

3.014 MATERIALS LABORATORY
MODULE - β 2
October 13 – 19, 2006
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CRYSTAL POLYMORPHS
X-ray Diffraction Study of Tetragonal – Cubic Transition
in Lead Titanate

OBJECTIVES

- Understand polymorphism and confirm the main polymorphic forms of lead titanate (lead titanium oxide)
- Determine the transition temperature at which the tetragonal phase of lead titanate converges to a cubic phase
- Understand thermal expansion coefficients. Confirm that lead titanate possesses a negative thermal expansion coefficient
- Understand the perovskite structure, and review how this structure can lead to ferroelectric and piezoelectric behavior
- Understand X-ray diffraction and diffractometers

BACKGROUND

POLYMORPHIC FORMS OF LEAD TITANATE

Two crystals of identical composition but of different crystallographic nature are called polymorphs [1]. For example, diamond and graphite are polymorphic forms of carbon, in which carbon atoms are bonded differently resulting in different crystal structures for diamond and graphite.

There are two general families of transformations that can drive the transformation between one polymorph to another.

The first type of transformation is the **displacive** one, in which no element changes its first coordination shell. These transformations are the least structurally demanding. The second type of transformation is called **reconstructive**, it requires a change in the coordination (i.e. the bonding) of at least one component of the crystal. (see figure 1).

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Figure 1: Schematic representation of possible transformations between polymorphic forms of a generic crystal. The transformations between (a) and (b) or (c) are displacive, while the transformation between (a) and (d) is reconstructive. (Picture taken from reference [1])

Lead Titanate (PbTiO_3) is a ceramic material of the family of perovskites. [2] These are ternary compounds of the general formula ABO_3 where the two cations (A and B) differ considerably in size. The unit cell of perovskites is illustrated in figure 2 for the case of BaTiO_3 . It should be noticed that no sub-lattice (e.g. the lattice formed by Ti atoms) is closed packed, but the sub-lattice formed by the Barium and the Oxygen atoms (fig. 2a) is an FCC lattice. In the center of the unit cell there is a Ti atom. One of the driving forces that leads to the formation of this unique arrangement is the formation of 6 octahedral bonds between the Ti atom and 6 oxygen atoms surrounding it. These bonds are not purely ionic, in fact they have been known to be partially covalent.[3] The

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Figure 2: Schematic drawing of BaTiO_3 unit cell (A) and crystallographic arrangement (B). This is a good example of a perovskite. Lead titanate is also a perovskite. (Picture taken from reference [2])

Perovskites are among the many crystals that can exist in different crystalline forms. Lead Titanate, like many other perovskites, has two main polymorphic forms. The first, stable at lower temperatures, is a tetragonal cell in which the titanium atom is not in the exact center of the cubic cell defined by the oxygen and lead atoms (see figure 3). The second, stable at higher temperatures, has a cubic cell in which the Titanium atom is exactly in the center of the cubic cell.

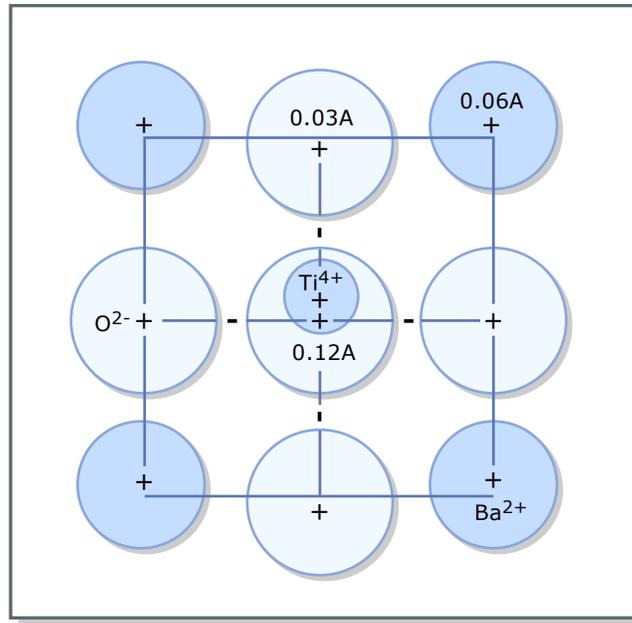


Figure by MIT OCW.

Figure 3. Schematic representation of the ion position in a tetragonal BaTiO_3 cell. The Ti ion is elevated 0.12 \AA respect to the center of the cell. (Figure adopted from reference [2])

In the case of perovskites polymorphic transformation are responsible for changes in a large number of properties. First of all, while the cubic cell is centrosymmetric the tetragonal is not. The cubic unit cell has no net dipole; on the other end (as illustrated in figure 3) in the tetragonal cell, the center of gravity for the negative ions is in the center of the cubic cell while the center of gravity for the positive ions is close to the titanium atom. Hence, the tetragonal cell has a finite dipole. The presence of this dipole is responsible for the ferroelectric and piezoelectric properties of lead titanate. The transition temperature where piezoelectricity is lost (that is the temperature where the tetragonal polymorph converts into the cubic one) is called the Curie temperature. In the case of lead titanate that temperature is 490°C . [4,5]

Lead titanate has another very interesting and unique property, it possesses a negative thermal expansion coefficient. That is, it contracts as temperature increases from 0°C to 490°C . Typically, materials expand as temperature increases. This is due to the anharmonicity of the bond energy as illustrated in figure 4. This leads to a positive expansion coefficient.

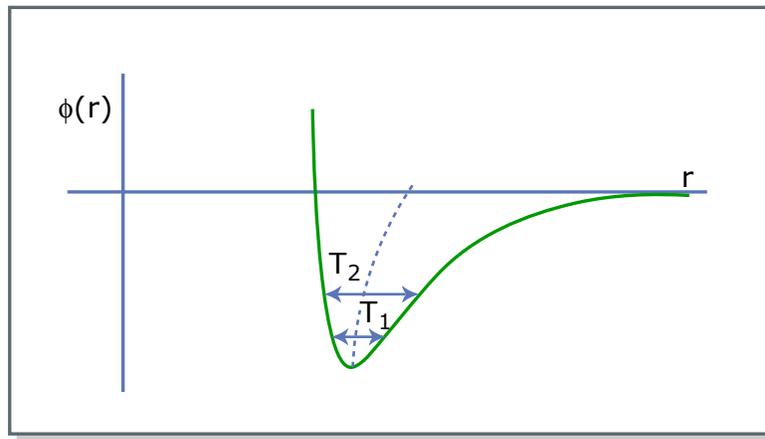


Figure by MIT OCW.

Figure 4 Leonard-Jones energy plot for a typical bond. Due to the anharmonicity of shape of the curve as the temperature increases the equilibrium distance for the bond increases as indicated by the dotted line. Figure adopted from reference [6]

In the case of lead titanate the cell contracts with temperature (figure 5). This probably happens because as temperature raises there is more space for the central titanium atom to find a more central position.

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Figure 5 Temperature dependence of lattice parameters for PbTiO_3 derived from temperature X-ray diffraction studies in reference [4]. Also see reference 5.

THEORY:

X-ray Diffraction from Crystalline Materials [7]

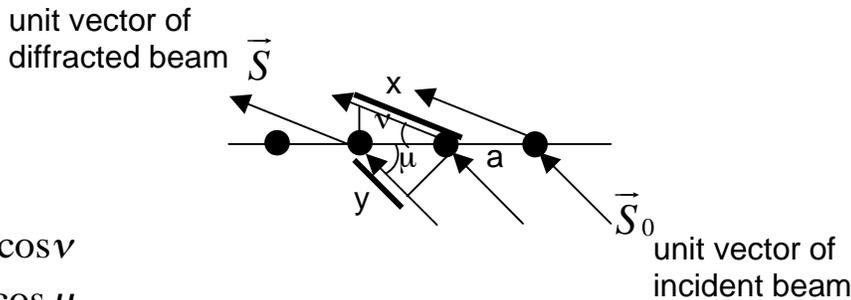
As discussed in 3.012, a periodic arrangement of atoms will give rise to constructive interference of scattered radiation having a wavelength λ comparable to the periodicity d when Bragg's law is satisfied:

$$n\lambda = 2d \sin \theta$$

where n is an integer and θ is the angle of incidence.

Bragg's law tells us necessary conditions for diffraction, but provides no information regarding **peak intensities**. To use x-ray diffraction as a tool for materials identification, we must understand the relationship between structure/chemistry and the intensity of diffracted x-rays.

Recall from 3.012 class that for a 1d array of atoms, the condition for constructive interference can be determined as follows:



$$x = a \cos \nu$$

$$y = a \cos \mu$$

The total path difference: $x - y = a \cos \nu - a \cos \mu = h\lambda$

$$(\vec{S} - \vec{S}_0) \cdot \vec{a} = h\lambda$$

Defining $\vec{s} = \frac{(\vec{S} - \vec{S}_0)}{\lambda}$, the condition for 1d constructive interference becomes:

$$\vec{s} \cdot \vec{a} = h$$

For 3 dimensions, we have: $\vec{s} \cdot \vec{a} = h$

$$\vec{s} \cdot \vec{b} = k$$

$$\vec{s} \cdot \vec{c} = l$$

where h, k and l are the Miller indices of the scattering plane.

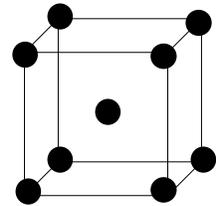
For a single unit cell having M atoms, the scattered amplitude is proportional to the **structure factor**, defined as:

$$F(s) = \sum_{n=1}^M f_n \exp \left[2\pi i \vec{s} \cdot \vec{r}_n \right]$$

where \vec{r}_n is the atomic position vector for the nth atom in the unit cell:

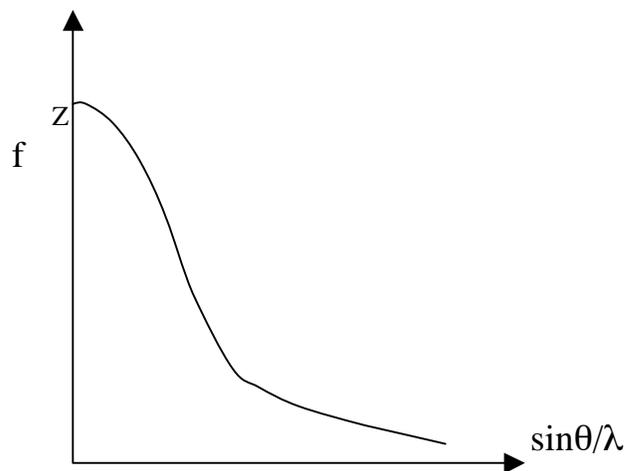
$$\vec{r}_n = x_n \vec{a} + y_n \vec{b} + z_n \vec{c}$$

where (x_n, y_n, z_n) are the atomic position coordinates.



Example: for a BCC structure, there are 2 atoms/cell at $(0,0,0)$ and $(1/2,1/2,1/2)$.

The parameter f_n is the **atomic scattering factor**, proportional to the atomic number Z of the nth atom. Hence, atoms of high Z scatter more strongly than light elements. The atomic scattering factor is a function of θ and λ .



Substituting \vec{r}_n into the structure factor:

$$F(s) = \sum_{n=1}^M f_n \exp \left[2\pi i \vec{s} \cdot (x_n \vec{a} + y_n \vec{b} + z_n \vec{c}) \right]$$

$$F_{hkl} = \sum_{n=1}^M f_n \exp \left[2\pi i (hx_n + ky_n + lz_n) \right]$$

For a BCC crystal:

$$F_{hkl} = f \exp \left[2\pi i (0) \right] + f \exp \left[2\pi i \left(\frac{h}{2} + \frac{k}{2} + \frac{l}{2} \right) \right] = f + f \exp \left[\pi i (h + k + l) \right]$$

$$F_{hkl} = 2f \quad \text{h+k+l even}$$

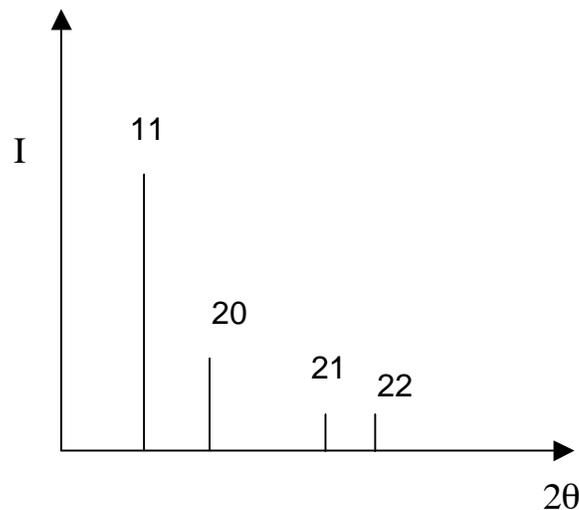
$$F_{hkl} = 0 \quad \text{h+k+l odd}$$

The scattered intensity is related to the structure factor:

$$I_{coh} \propto FF^* = |F_{hkl}|^2 = 4f^2 \quad \text{h+k+l even}$$

$$I_{coh} = 0 \quad \text{h+k+l odd}$$

Note that the total coherent intensity will be a sum of the contributions of all unit cells in the crystal. For a BCC crystal, reflections from planes with Miller indices where h+k+l is an odd integer will be absent from the diffraction pattern, while reflections from (110), (200), (211), etc. will be present with reduced intensity as h+k+l increases.



In our hypothetical case above, constructive interference occurs only at the exact Bragg angle and the I vs. 2θ curve exhibits sharp lines of intensity. In reality, diffraction peaks exhibit finite breadth, due both to instrumental and material effects. An important source of line broadening in polycrystalline materials is finite crystal size. In crystals of finite dimensions, there is incomplete destructive interference of waves scattered from angles slightly deviating from the Bragg angle. If we define the angular width of a peak as:

$$B = \frac{1}{2}(2\theta_1 - 2\theta_2)$$

then the average crystal size can be estimated from the Scherrer formula as:

$$t = \frac{0.9\lambda}{B \cos \theta_B}$$

Interplanar spacings can be calculated for different hkl planes from geometric relationships for a given crystal system:

$$\text{Cubic: } 1/d^2 = \frac{h^2 + k^2 + l^2}{a^2}$$

$$\text{Orthorhombic: } 1/d^2 = \frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2}$$

$$\text{Tetragonal: } 1/d^2 = \frac{h^2 + k^2}{a^2} + \frac{l^2}{c^2}$$

$$\text{Hexagonal: } 1/d^2 = \frac{4}{3} \left(\frac{h^2 + hk + k^2}{a^2} \right) + \frac{l^2}{c^2}$$

$$\text{Monoclinic: } 1/d^2 = \frac{1}{\sin^2 \beta} \left(\frac{h^2}{a^2} + \frac{k^2 \sin^2 \beta}{b^2} + \frac{l^2}{c^2} - \frac{2hl \cos \beta}{ac} \right)$$

OPEN QUESTIONS

- 1) Why does a diffraction pattern change with temperature?
- 2) Why does the diffraction pattern contain information about the materials volume?
- 3) What is the difference between a 002 and a 200 peak in a tetragonal cell?

MATERIALS:

Lead Titanate / Lead Titanium Oxide, PbTiO_3 (325 mesh powder) *Alfa Aesar*
Purity: 99.5%

Density: 7.520 g / cm^3

Formula Mass: 303.09 g

METHOD:

High Temperature X-ray Diffraction (HTXRD) or In-situ, Non-ambient X-ray Diffraction

INSTRUMENT: *PANalytical X'pert PRO MPD*, X-ray Diffractometer
and *X'Pert Data Collector* software

PROCEDURE:

1. Fill the ceramic cup with the PbTiO_3 powder. Ensure a flat surface
2. Place the cup on the sample holder and secure with the ceramic holding ring
3. Mount the sample holder on the hot stage of the X-ray unit, and connect the thermocouple
4. Collect data (Intensity vs. 2θ) at room temperature (RT), 400 C, 530 C and at RT (on cooling)

SCAN CONDITIONS:

Program type: ABSOLUTE TYPE

$\theta_i = 19.993^\circ$

$\theta_f = 60.000^\circ$

Step size = 0.0167°

Scan speed = $0.139261 (^\circ/\text{s})$

Time per scan at a given 'T' = 5 min 5 sec

[Note: A data set pre-collected at a wide range of temperature will be provided to you for complete analysis]

ANALYSIS: Using the MDI JADE 7 X-ray analysis routine

1. Confirm the crystal structure for PbTiO_3 at room temperature (RT), 400 C and 530 C.
2. Confirm the phase transition. Identify the phase transition temperature (Curie temperature).
3. Calculate the lattice parameters from the x-ray profile collected over a wide range of temperature. Plot a graph of Cell Parameters as a function of Temperature.
4. Calculate the cell volume from the parameters obtained in Q.3. Plot a graph of Cell Volume vs. T. Confirm that PbTiO_3 has a negative thermal expansion coefficient.
5. Calculate the thermal expansion coefficient of Lead Titanate
6. Compare your results with literature values, and include error analysis where relevant.

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