High temperature actuators & motors

Lecture outline

- Electromechanical actuators
- Materials for high temperature actuators
- Competitive materials for high temperature use
- High temperature electric motor

Actuator

- While sensors convert energy into electrical signal, actuators reverse this process by converting electrical signals into mechanical force.
- Term “actuator” stands for virtually any kind of mechanism that introduce motion. It is a component of a machine responsible for moving or controlling a specific mechanism or system (mechanical or electrical)
  - Actuators
  - Electric motors
- In electronic engineering, actuators are a subdivision of transducers. They are devices which transform an input signal (mainly an electrical signal) into some form of motion.

Work of actuator

- Actuation occurs when one or more forms of energy are converted into mechanical motion of an object.
- For proper work an actuator requires a control signal and a source of energy.
- The control signal is relatively low energy and may be:
  - electric voltage
  - current
  - pneumatic or hydraulic pressure
  - human power
- The supplied main energy source may be:
  - electric current
  - hydraulic fluid pressure, or pneumatic pressure.
- When the control signal is received, the actuator responds by converting the energy into mechanical motion.

Types of actuators

- Hydraulic
- Pneumatic
- Electric
- Thermal or magnetic (shape memory alloys)
- Mechanical

Depending on the mechanisms and operational conditions, different materials are used to fabricate actuators

Influence of the environment on actuator performance

- The physical properties of any material depends on environmental factors (temperature, pressure, humidity)
- The physical properties that can be affected include mechanical properties (size, shape, strength), electrical properties (conductivity, dielectric strength) magnetic properties (permeability and retentivity)
- Change in these properties alter the performance characteristics of an actuator
- Increase of temperature in mechanical system will cause thermal expansion, oxidation and dust generation on interacting surfaces (and in consequence increase in friction and following increase in energy consumption)
- In electrical systems, resistance increases linearly with temperature due to the temperature coefficient of resistance (again, increase in power consumption)

Parameters influencing the actuation materials work

- Elevated temperature
- High pressure
- High radiation
- Aggressive components from environment (at low and high temperatures)
- Thermal cycles (cause of stress)
- Appropriate additional components (gearing, linear and rotary bearings etc.)

Typical applications for high temperature actuators

- High temperature fans & turbines
- Motors for valves (oil & natural gas industries)
- Kiln automation
- Actuators for automotive engines (fuel injectors)
- Cooling system elements

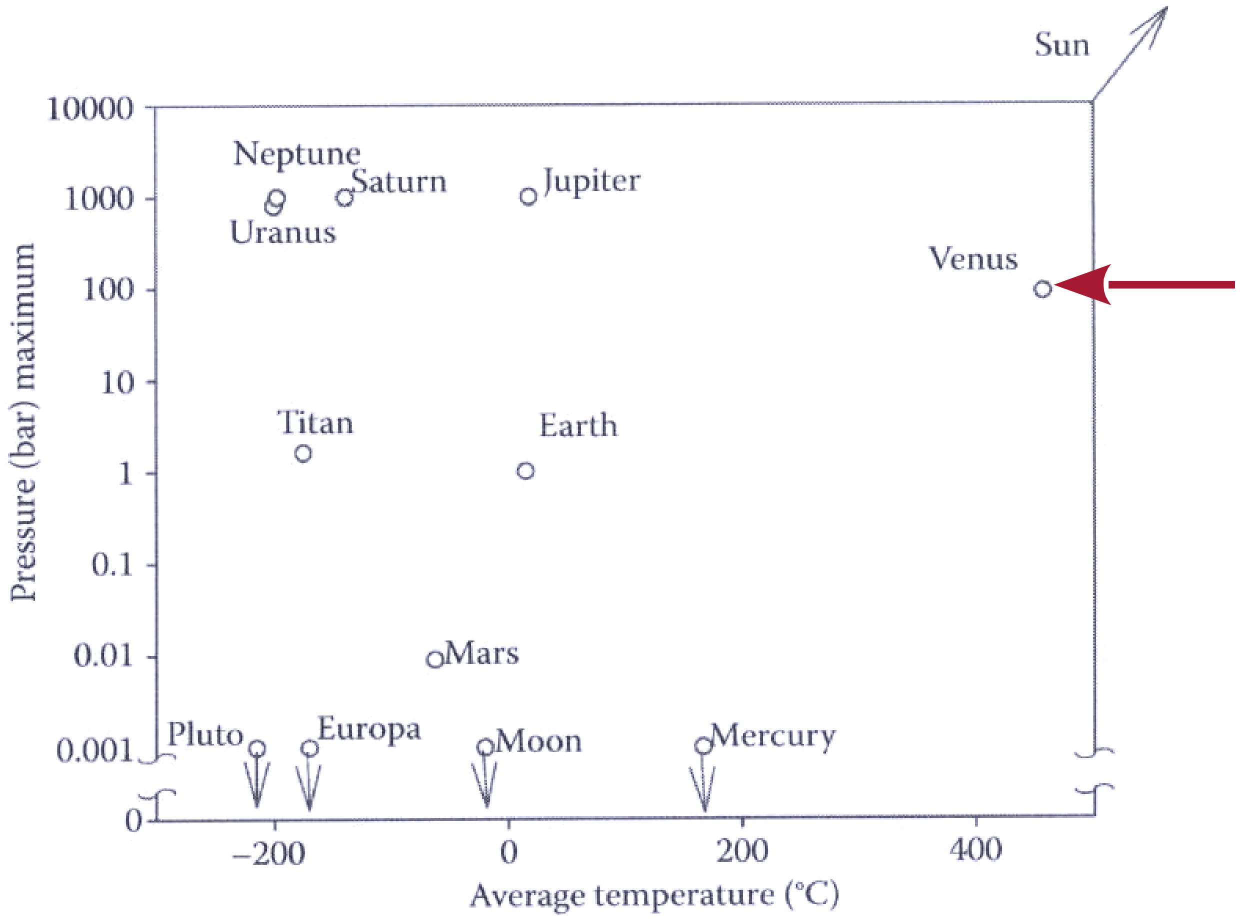
Most of these applications operates at temperatures lower or equaled to 250^{o}C.

New applications of electromechanical actuators

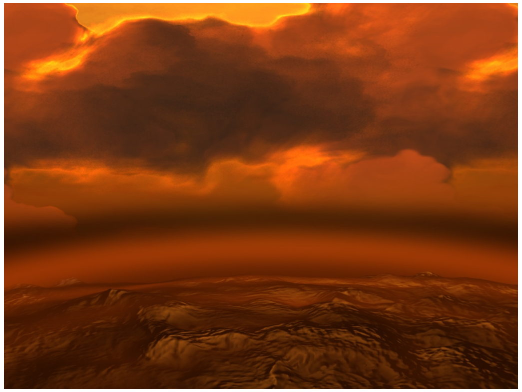
Extraterrestrial exploration (severe conditions)

- Wide range of pressure (vacuum to 1000 bar)
- Wide range of temperatures (-215°C on Pluto to 460°C on Venus)
- Wide range of gravity field (µg on comets to 2.5 g on Jupiter)
- Large radiation dose from the space (metals, ceramic and C/C composites can withstand dosage of the order of 10^{12} Rads without degradation in mechanical properties)

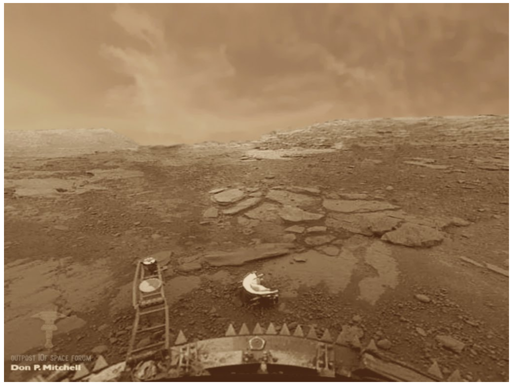
Thermal conditions in solar system



Estimated pressure maximums vs. temperature for selection of proposed mission destinations



Source: http://www.universetoday.com/47905/why-is-venus-so-hot/



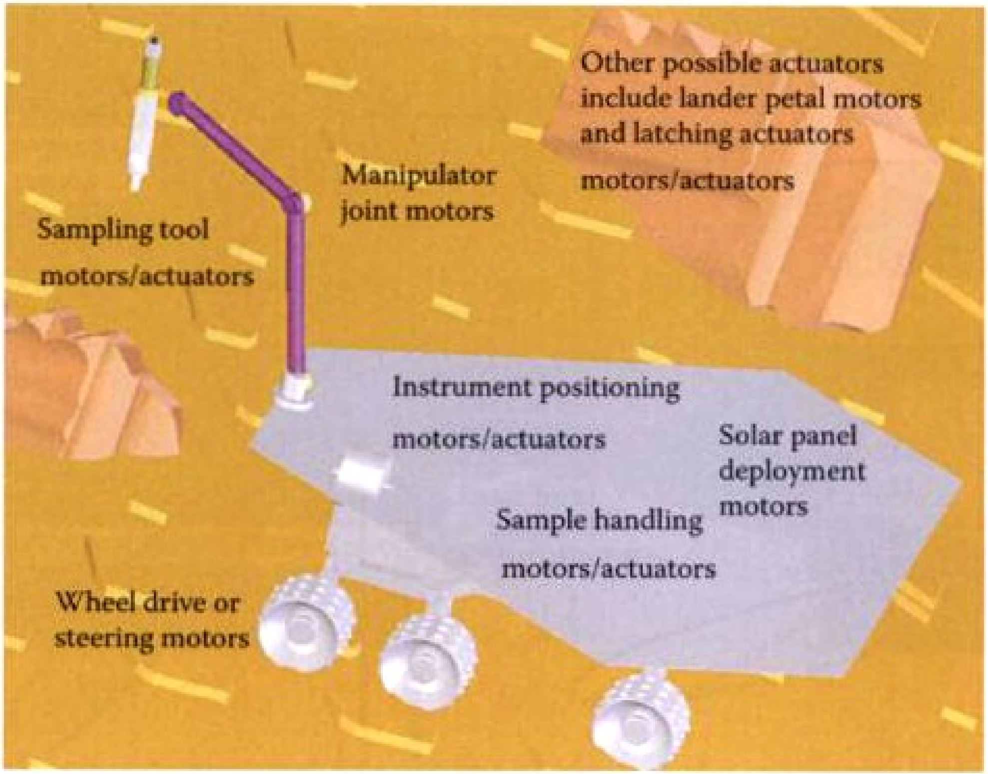
Source: https://pics-about-space.com/planet-venus-surface-reala?p=1

Source:
Sherrit, S., 2005, Smart material/actuator needs in extreme environments in space, Proceeding of the Active Materials and Behaviour Conference, SPIE Smart Structures and Materials Symposium, Paper #5761-48, San Diego, CA, March 7-10.

Actuators for extraterrestrial applications

- There are no commercially available motors that can operate in conditions similar to those on Venus (high temperature and pressure).
- Only electromechanical materials (piezoelectrics & electrostrictive) have the potential to operate at these severe conditions

Actuators for extraterrestrial applications



Actuators needed for robotic exploration of other planets:
- lander petal motors
- drive/steering motors
- manipulator joint motors
- latching & deployment motors
- sampling tools motors

The highest challenge is **high temperature** and **extended time** of operation.
Most of the actuators being in use are designed to work rather in Mars-like conditions (-60^{o}C, 1kPa CO_2)

Schematic drawing of the possible actuator/motor locations on a rover.

Source:
Sherrit S, 2005, Smart material/actuator needs in extreme environments in space, Proceedings of the Active Materials and Behaviour Conference, SPIE Smart Structures and Materials Symposium, Paper #5761-48, San Diego, CA, March 7-10

Electromechanical actuators

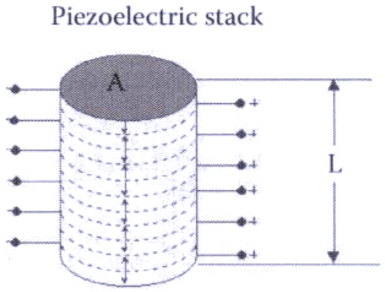
- Electromechanical materials can deform or move under an external electrical stimulus.
- Such materials can be applied in variety of configurations to produce actuators to do useful work
- Linear actuators (classification by: stroke, force, frequency of operation)
- Rotary actuators (specified by: speed and torque)
- Efficiency of the actuator: the work done divided by the input energy per cycle

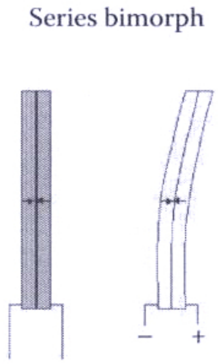
Limitation

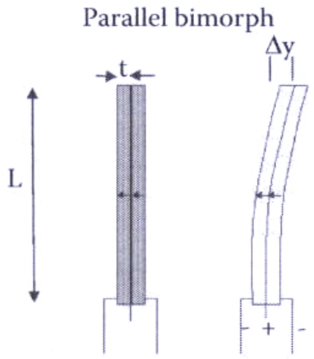
- Major limitation of solid state electromechanical materials is that the strain in the material is small compared to electromagnetic actuators even though the generated stresses can be very large

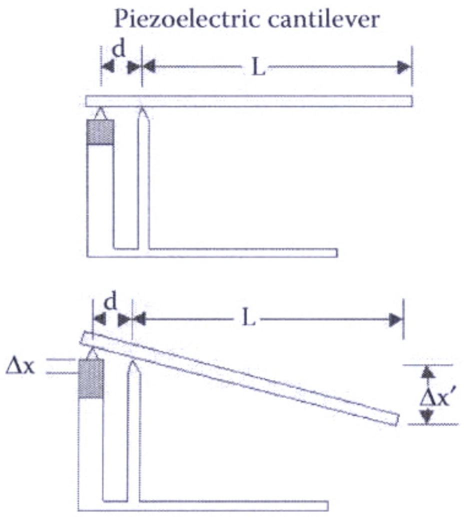
- A wide variety of techniques have been developed to increase the strain for a given applied voltage

Electromechanical actuators









Schematic diagrams of a variety of techniques used to increase the strain in electromechanical actuators

Source: Bar-Cohen, Y., 2014, High temperature materials and mechanisms, CRC Press, Taylor & Francis Group, LLC

Displacement in different actuators:

-piezoelectric stack: **100 µm**

-bimorphs: **1 cm**

-cantilever: **1 mm**

Source:
Bar-Cohen, Y., 2014, High temperature materials and mechanisms,CRC Press, Taylor & Francis Group

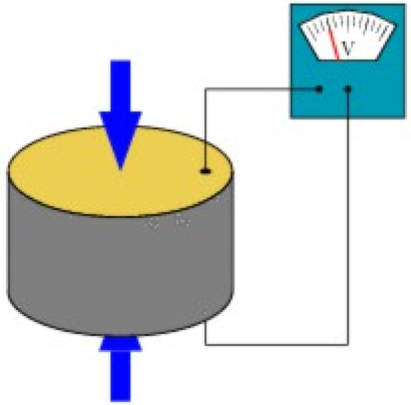
Materials for high temperature actuators

- Piezoelectric materials
- Ferroelectric materials
- Corrundum-structure single crystals
- Electrostrictive materials

Piezoelectric materials

“The word piezoelectricity means electricity resulting from pressure” (Wikipedia)

Direct effect:
Generation of charge on a crystal face as a result of application of a stress



Converse effect:
Generation of mechanical strain as a result of the applications of an electric field

Source: https://en.wikipedia.org/wiki/Piezoelectricity#/media/File:SchemaPiezo.gif

Piezoelectric materials

- Do not have centre of symmetry
- Only 20 of 32 crystallographic point groups allow piezoelectricity
- Only 10 groups possess a temperature-dependant spontaneous polarization (pyroelectrics)
- Ferroelectrics – spontaneous electric polarization can be permanently reoriented between two or more distinct directions with respect to the crystal axes trough the applications of an electric field
- Ferroelectrics can be characterized by measuring their polarization P(D) as function of applied AC electric field (E) – P vs. E hysteresis loop

Piezoelectric materials

At low values of stress and electric field, the relationship between charge and stress, strain, and field, is observed to be linear for piezoelectric materials

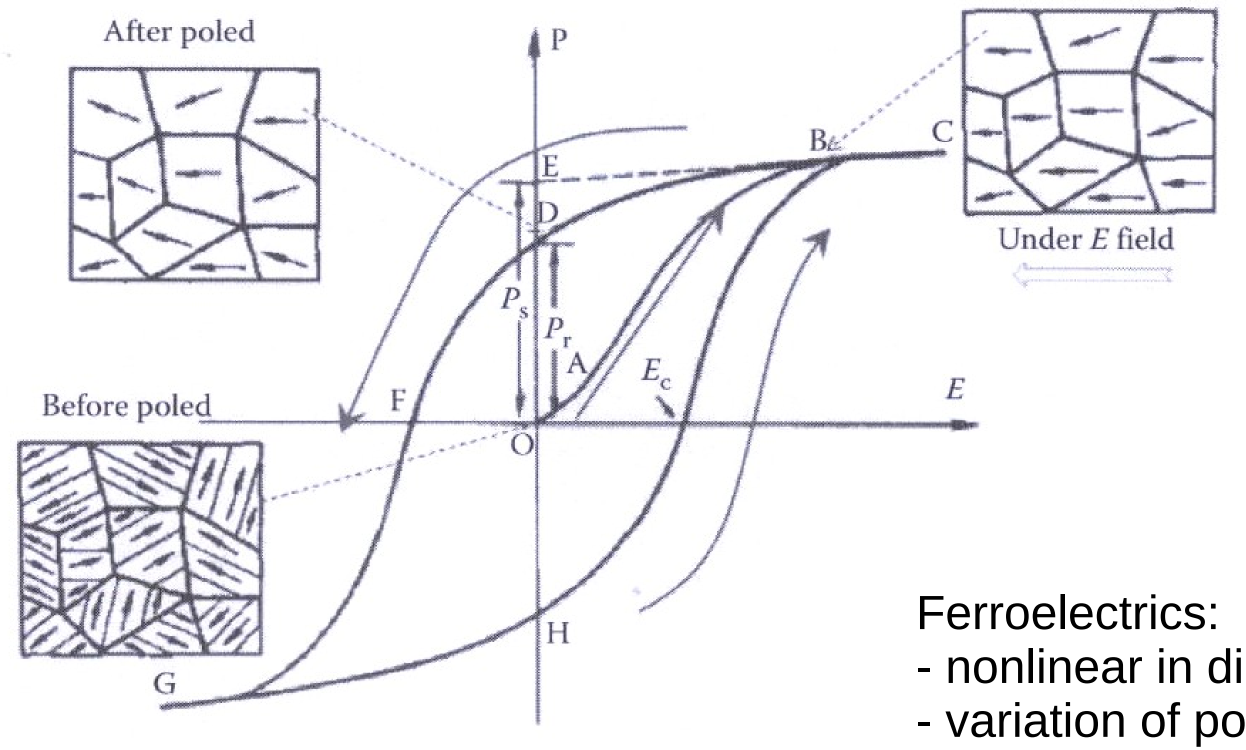
$$S = s^E T + dE$$

$$D = \varepsilon^T E + dT$$

d – piezoelectric coefficient
S – strain
T – stress
D – electric displacement
E – electric field
s^E – elastic compliance
ε^T – dielectric permittivity

Ferroelectrics

A typical polarization electric field hysteresis loop for a ferroelectric material.



Ferroelectrics:
- nonlinear in dielectric behaviour
- variation of polarization with electric field

Source:
Bar-Cohen, Y., 2014, High temperature materials and mechanisms,CRC Press, Taylor & Francis Group

High-temperature piezoelectrics

In order to use piezoelectric materials for a specific high temperature applications, many aspects need to be considered along with piezoelectric properties, such:

- phase transformation
- thermal aging
- thermal expansion
- electrical resistivity
- chemical stability (decomposition and defect creation)
- stability of properties at elevated temperatures

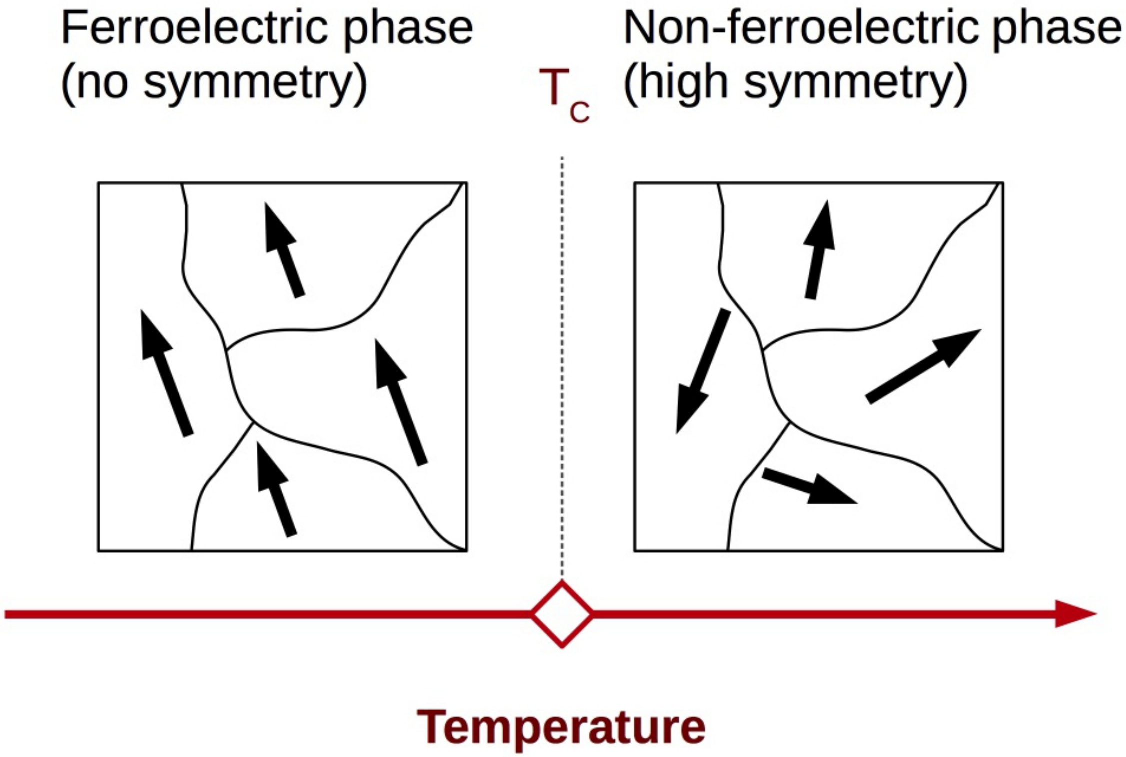
High-temperature piezoelectrics

In order to use piezoelectric materials for a specific high temperature applications, many aspects need to be considered along with piezoelectric properties, such:

- phase transformation
- thermal aging
- thermal expansion
- electrical resistivity
- chemical stability (decomposition and defect creation)
- stability of properties at elevated temperatures

These parameters are critical for use at high temperatures

Curie temperature (T_C)



- Above T_C, the materials are permanently depolarized and cannot be used for piezoelectric applications.
- The maximum operating temperature is determined by Curie temperature. In practice, the operating temperature must be substantially lower than the Curie temperature (**< ½ T_C**) in order to minimize thermal aging and property degradation.

Candidates for high-temperature piezoelectrics

- Polycrystalline ceramics with perovskite structure
- Tungsten bronze
- Bismuth layer
- Double perovskite layer structures (PLSs)
- Single crystals with corundum structure ($LiNbO_3$ (LN) and $LiTaO_3$ (LT)) and Curie temperature of 1150 and 720^{o}C respectively.

Examples of high-temperature ferroelectric materials

Ferroelectric polycrystalline ceramics with the perovskite structure ($Pb(Zr,Ti)O_3$ (PZT))

- Based on specific set of compositions that have two phases in equilibrium
- High piezoelectric coefficients $d_{33}>350$ pm/V
- Electromechanical coupling factors $k_{33}>0.7$
- Curie temperature ranging from 160 to 350^{o}C
- Usage limited to about ½ T_c due to to aging
- Bismoth-based perovskite policrystalline ceramics can offer about 100^{o}C higher Curie temperature with comparable other piezoelectric properties.

Examples of ferroelectric materials

- The tungsten bronze family $(A1)_2(A2)_4C_4(B1)_2(B2)_8O_{30}$

  Where:

  - A – sites occupied by Pb^{2+}
  - B – sites occupied by Nb^{5+}
  - C – empty sites
- Example: lead metaniobate $PbNb_2O_6$ (PN)
- Commercial PN composites are modified to enhanced specific electrical characteristics but at a cost of lower T_C. Commonly used compositions contains about 10% Ba (PBN) and has a T_C of about 400°C, being further limited by high electrical conductivity above 300°C.

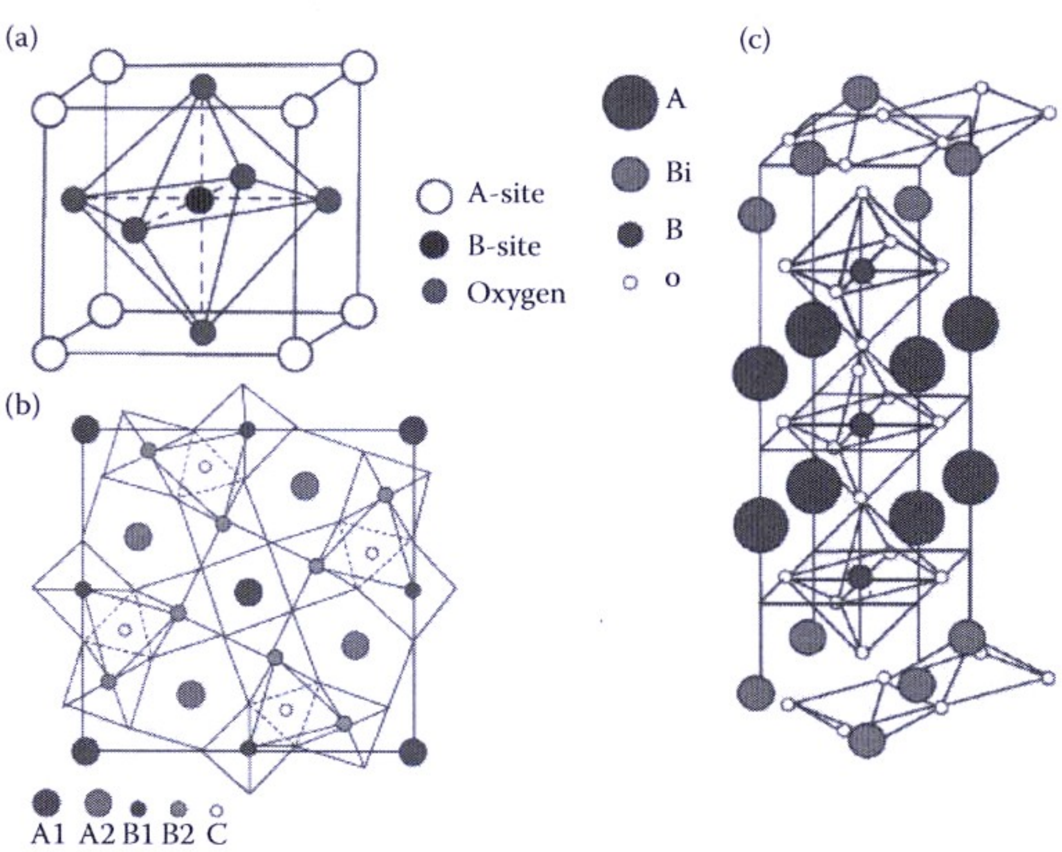
Examples of high-temperature ferroelectric materials

Bismuth layer structured ferroelectrics (BLSFs)

- General formula $(Bi_2O_2)^{2+}(A_{m-1}B_mO_{3m+1})^{2-}$

  where

  - A is a mono-, di- or trivalent ion or mixture of the three, allowing dodecahedral coordination
  - B is a combination of cations well suited for octahedral coordination,
  - m is the number of octahedral layers in the perovskite slab (from 1 to 6)
- High Curie temperatures (e.g., T_C 650°C for $Bi_4Ti_3O_{12}$, T_C 940°C for $BiTiNbO_9$)
- Low aging effects
- Low dielectric loss
- High mechanical quality factor Qm up to 10 000
- Relatively low dielectric and piezoelectric properties (d_{33}=10pm/V)
- Low electrical resistivity at high temperatures limits use to well below 600°C



Schematic structures for perovskit (a), tungsten bronze (b) and bismuth layer (c) materials.

Source:
Trolier-McKinstry, S., Piezoelectric and acoustic materials for transducer applications, Crystal chemistry of piezoelectric materials, 2008, 39-56.

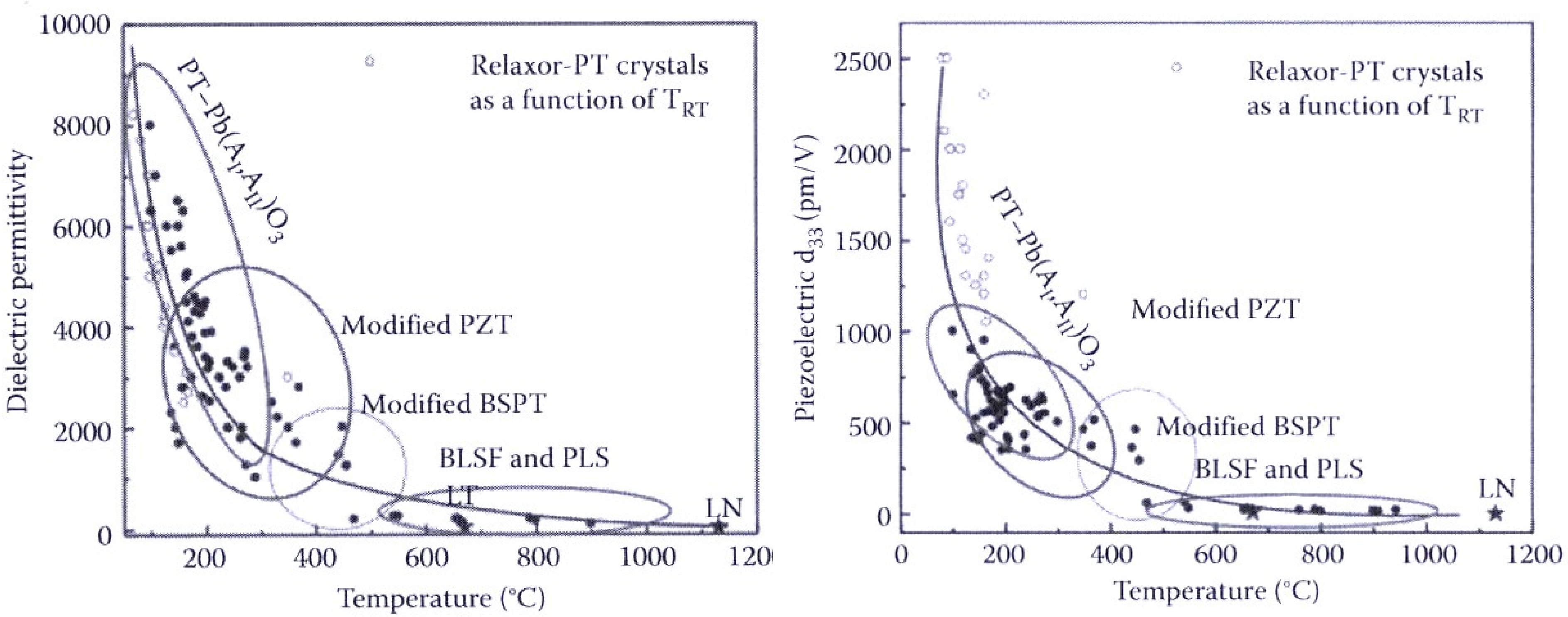
Examples of high-temperature ferroelectric materials

- Double perovskite layer structures (PLS) ferroelectrics general formula is: $A_2B_2O_7$
- $Sr_2Nb_2O_7$ and $La_2Ti_2O_7$ posses the highest known ferroelectric Curie temperature, 1342 and 1500°C, respectively, as well as high electrical resistivity at elevated temperatures, of order of 10^7 Ohm·cm at 700°C.

Single crystals with corundum structure

- $LiNbO_3$ (LN) and $LiTaO_3$ (LT) exhibits high Curie temperatures 1150^{o}C and 720^{o}C, respectively
- The piezoelectric coefficients d_{33} are about 6 pm/V for LN and 9 pm/V for LT crystals
- Usage temperature for LN is limited to 600^{o}C, due to its low resistivity (10^4 ~10^6 Ohm·cm at 500^{o}C)
- LN crystals suffer from chemical decomposition at modest temperatures

Dielectric and piezoelectric properties of different groups of materials



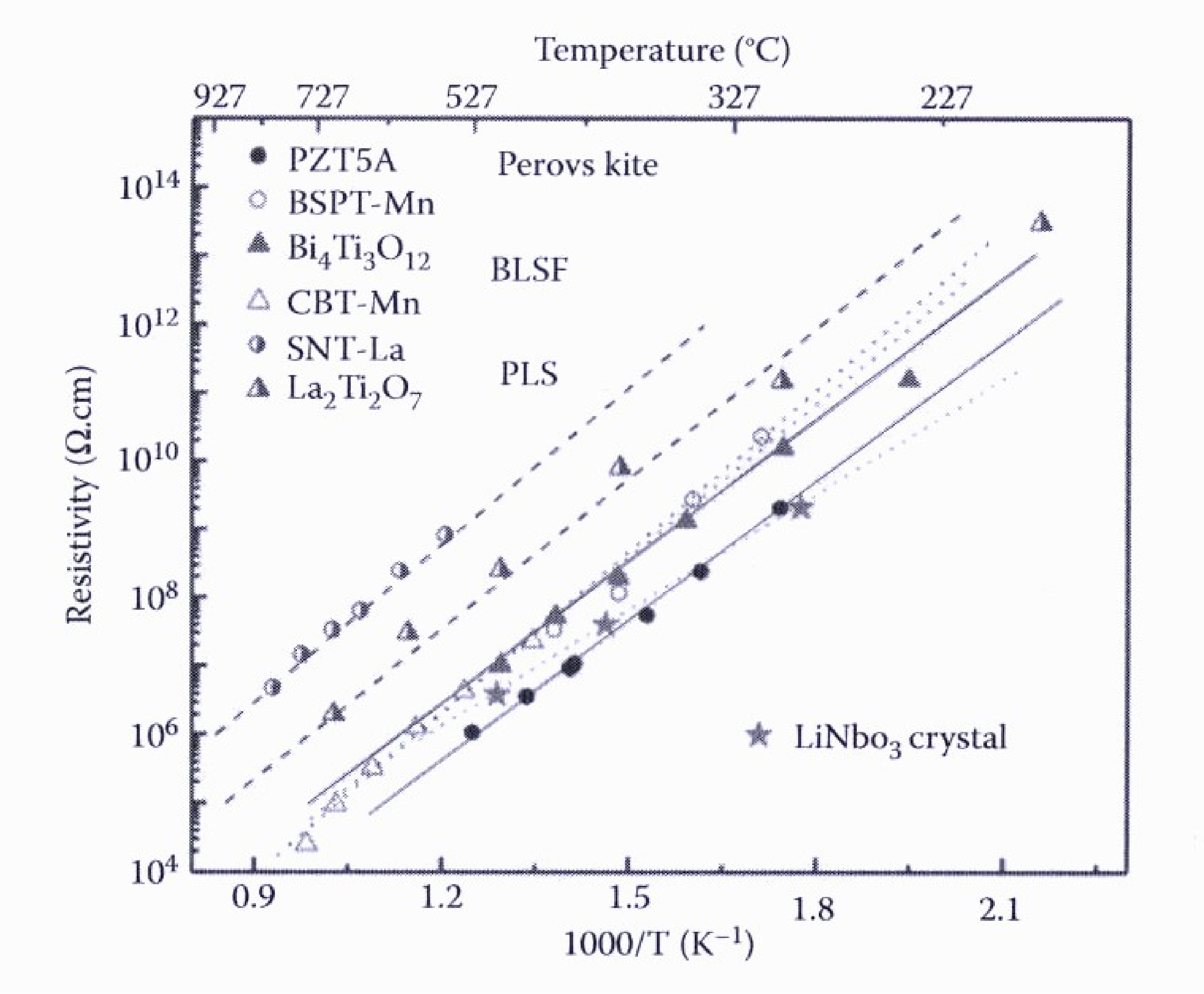
Temperature dependent dielectric (left) and piezoelectric (right) properties for various ferroelectric families.

Source:
Bar-Cohen, Y., 2014, High temperature materials and mechanisms,CRC Press, Taylor & Francis Group

Dielectric and piezoelectric properties of different groups of materials

- In addition to high piezoelectric properties and transition temperature, ferroelectrics with high electrical resistivity are also desired so that a large field can be applied during the poling process without breakdown or excessive charge leakage.
- The highest resistivity is observed for ceramic with the PLS (10^8-10^9 Ohm·cm at 500°C), decreasing for BLSF ceramics (10^7 Ohm·cm) and further reduced for PZT ceramics and LN crystals (10^6 Ohm·cm).
- In each case activation energy is of order of 1.3-1.5 eV for ceramics and 1.1 eV for LN crystals (oxygen vacancies dominate the conductivity).

Electrical resistivity as a function of temperature for various ferroelectric materials



Source:
Zhang, S.J. and Yu, F.P., 2011, Journal of the American Ceramic Society, 94, 3153-3170.

Non-ferroelectric piezoelectric crystals

- Minimal aging
- High mechanical quality factors (due to absence of ferroelectric domains)
- High electrical resistivity
- No Curie temperature prior to their respective melting temperatures (expanded usage temperature range)
- Low properties (in comparison with ferroelectrics), for example: piezoelectric coefficients of α-Quartz and AlN are ~2pm/V / ~5pm/V respectively.

Non-ferroelectric piezoelectric crystals

- Quartz (SiO_2)
- $GaPO_4$
- AlN
- CGG ($Ca_3Ga_2Ge_4O_{14}$)

Non-ferroelectric piezoelectric crystals

- Quartz (SiO_2)
- Best known and earliest piezoelectric material
- Excellent electrical resistivity ($>10^{17}$ Ohm·cm at room temperature)
- Ultra low mechanical loss
- Highly temperature-stable
- Relatively small piezoelectric coefficient
- Phase transition temperature at 573°C

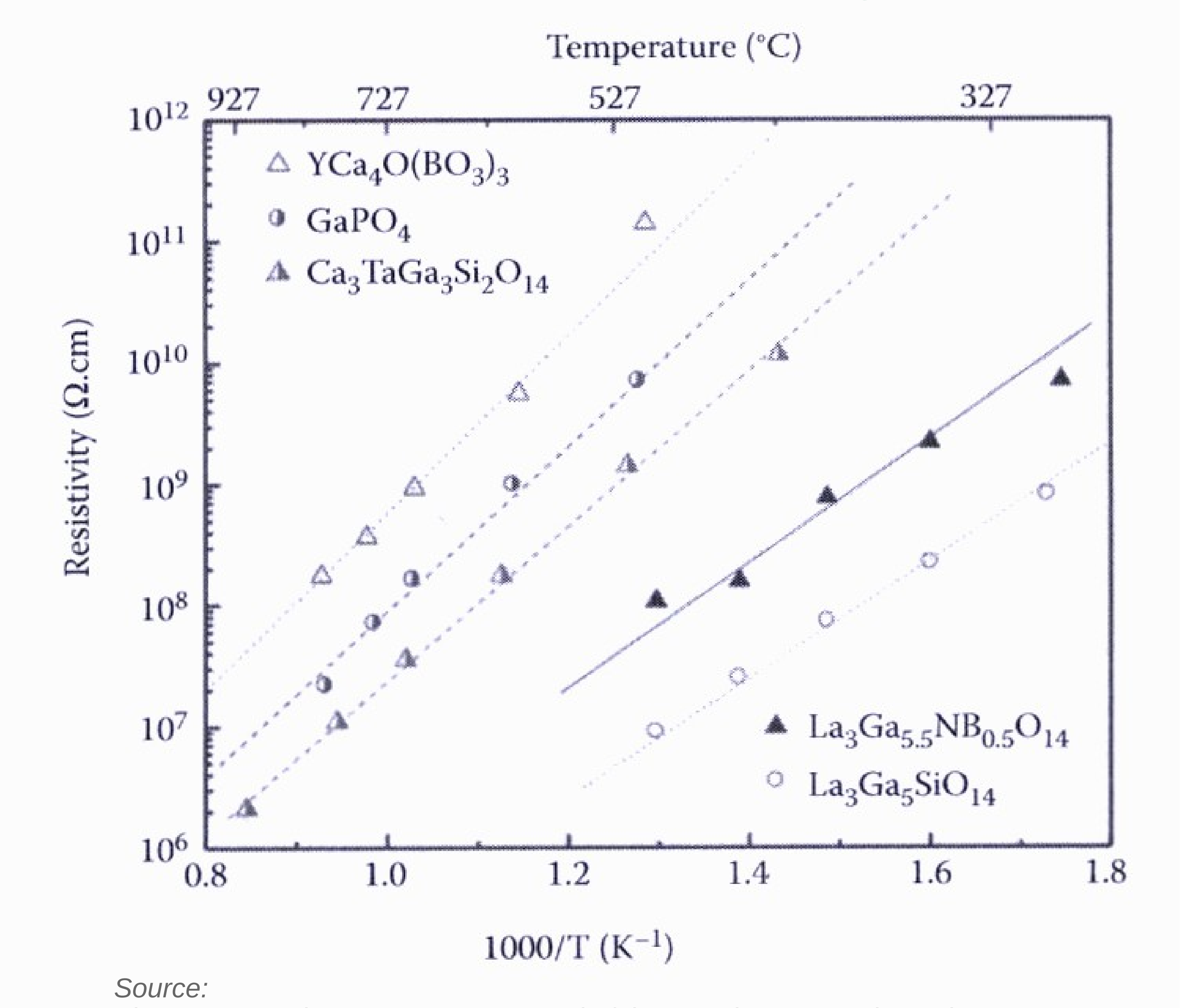
Non-ferroelectric piezoelectric crystals

- $GaPO_4$
- High electrical resistivity
- Mechanical quality factor at temperatures up to 970^{o}C
- Low mechanical loss at room temperature, increases with temperature due to the increase in structural disorder

Non-ferroelectric piezoelectric crystals

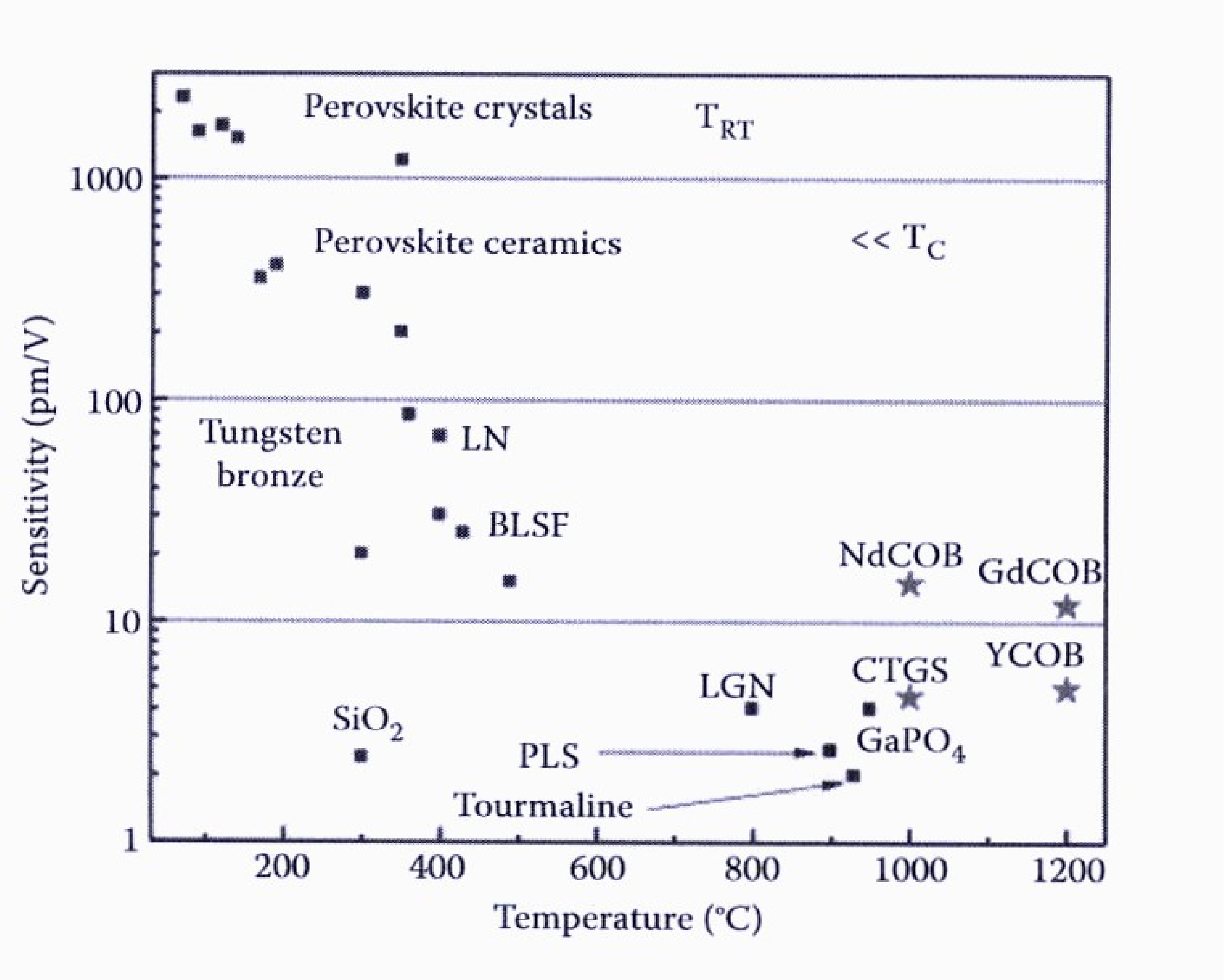
- CGG ($Ca_3Ga_2Ge_4O_{14}$) a wide group of crystal materials
- Crystals grown by the Czochralski pulling or Bridgman growth method
- No phase transitions
- Melting temperature in the range of 1200-1550°C
- Langasite family crystals have general formula of $A_3BC_3D_2O_{14}$
- Do not have pyroelectric properties

Electrical resistivity vs. temperature for selected non-ferroelectric piezoelectric single crystals.



Source:
Zhang, S.J. and Yu, F.P., 2011, Journal of the American Ceramic Society, 94, 3153-3170

Potential operational temperatures and sensitivity range for various piezoelectric materials



Parameters considered during evaluation of materials for high temperature applications:

-piezoelectric coefficient

-electromechanical coupling factors

-usage temperature range

-temperature stability of properties

-mechanical quality factor

-radiation resistance

-corrosion resistance

Source:
Bar-Cohen, Y., 2014, High temperature materials and mechanisms,CRC Press, Taylor & Francis Group

Electrostrictive materials

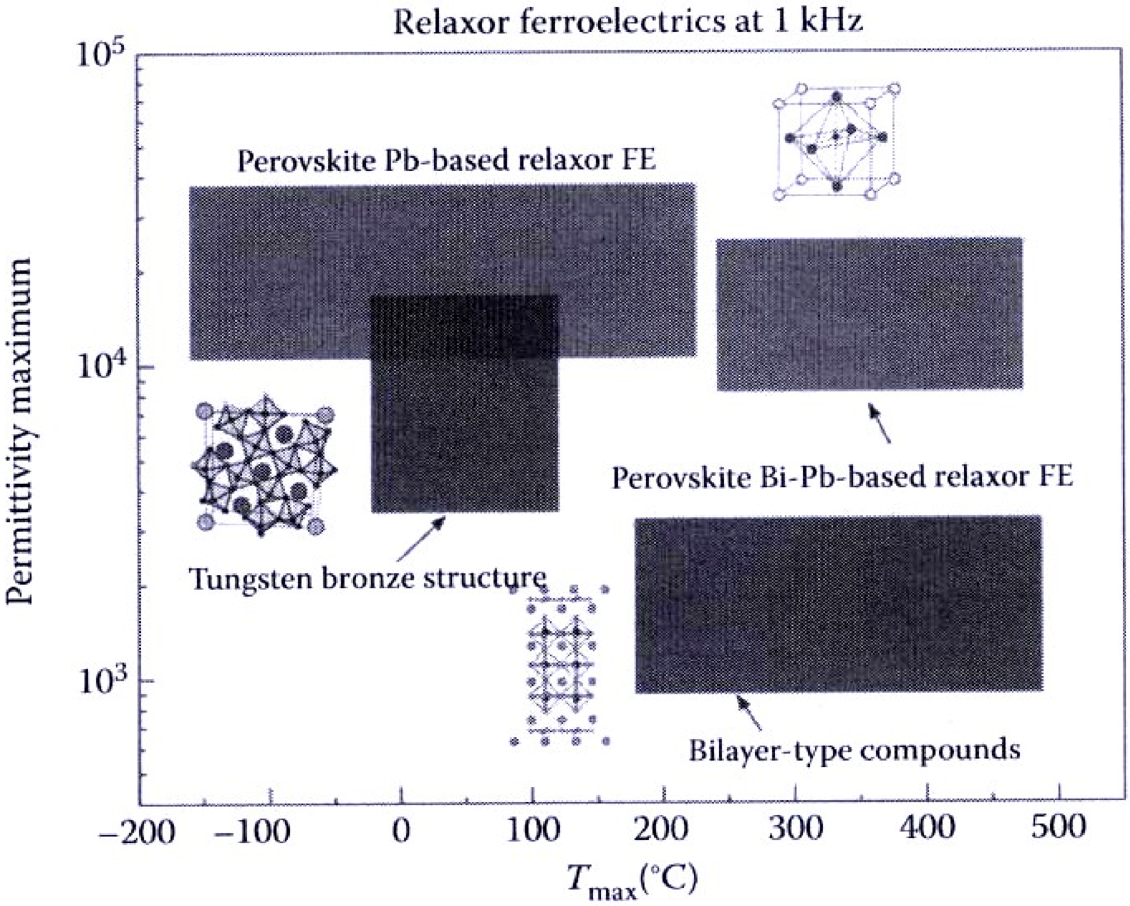
- Electrostriction is used to describe the electric-field induced strain, which is present in all dielectric materials. A key difference between piezoelectricity (converse piezoelectric effect) and electrostriction is that piezoelectricity displays a linear relationship between strain S and electric field E, while the electrostrictive strain shows a quadratic dependence on the electric field E, or electric polarization P

Electrostrictive materials

- All dielectric materials posses electrostriction
- Practical applications for electrostrictive actuators are limited to the perovskite ferroelectric family that has relatively high dielectric permittivities
- The usefulness over piezoelectric materials for actuators materials arises from the absence of macroscale domains as they are generally operated in the para-electric state above the temperature of dielectric permittivity maximum (T_{max})
- The absence of macroscale domains results in low hysteresis loss, low aging, improved reproducibility, reduced creep effects and high-response speed (<10 µs).
- Materials suitable for actuator devices, such as servo transducers and micro-positioning devices

Electrostrictive materials

- Lead magnesium niobate (PMN) pure and with modifications, known as relaxos, offer relatively broad operating temperatures range
- Lanthanum-doped lead zirconate-lead titanate $Pb_{1-x}La_x(Zr_{1-y}Ti_y)_{1-x/4}O_3$ (PLZT) – relaxor ferroelectrics
- Strontium doped barium titanate $(Ba_{1-x}Sr_x)TiO_3$ (BST)



Comparisons of various dielectric materials in terms of relative permittivity maximum (K_{max}) and the temperature of relative permittivity maximum (T_{max}) for Pb-based perowskites, Bi-Pb relaxors, tungsten bronze structured relaxors, and Bi-layered compounds.

Source:
Stringer, C.J., 2006, Structure property performance relationship of new high temperature relaxors for capasitor spplications, PhD Dissertation, Pennsylvania State University.

Competitive materials for high temperature use

Magnetostrictive materials

- Have been known to exhibit strain as a function of the charge in the magnetic state of a material for over a century.
- These materials have been used to produce high frequency high power sonar projects, optics and ultrasonic actuators
- Materials:
- RFe_2 alloys (R=Tb, Dy, Sm) have very high magnetostriction at temperatures as high as 200^{o}C
- Piezomagnetism
- a phenomenon related to magnetostriction
- A change in strain is linear with the magnetic field change.
- Magnetostrictive materials with operational temperatures around 500^{o}C are available but have small magnetostrictive coefficients.

Shape memory alloys

- Shape memory alloys (SMA) are alloys that have the ability to recover a permanent strain when heated above a certain temperature
- Exhibit stable high- and low-temperature phase that has different crystal strain in a given direction
- SMA have been implemented in variety of low frequency applications where high force is required
- High-temperature SMA materials (NiTiHf) have been developed that can actuate above 400°C with reduced strain and increased aging
- Variety of materials are available in the 100-400°C range
- These materials have been used in applications where simplicity and high force are required but large number of cycles and frequency of operation are not critical

Phase Change Materials

- New class of materials for actuators for space applications
- Applications where large stroke and force are required
- Use the material volume expansion during phase change do drive a piston
- Large stroke, up to few centimetres
- Forces up to 500N or more
- Actuators can be driven by heater or local environmental changes to balance thermal environments or act as a thermal switches.

Conventional Electromagnetic Actuators

- Conventional motors for rotary and linear actuators are designed to withstand high temperatures and pressures expected in the oil and gas industries.
- Commercially available actuators ready to operate in the range of 200-300^{o}C
- Build using variety of high-temperature magnetic materials such as Samarium Cobalt SmCo or Alinco (high remnance, coercivity and energy density) can operate up to 350^{o}C
- Specially designed motors for extrateréstial applications such as exploration of Venus can operate under high pressure conditions in temperature of 500^{o}C (relatively short lifetime)

Thermal aging and degradation

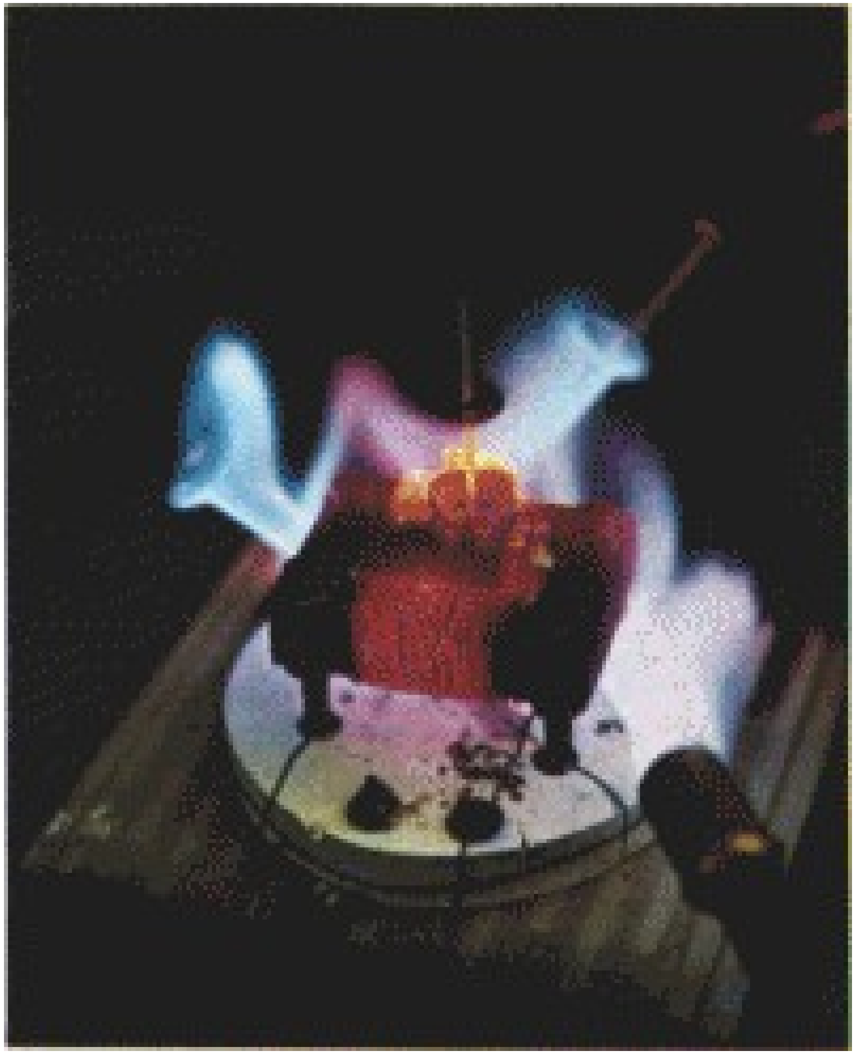
- **Aging** is a process of reduction in magnetization or polarization over time and is a consequence of domain wall mobility and stability which is thermally activated.
- Aging effects are reversible (by applying high enough electric or magnetic field)
- **Degradation** is a consequence of chemical reactions between actuator material and ambient environment (e.g., oxidation, rusting, hydrogen embrittlement, grain growth caused by high temperature that changes both elastic and electromechanical properties of active material)
- **Creep** (continuing time dependant deformation at constant temperature of a structure under constant load or stress)

High-temperature electric motor

High-temperature electric motor

- Motors are actuator devices that convert electrical energy into rotating mechanical motion.
- They can have different sizes and construction (brushed or brushless)
- In brushless motors there is no electrical connection between the stator (non-moving part of the motor) and rotor (better for high temperature applications).
- Different types of brushless motors:
- AC induction motors
- Stepper motors
- Switched reluctance motors (SRM)
- Brushless direct current (BLDC) motors
- Brushless motors are favourable for high-temperature applications because of absence of contacting commutation brushes

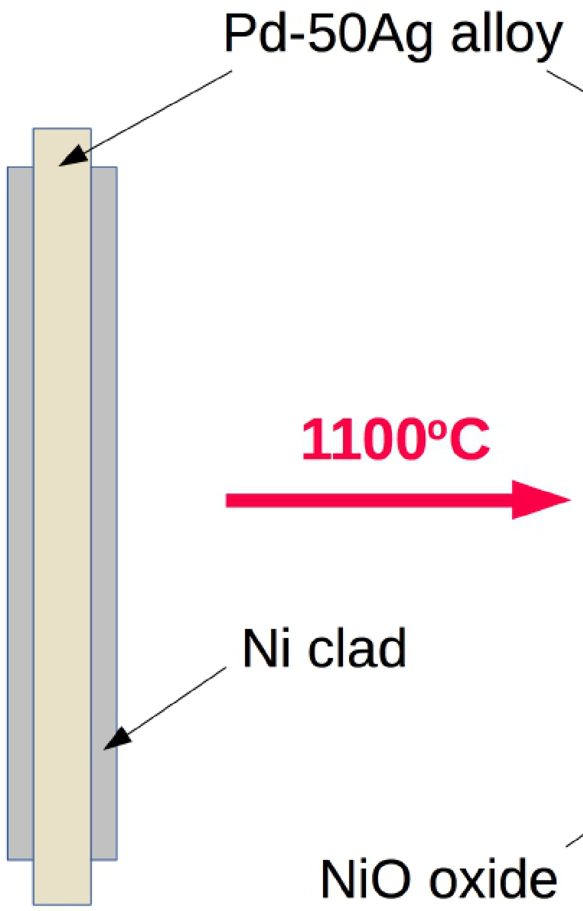
A high-temperature electric motor



Source:
http://www.technology.matthey.com/article/15/3/100-101/

- Synchronous A.C. motor
- Designed by General Electric
- Can operate in temperatures up to 725°C in oxidizing atmosphere (limited by the Curie temperature of Fe-6Si magnetic material)
- Built using innovative materials

Nickel-clad 50 per cent silver-palladium wire



NiO coating:

- is inert to oxidizing atmosphere and conducting core

- prevents volatilisation of Ag / oxidation of Pd

-provides electrical isolation at low voltage loads

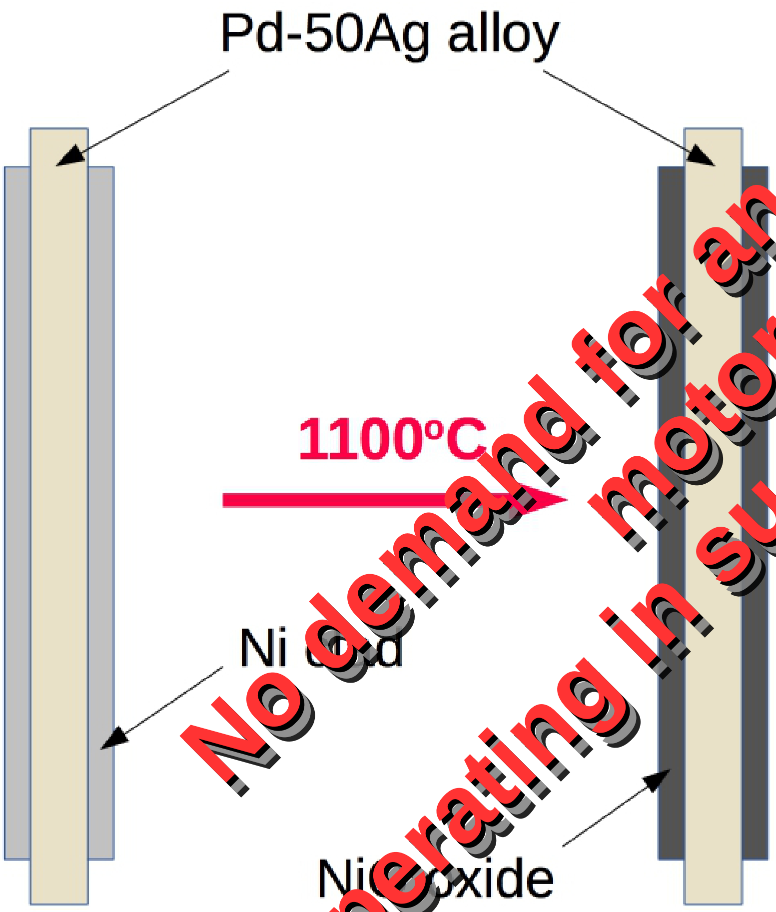
-clad and core have similar thermal expansion coefficients

-melting point of Pd-50Ag is 1200°C

-operational range up to melting point of the wire core

-excellent consistency in electrical and mechanical characteristics over relatively long period of time

Nickel-clad 50 per cent silver-palladium wire



No demand for an electric motor operating in such conditions!

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9. *Platinum Metals Rev., 1971, 15, (3), 100-101*

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