Crystal Physics

The properties of solids

$$H = -\sum_i \frac{\hbar^2}{2m_e}\nabla_i^2 - \sum_A \frac{\hbar^2}{2m_A}\nabla_A^2 - \sum_{i,A}\frac{Z_A e^2}{4\pi\varepsilon_0 r_{iA}} + \sum_{i<j}\frac{e^2}{4\pi\varepsilon_0 r_{ij}} + \sum_{A<B}\frac{Z_A Z_B e^2}{4\pi\varepsilon_0 r_{AB}}$$

electronic band structure E vs. k

structure
bond potentials

phonon band structure ω vs. k

density of states

density of states

equilibrium properties
c_v, free energies, bulk modulus,...

Boltzmann transport

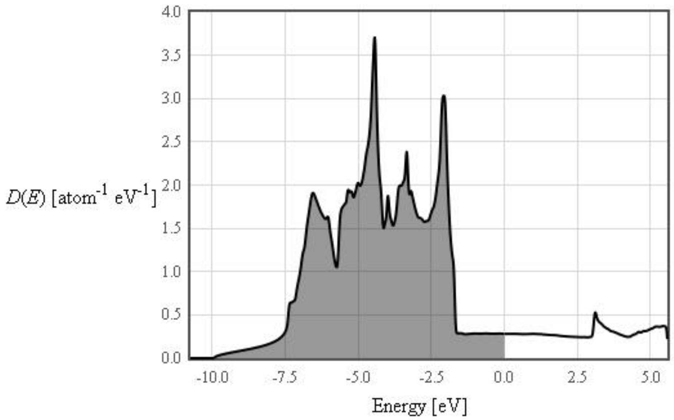
optical
absorption

optical properties

Calculating free energies

Electronic component

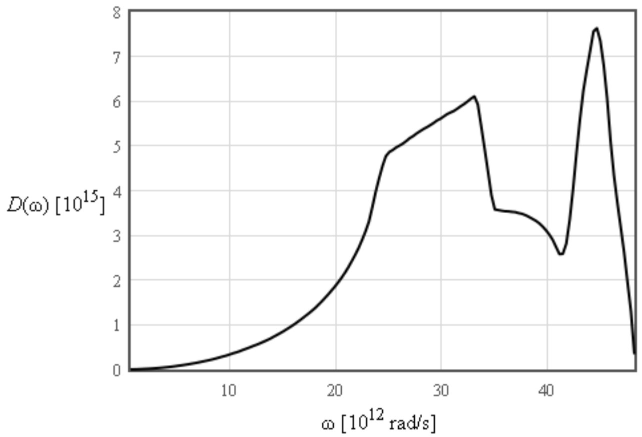
$$n = \int_{-\infty}^{\infty} \frac{D(E)}{1+\exp\left(\frac{E-\mu}{k_B T}\right)} dE$$



$$u = \int_{-\infty}^{\infty} \frac{ED(E)}{1+\exp\left(\frac{E-\mu}{k_B T}\right)} dE$$

Phonon component

$$u = \int_{-\infty}^{\infty} \frac{ED(E)}{\exp\left(\frac{E-\mu}{k_B T}\right)-1} dE$$



Gibbs free energy

$$G(T, \mu, H, E, \sigma)$$

$$G = U - TS - \mu_i N_i - \sigma_{ij}\varepsilon_{ij} - E_k P_K - H_l M_l$$

$$S = -\left(\frac{\partial G}{\partial T}\right)_{\sigma,E,H,\mu} \qquad N_i = -\left(\frac{\partial G}{\partial \mu_i}\right)_{T,E,H,\sigma} \qquad \varepsilon_{ij} = -\left(\frac{\partial G}{\partial \sigma_{ij}}\right)_{T,E,H,\mu}$$

$$P_k = -\left(\frac{\partial G}{\partial E_k}\right)_{T,\mu,H,\sigma} \qquad M_l = -\left(\frac{\partial G}{\partial H_l}\right)_{T,\mu,E,\sigma}$$

$$d\varepsilon_{ij} = \underset{1}{\left(\frac{\partial \varepsilon_{ij}}{\partial \sigma_{kl}}\right)} d\sigma_{kl} + \underset{2}{\left(\frac{\partial \varepsilon_{ij}}{\partial E_k}\right)} dE_k + \underset{3}{\left(\frac{\partial \varepsilon_{ij}}{\partial H_l}\right)} dH_l + \underset{4}{\left(\frac{\partial \varepsilon_{ij}}{\partial T}\right)} dT$$

$$dP_i = \underset{5}{\left(\frac{\partial P_i}{\partial \sigma_{kl}}\right)} d\sigma_{kl} + \underset{6}{\left(\frac{\partial P_i}{\partial E_k}\right)} dE_k + \underset{7}{\left(\frac{\partial P_i}{\partial H_l}\right)} dH_l + \underset{8}{\left(\frac{\partial P_i}{\partial T}\right)} dT$$

$$dM_i = \underset{9}{\left(\frac{\partial M_i}{\partial \sigma_{kl}}\right)} d\sigma_{kl} + \underset{10}{\left(\frac{\partial M_i}{\partial E_k}\right)} dE_k + \underset{11}{\left(\frac{\partial M_i}{\partial H_l}\right)} dH_l + \underset{12}{\left(\frac{\partial M_i}{\partial T}\right)} dT$$

$$dS = \underset{13}{\left(\frac{\partial S}{\partial \sigma_{kl}}\right)} d\sigma_{kl} + \underset{14}{\left(\frac{\partial S}{\partial E_k}\right)} dE_k + \underset{15}{\left(\frac{\partial S}{\partial H_l}\right)} dH_l + \underset{16}{\left(\frac{\partial S}{\partial T}\right)} dT$$

1. Elastic deformation.
2. Reciprocal (or converse) piezo-electric effect.
3. Reciprocal (or converse) piezo-magnetic effect.
4. Thermal dilatation.
5. Piezo-electric effect.
6. Electric polarization.
7. Magneto-electric polarization.
8. Pyroelectricity.
9. Piezo-magnetic effect.
10. Reciprocal (or converse) magneto-electric polarization.
11. Magnetic polarization.
12. Pyromagnetism.
13. Piezo-caloric effect.
14. Electro-caloric effect.
15. Magneto-caloric effect.
16. Heat transmission.

http://www.iucr.org/education/pamphlets/18

Groups

Crystals can have symmetries: translation, rotation, reflection, inversion,...

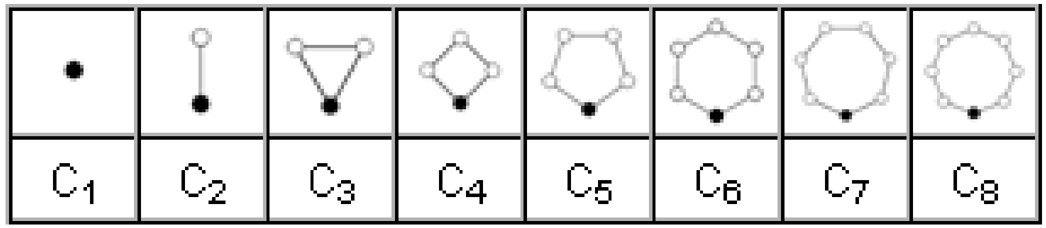
$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Point symmetries can be represented by matrices.
All such matrices that bring the crystal into itself form the group of the crystal.

$$A, B \in G \qquad AB \in G$$

32 point groups (one point remains fixed during transformation)
230 space groups

Cyclic groups



C_2

$$E=\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix},C_2=\begin{bmatrix}-1&0&0\\0&-1&0\\0&0&1\end{bmatrix}$$

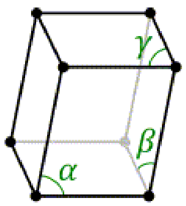
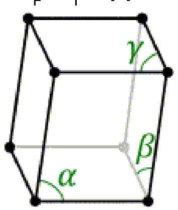
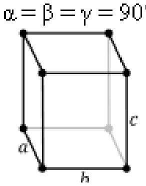
C_4

$$E=\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix},C_4=\begin{bmatrix}0&-1&0\\1&0&0\\0&0&1\end{bmatrix},C_2=\begin{bmatrix}-1&0&0\\0&-1&0\\0&0&1\end{bmatrix},C_4^3=\begin{bmatrix}0&1&0\\-1&0&0\\0&0&1\end{bmatrix}$$

$$E=\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix},C_6=\begin{bmatrix}\frac{1}{2}&-\frac{\sqrt{3}}{2}&0\\\frac{\sqrt{3}}{2}&\frac{1}{2}&0\\0&0&1\end{bmatrix},C_3=\begin{bmatrix}-\frac{1}{2}&-\frac{\sqrt{3}}{2}&0\\\frac{\sqrt{3}}{2}&-\frac{1}{2}&0\\0&0&1\end{bmatrix},C_2=\begin{bmatrix}-1&0&0\\0&-1&0\\0&0&1\end{bmatrix},C_3{}^2=\begin{bmatrix}-\frac{1}{2}&\frac{\sqrt{3}}{2}&0\\-\frac{\sqrt{3}}{2}&-\frac{1}{2}&0\\0&0&1\end{bmatrix},C_6{}^5=\begin{bmatrix}\frac{1}{2}&\frac{\sqrt{3}}{2}&0\\-\frac{\sqrt{3}}{2}&\frac{1}{2}&0\\0&0&1\end{bmatrix}$$

http://en.wikipedia.org/wiki/Cyclic_group

The 32 Crystal Classes

Crystal system	Crystal Class	International symbol	Schoenflies symbol	Space groups	2-fold axes	3-fold axes	4-fold axes	6-fold axes	mirror planes	inversion	Examples	Number of symmetry elements
Triclinic $a \neq b \neq c$ $\alpha \neq \beta \neq \gamma$ 	triclinic-pedial	1	C_1	1	-	-	-	-	-	n		1
	triclinic-pinacoidal	$\bar{1}$	$S_2 = C_i$	2	-	-	-	-	-	y		2
Monoclinic $a \neq b \neq c$ $\alpha \neq 90°$, $\beta = \gamma = 90°$ 	monoclinic-sphenoidal	2	C_2	3-5	1	-	-	-	-	n		2
	monoclinic-domatic	m	$C_{1h} = C_s$	6-9	-	-	-	-	1	n		2
	monoclinic-prismatic	$2/m$	C_{2h}	10-15	1	-	-	-	1	y		4
Orthorhombic $a \neq b \neq c$ $\alpha = \beta = \gamma = 90°$ 	orthorhombic-disphenoidal	222	$V = D_2$	16-24	3	-	-	-	-	n		4
	orthorhombic-pyramidal	$mm2$	C_{2v}	25-46	1	-	-	-	2	n		4
											47: $YBa_2Cu_3O_{7-x}$	

Pyroelectricity

$$\pi_i = -\left(\frac{\partial^2 G}{\partial E_i \partial T}\right)$$

Pyroelectricity is described by a rank 1 tensor

$$\pi_i = \frac{\partial P_i}{\partial T}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \pi_x \\ \pi_y \\ \pi_z \end{bmatrix} = \begin{bmatrix} \pi_x \\ \pi_y \\ -\pi_z \end{bmatrix} \Rightarrow \begin{bmatrix} \pi_x \\ \pi_y \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \pi_x \\ \pi_y \\ \pi_z \end{bmatrix} = \begin{bmatrix} -\pi_x \\ -\pi_y \\ -\pi_z \end{bmatrix} \Rightarrow \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

Pyroelectricity

Quartz, ZnO, $LaTaO_3$

example
Turmalin: point group 3m
for $\Delta T = 1°C$,
$\Delta E \sim 7 \cdot 10^4$ V/m

Pyroelectrics have a spontaneous polarization. If it can be reversed by an electric field they are called Ferroelectrics ($BaTiO_3$)

Pyroelectrics are at Joanneum research to make infrared detectors (to detect humans).

10 Pyroelectric crystal classes: 1, 2, m, mm2, 3, 3m, 4, 4mm, 6, 6mm

Rank 2 Tensors

Electric susceptibility
Dielectric constant
Magnetic susceptibility
Thermal expansion
Electrical conductivity
Thermal conductivity
Seebeck effect
Peltier effect

Electric susceptibility

$$\chi_{ij} = -\left(\frac{\partial^2 G}{\partial E_i \partial E_j}\right)$$

$$P_i = \chi_{ij} E_j$$

$$\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = \begin{bmatrix} \chi_{xx} & \chi_{xy} & \chi_{xz} \\ \chi_{yx} & \chi_{yy} & \chi_{yz} \\ \chi_{zx} & \chi_{zy} & \chi_{zz} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$$

Transforming *P* and *E* by a crystal symmetry must leave the susceptibility tensor unchanged

$$U\vec{P} = \chi U\vec{E} \qquad U^{-1}U\vec{P} = U^{-1}\chi U\vec{E} \qquad \chi = U^{-1}\chi U$$

If rotation by 180 about the *z* axis is a symmetry,

$$U = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad U^{-1} = U = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad U^{-1}\chi U = \begin{bmatrix} \chi_{xx} & \chi_{xy} & -\chi_{xz} \\ \chi_{yx} & \chi_{yy} & -\chi_{yz} \\ -\chi_{zx} & -\chi_{zy} & \chi_{zz} \end{bmatrix}$$

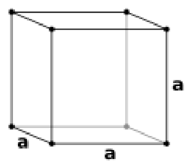
$$\chi_{xz} = \chi_{yz} = \chi_{zx} = \chi_{zy} = 0$$

Cubic crystals

All second rank tensors of cubic crystals reduce to constants

216: ZnS, GaAs, GaP, InAs
221: CsCl, cubic perovskite
225: Al, Cu, Ni, Ag, Pt, Au, Pb, NaCl
227: C, Si, Ge, spinel
229: Na, K, Cr, Fe, Nb, Mo, Ta

Cubic



23	T	195-199		12
$m3$	T_h	200-206		24
432	O	207-214		24
$\bar{4}3m$	T_d	215-220	216: Zincblende, ZnS, GaAs, GaP, InAs, SiC	24
$m3m$	O_h	221-230	221: CsCl, cubic perovskite 225: fcc, Al, Cu, Ni, Ag, Pt, Au, Pb, γ-Fe, NaCl 227: diamond, C, Si,	48

$$\begin{bmatrix} g_{11} & 0 & 0 \\ & g_{11} & 0 \\ & & g_{11} \end{bmatrix}$$

Multiferroics

simultaneously ferroelectric and ferromagnetic

$BiFeO_3$

If two magnetic sublattices have different charge, changing the magnetic field can change the polarization and changing the electric field can change the magnetization.

Material	ρ (Ω•m) at 20 °C	σ (S/m) at 20 °C	Temperature coefficient[note 1] (K^{-1})	Reference
Silver	1.59×10^{-8}	6.30×10^{7}	0.0038	[7][8]
Copper	1.68×10^{-8}	5.96×10^{7}	0.0039	[8]
Annealed copper[note 2]	1.72×10^{-8}	5.80×10^{7}		[citation needed]
Gold[note 3]	2.44×10^{-8}	4.10×10^{7}	0.0034	[7]
Aluminium[note 4]	2.82×10^{-8}	3.5×10^{7}	0.0039	[7]
Calcium	3.36×10^{-8}	2.98×10^{7}	0.0041	
Tungsten	5.60×10^{-8}	1.79×10^{7}	0.0045	[7]
Zinc	5.90×10^{-8}	1.69×10^{7}	0.0037	[9]
Nickel	6.99×10^{-8}	1.43×10^{7}	0.006	
Lithium	9.28×10^{-8}	1.08×10^{7}	0.006	
Iron	1.0×10^{-7}	1.00×10^{7}	0.005	[7]
Platinum	1.06×10^{-7}	9.43×10^{6}	0.00392	[7]
Tin	1.09×10^{-7}	9.17×10^{6}	0.0045	
Carbon steel (1010)	1.43×10^{-7}	6.99×10^{6}		[10]
Lead	2.2×10^{-7}	4.55×10^{6}	0.0039	[7]
Titanium	4.20×10^{-7}	2.38×10^{6}	X	
Grain oriented electrical steel	4.60×10^{-7}	2.17×10^{6}		[11]
Manganin	4.82×10^{-7}	2.07×10^{6}	0.000002	[12]
Constantan	4.9×10^{-7}	2.04×10^{6}	0.000008	[13]
Stainless steel[note 5]	6.9×10^{-7}	1.45×10^{6}		[14]
Mercury	9.8×10^{-7}	1.02×10^{6}	0.0009	[12]
Nichrome[note 6]	1.10×10^{-6}	9.09×10^{5}	0.0004	[7]
GaAs	5×10^{-7} to 10×10^{-3}	5×10^{-8} to 10^{3}		[15]
Carbon (amorphous)	5×10^{-4} to 8×10^{-4}	1.25 to 2×10^{3}	−0.0005	[7][16]
Carbon (graphite)[note 7]	$2.5e\times10^{-6}$ to 5.0×10^{-6} //basal plane 3.0×10^{-3} ⊥basal plane	2 to 3×10^{5} //basal plane 3.3×10^{2} ⊥basal plane		[17]
Carbon (diamond)[note 8]	1×10^{12}	$\sim10^{-13}$		[18]
Germanium[note 8]	4.6×10^{-1}	2.17	−0.048	[7][8]
Sea water[note 9]	2×10^{-1}	4.8		[19]
Drinking water[note 10]	2×10^{1} to 2×10^{3}	5×10^{-4} to 5×10^{-2}		[citation needed]

```
_symmetry_equiv_pos_as_xyz
1 '-y+1/2, x+1/2, -z+1/2'
2 'y+1/2, -x+1/2, -z+1/2'
3 'y, x, -z'
4 '-y, -x, -z'
5 'y+1/2, -x+1/2, z+1/2'
6 '-y+1/2, x+1/2, z+1/2'
7 '-y, -x, z'
8 'y, x, z'
9 'x+1/2, -y+1/2, -z+1/2'
10 '-x+1/2, y+1/2, -z+1/2'
11 'x, y, -z'
12 '-x, -y, -z'
13 '-x+1/2, y+1/2, z+1/2'
14 'x+1/2, -y+1/2, z+1/2'
15 '-x, -y, z'
16 'x, y, z'
loop_
_atom_type_symbol
_atom_type_oxidation_number
Ti4+ 4
O2- -2
loop_
_atom_site_label
_atom_site_type_symbol
_atom_site_symmetry_multiplicity
_atom_site_Wyckoff_symbol
_atom_site_fract_x
_atom_site_fract_y
_atom_site_fract_z
_atom_site_B_iso_or_equiv
_atom_site_occupancy
_atom_site_attached_hydrogens
Ti1 Ti4+ 2 a 0 0 0 . 1. 0
O1 O2- 4 f 0.30479(10) 0.30479(10) 0 . 1. 0
```

mineral web chime plug-in

view crystal in whole frame

Rutile [TiO_2]

Structure Tetragonal

Space Group : $P4_2/mnm$ (No. 136)

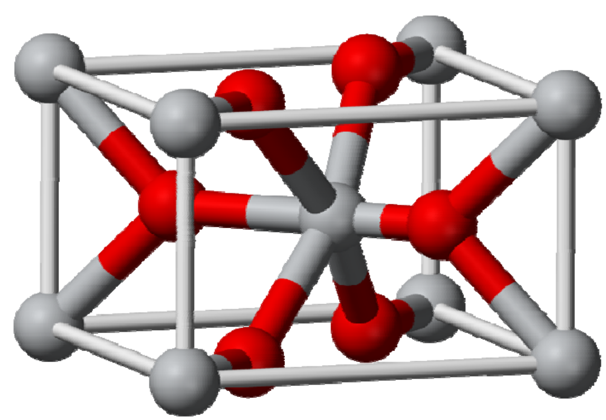
a=4.5937 Å c=2.9587 Å

a=b=g=90.00

Z=2

Atomic Positional Parameters

```
Ti 2a 0.0000 0.0000 0.0000
O  4f 0.3048 0.3048 0.0000
```



Rank 3 Tensors

Piezoelectricity
Piezomagnetism
Hall effect
Nerst effect
Ettingshausen effect
Nonlinear electrical susceptibility

Tensor notation

We need a way to represent 3rd and 4th rank tensors in 2-d.

$$1\,1 \rightarrow 1 \qquad 1\,2 \rightarrow 6 \qquad 1\,3 \rightarrow 5$$

$$2\,2 \rightarrow 2 \qquad 2\,3 \rightarrow 4$$

$$3\,3 \rightarrow 3$$

rank 3

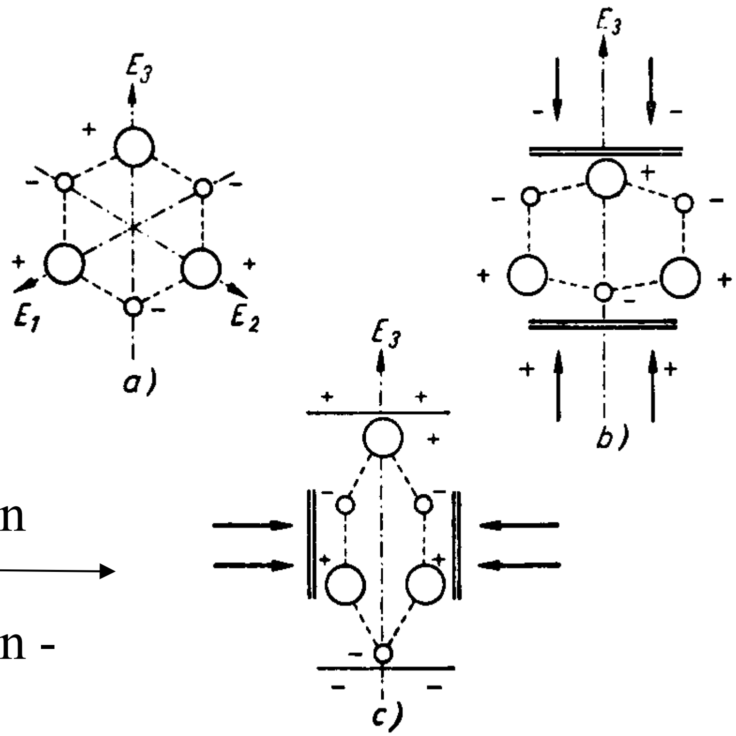
$$g_{36} \rightarrow g_{312}$$

rank 4

$$g_{14} \rightarrow g_{1123}$$

Piezoelectricity

average position
+ is
average position -



$$P_k = -\left(\frac{\partial G}{\partial E_k}\right)$$

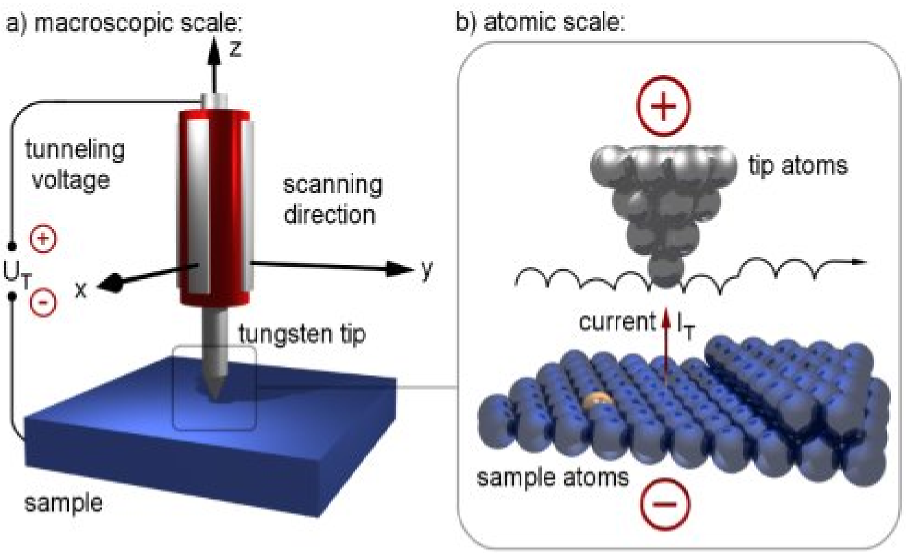
average position
+ not
average position -

$$\frac{\partial P_k}{\partial \sigma_{ij}} = -\left(\frac{\partial^2 G}{\partial E_k \partial \sigma_{ij}}\right) = d_{ijk}$$

Piezoelectricity (rank 3 tensor)

AFM's, STM's
Quartz crystal oscillators
Surface acoustic wave generators
Pressure sensors - Epcos
Fuel injectors - Bosch
Inkjet printers

No inversion symmetry



lead zirconate titanate ($Pb[Zr_xTi_{1-x}]O_3$ $0<x<1$)
—more commonly known as PZT
barium titanate ($BaTiO_3$)
lead titanate ($PbTiO_3$)
potassium niobate ($KNbO_3$)
lithium niobate ($LiNbO_3$)
lithium tantalate ($LiTaO_3$)
sodium tungstate (Na_2WO_3)
$Ba_2NaNb_5O_5$
$Pb_2KNb_5O_{15}$

Piezoelectric crystal classes: 1, 2, m, 222, mm2, 4, -4, 422, 4mm, -42m, 3, 32, 3m, 6, -6, 622, 6mm, -62m, 23, -43m

Nonlinear optics

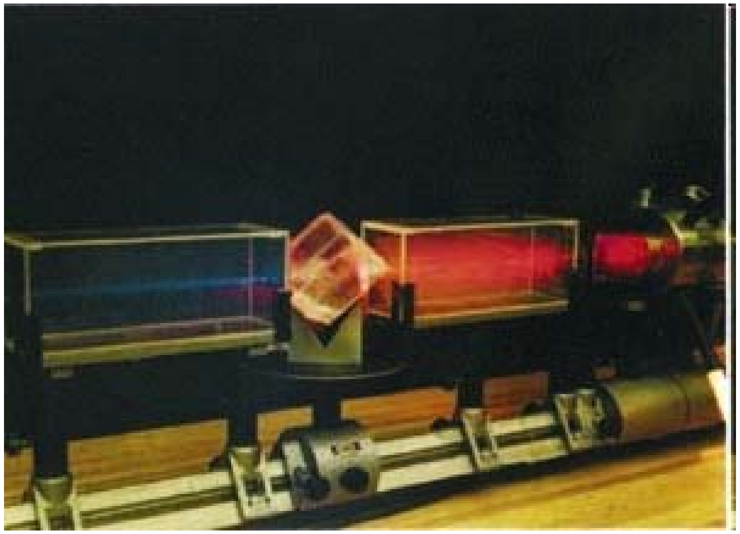
Period doubling crystals

no inversion symmetry

$$P = \chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \cdots$$

$$P_i = \frac{-\partial^2 G}{\partial E_i \partial E_j} E_j + \frac{1}{2} \frac{-\partial^3 G}{\partial E_i \partial E_j \partial E_k} E_j E_k + \cdots$$

$$\cos^2(\omega t) = \tfrac{1}{2}\left(1 + \cos(2\omega t)\right)$$

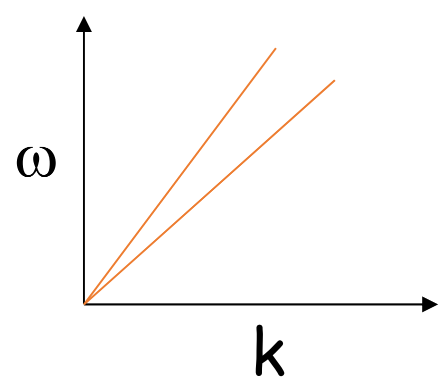


806 nm light : lithium iodate ($LiIO_3$)
860 nm light : potassium niobate ($KNbO_3$)
980 nm light : $KNbO_3$
1064 nm light : monopotassium phosphate (KH_2PO_4, KDP), lithium triborate (LBO).
1300 nm light : gallium selenide (GaSe)
1319 nm light : $KNbO_3$, BBO, KDP, lithium niobate ($LiNbO_3$), $LiIO_3$

Birefringence (Doppelbrechung)

Calcite

Two indices of refraction



http://en.wikipedia.org/wiki/Birefringent

Birefringence

Electric susceptibility

[edit]

In an isotropic and linear medium, this polarisation field **P** is proportional to and parallel to the electric field **E**:

$$\mathbf{P} = \chi \varepsilon_0 \mathbf{E}$$

where χ is the *electric susceptibility* of the medium. The relation between **D** and **E** is thus:

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \chi \varepsilon_0 \mathbf{E} = \varepsilon_0 (1 + \chi) \mathbf{E} = \varepsilon \mathbf{E}$$

where

$$\varepsilon = \varepsilon_0 (1 + \chi)$$

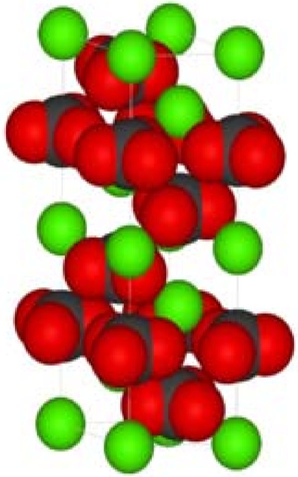
is the dielectric constant of the medium. The value $1+\chi$ is called the *relative permittivity* of the medium, and is related to the refractive index n, for non-magnetic media, by

$$n = \sqrt{1 + \chi}$$

http://en.wikipedia.org/wiki/Crystal_optics

Birefringence

Calcite



name	international	Schoenflies	examples
rhombohedral holohedral	$\bar{3}m$	D_{3d}	calcite, corundum, hematite
rhombohedral hemimorphic	$3m$	C_{3v}	tourmaline, alunite
rhombohedral tetartohedral	$\bar{3}$	S_6	dolomite, ilmenite
trapezohedral	32	D_3	quartz, cinnabar
rhombohedral tetartohedral	3	C_3	none verified

name	international	Schoenflies	examples
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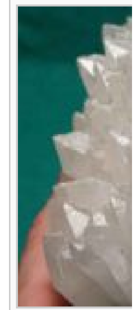
trapezohedral	32	D_3	quartz, cinnabar
rhombohedral tetartohedral	3	C_3	none verified

Rhombohedral crystal system

From Wikipedia, the free encyclopedia
(Redirected from Trigonal crystal system)

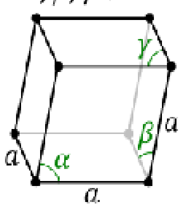
In crystallography, the **rhombohedral** (or **trigonal**) crystal system is one of the seven lattice point groups, named after the two-dimensional rhombus. A crystal system is described by three basis vectors. In the rhombohedral system, the crystal is described by vectors of equal length, of which all three are not mutually orthogonal. The **rhombohedral system** can be thought of as the cubic system stretched diagonally along a body. $a = b = c$; $\alpha, \beta, \gamma \neq 90°$. In some classification schemes, the **rhombohedral system** is grouped into a larger hexagonal system.



An example crystals, qua

Rhombohedral = Trigonal

Trigonal
$\alpha, \beta, \gamma \neq 90°$



Trigonal	$\bar{3}$	$S_6 = C_{6i}$	147-148		6
	32	D_3	149-155		6
	$3m$	C_{3v}	156-161		6
	$\bar{3}m$	D_{3d}	162-167		12

$$\begin{bmatrix} g_{11} & 0 & 0 \\ & g_{11} & 0 \\ & & g_{33} \end{bmatrix}$$

Optical effects

$$P_i = P_i^0 + \frac{\partial P_i}{\partial E_j} E_j + \frac{\partial^2 P_i}{\partial E_j \partial E_k} E_j E_k + \frac{\partial^2 P_i}{\partial E_j \partial E_k \partial E_l} E_j E_k E_l + \cdots$$

spontaneous
polarization

E_k DC
Pockels effect

E_k, E_l DC
Kerr effect

$$P_i = \frac{\partial^2 P_i}{\partial E_j \partial H_k} E_j H_k + \frac{\partial^2 P_i}{\partial E_j \partial H_k \partial H_l} E_j H_k H_l + \cdots$$

H_k DC
Faraday effect

H_k, H_l DC
Cotton–Mouton effect

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Chapter 1.6. Classical linear crystal optics[1]

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Chapter 1.7. Nonlinear optical properties

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Electrostriction

$$\frac{\partial P_k}{\partial \sigma_{ij}} = \frac{\partial \varepsilon_{ij}}{\partial E_k} - \left(\frac{\partial^2 G}{\partial E_k \partial \sigma_{ij}} \right) = d_{ijk}$$

$$\epsilon_{ij} = d_{ijk} E_k + Q_{ijkl} E_k E_l + \cdots$$

piezoelectricity

Electrostriction

Rank 4 Tensors

Stiffness tensor
Compliance tensor
Piezoconductivity
Electrostriction
Magnetostriction
How the Seebeck effect depends on stress
How the electric susceptibility depends on stress
How the magnetic susceptibility depends on stress
Nonlinear electric susceptibility
Nonlinear magnetic susceptibility

Symmetric and asymmetric tensors

$$-\left(\frac{\partial^2 G}{\partial E_j \partial E_k}\right) = \frac{\partial P_k}{\partial E_j} = \chi_{kj} = -\left(\frac{\partial^2 G}{\partial E_k \partial E_j}\right) = \frac{\partial P_j}{\partial E_k} = \chi_{jk}$$

<u>Symmetric</u>
electric susceptibility
magnetic susceptibility
electrical conductivity
thermal conductivity
stiffness tensor

<u>Asymmetric</u>
Seebeck effect
Peltier effect
piezoconductivity