (*i.e.,* if $\delta = 0$), otherwise**

$$P = 0.5\, P_{max} E_{max} \omega . \sin(\delta)$$

The penetration depth, D_p, is the distance into the sample at which the electric field is attenuated to 1/e of its surface value

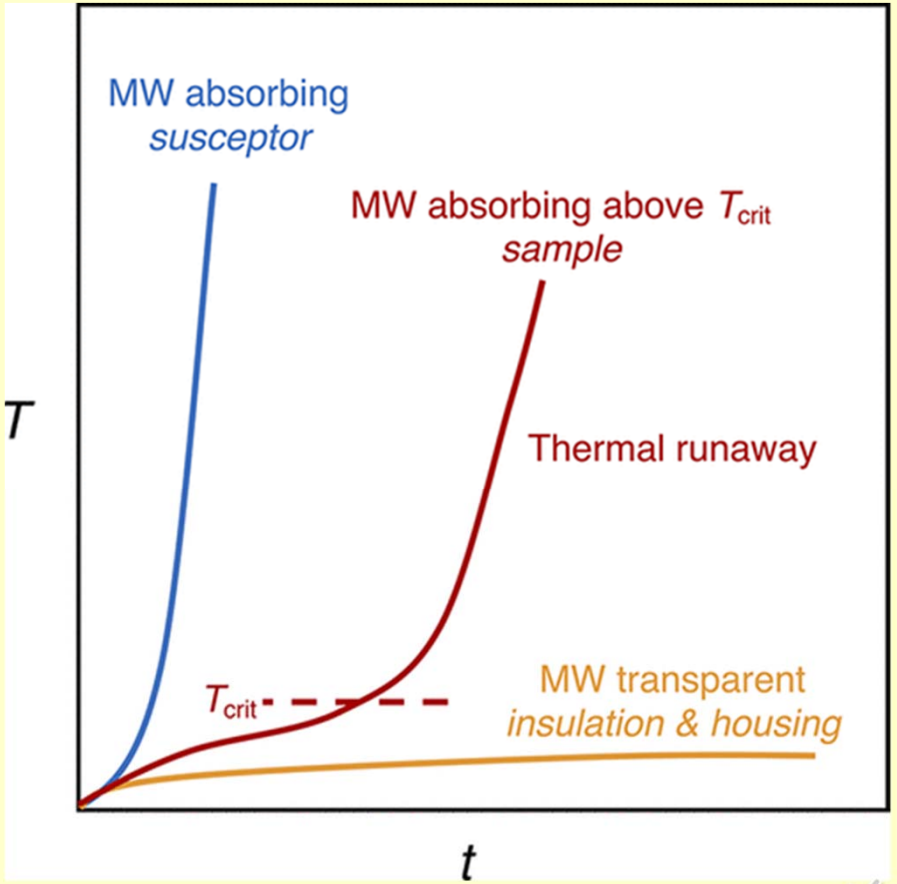
$$D_p = \frac{\lambda \sqrt{e'}}{2\pi e''}$$

λ = wavelength of the microwave radiation
D_p = several micrometers for metals and several tens of meters for low-loss polymers

Microwave-Assisted Synthesis

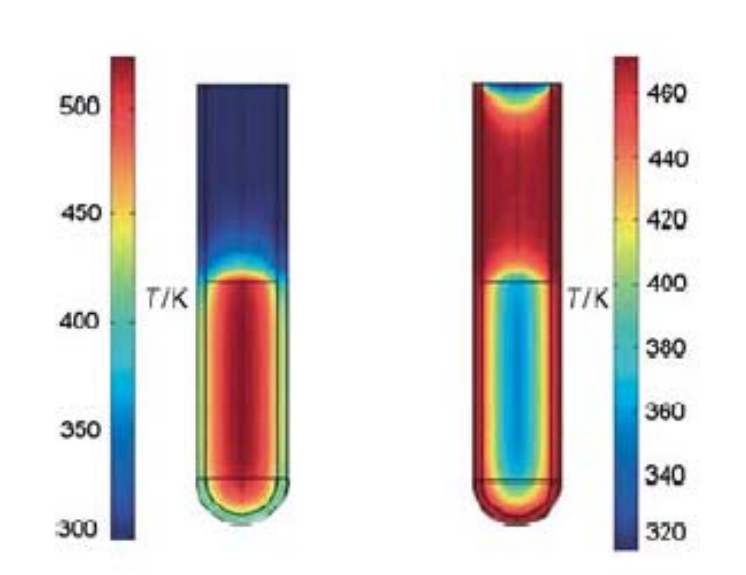
Interaction of materials with microwaves:

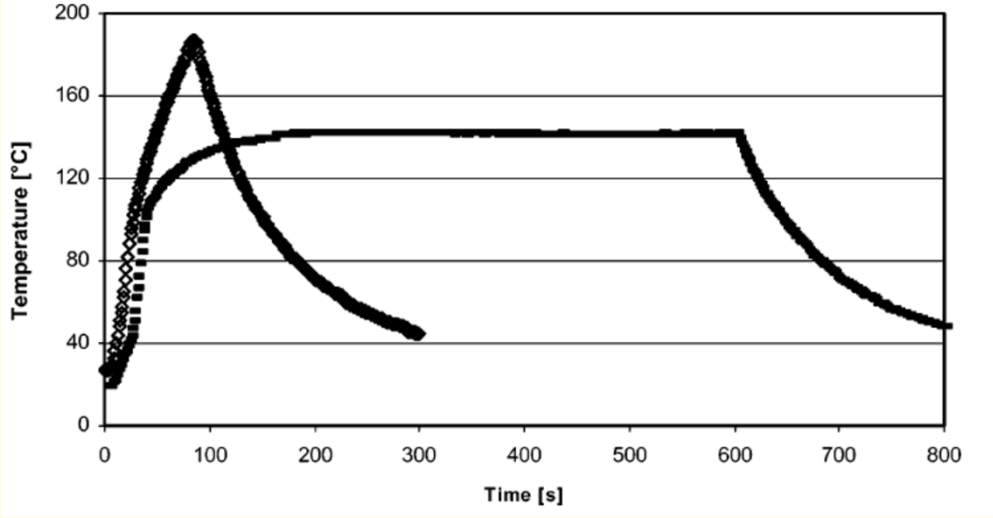
- **Reflectors: metals, alloys (D_p = skin depth, large E gradients, discharges)**
- **Transmitters: quartz, zircon, glasses, ceramics (TM free), Teflon**
- **Absorbers: amorphous carbon, graphite, powdered metals, metal oxides, sulfides, halides, water**



Temperature Gradients

MW Oil bath





Microwave heating profiles for
pure water (■)
0.03 M sodium chloride solution (♦)
at constant 150 W power

Solvent	T, °C	ε'	ε''	Skin, cm	tanδ
Ethylene glycol	25	37	49.95	0.55	1.35
Water	25	78	10.33	3.33	0.13

Microwave-Assisted Synthesis

Examples of Microwave-assisted syntheses

Si + C $\rightarrow$ β-SiC ΔG°_{298} = –64 kJ/mol
silica crucible, 1 kW, 4-10 min, 900 °C, inert ambient (I_2), conventional process requires 1400 °C

metal + chalcogenide $\rightarrow$ ME evacuated quartz ampoules, 5-10 min, 900 W, melting, light emission
PbSe, PbTe, ZnS, ZnSe, ZnTe, Ag_2S

Mo + Si + graphite $\rightarrow$ $MoSi_2$
high mp, oxidation and carbidation resistance, metallic conductivity, heating elements and high-T engine parts

Microwave-Assisted Synthesis

Mixed oxides

$Y_2O_3 + BaO + CuO \rightarrow YBa_2Cu_3O_{7-x}$ 200 W, 25 min

$BaO + WO_3 \rightarrow BaWO_3$ 500 W, 30 min

Amorphous carbon is a secondary susceptor, does not react with reagents or products (carbothermal reduction)

C burns and initiates decomposition of carbonates or nitrates

$BaCO_3 + TiO_2 + C \rightarrow BaTiO_3 + CO_2$

$Pb(NO_3)_2 + TiO_2 + C \rightarrow PbTiO_3 + CO_2$

$NaH_2PO_4.2H_2O$ = good MW susceptor, rotational excitation of water, dehydrates to $NaPO_3$, melts, 700 °C in 5 min

$Na_2HPO_4.2H_2O$, KH_2PO_4 no MW heating

$NaH_2PO_4.2H_2O + ZrO_2 \rightarrow NaZr_2(PO_4)_3$ **NASICON superionic conductor, 8 min**

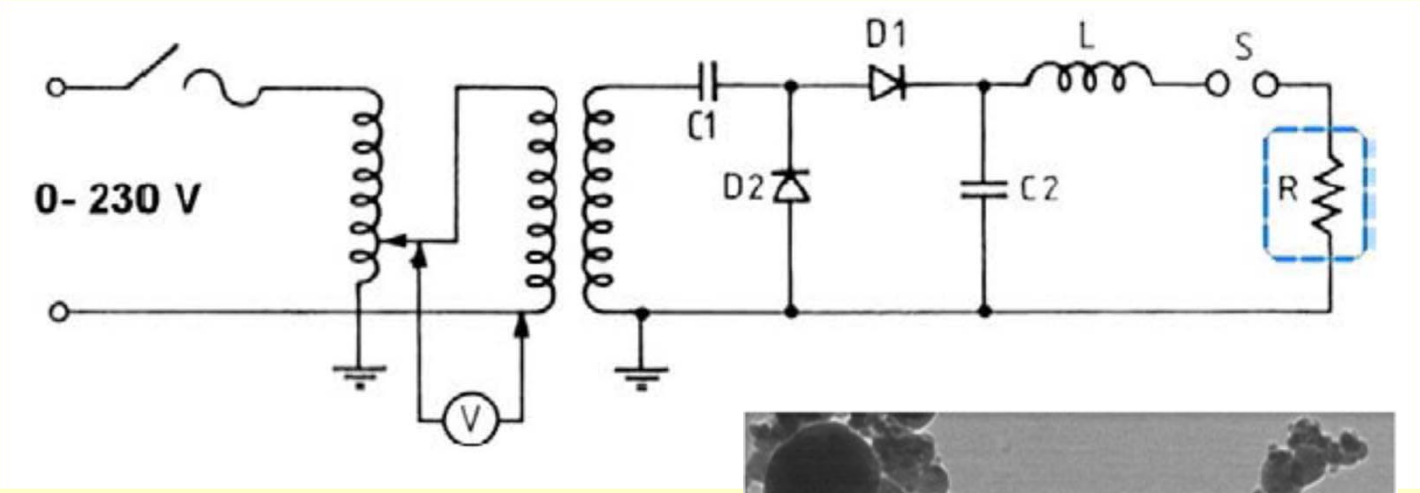
Microwave-Assisted Synthesis

Microvawe-Active Elements, Natural Minerals, and Compounds (2.45 GHz, 1 kW)					
element/ mineral/compound	time (min) of microvawe exposure	T, K	element/ mineral/compound	time (min) of microvawe exposure	T, K
Al	6	850	MnO_2	6	1560
C (amorphous, < 1 μm)	1	1556	NiO	6.25	1578
C (graphite, 200 mesh)	6	1053	V_2O_5	11	987
C (graphite, < 1 μm)	1.75	1346	WO_3	6	1543
Co	3	970	Ag_2S	5.5	925
Fe	7	1041	Cu_2S	7	1019
Mo	4	933	$CuFeS_2$ (chalcopyrite)	1	1193
V	1	830	FeS_2 (pyrite)	6.75	1292
W	6.25	963	MoS_2	7	1379
Zn	3	854	PbS	1.25	1297
TiB_2	7	1116	CuBr	11	995
Co_2O_3	3	1563	CuCl	13	892
CuO	6.25	1285	$ZnBr_2$	7	847
Fe_3O_4 (magnetite)	2.75	1531	$ZnCl_2$	7	882

Wire Explosion

Nano tungsten oxide WO_3 particles

W wire in low pressure of oxygen



TEM