Piezo basics
– tutorial

This tutorial provides an introduction to the basics of piezoelectricity. This includes an introduction to the nature of piezoelectricity, and a description of the two types of piezoceramic materials (hard doped and soft doped).

In this tutorial, you will also be introduced to the constitutive equations as well as the properties of piezoceramic material at high field. You will also find a description of the thermal properties of piezoceramic material, and you can find an overview helping you choose a ceramic material.

The tutorial on the basics of piezo consist of these sections:

- Nature of piezoelectricity
- Hard doped and soft doped piezoceramic material
- Constitutive equations
- Properties of piezoceramic material at high field
- Thermal properties of piezoceramic material
- How to choose a ceramic material

NATURE OF PIEZOELECTRICITY

The piezoelectric effect was discovered by Jacques and Pierre Curie in 1880. The initial observation was the development of charge on a crystal proportional to an applied mechanical stress. Soon thereafter, the converse effect i.e. the geometrical strain of a crystal proportional to an applied voltage, was discovered.

Basics on piezoelectric material

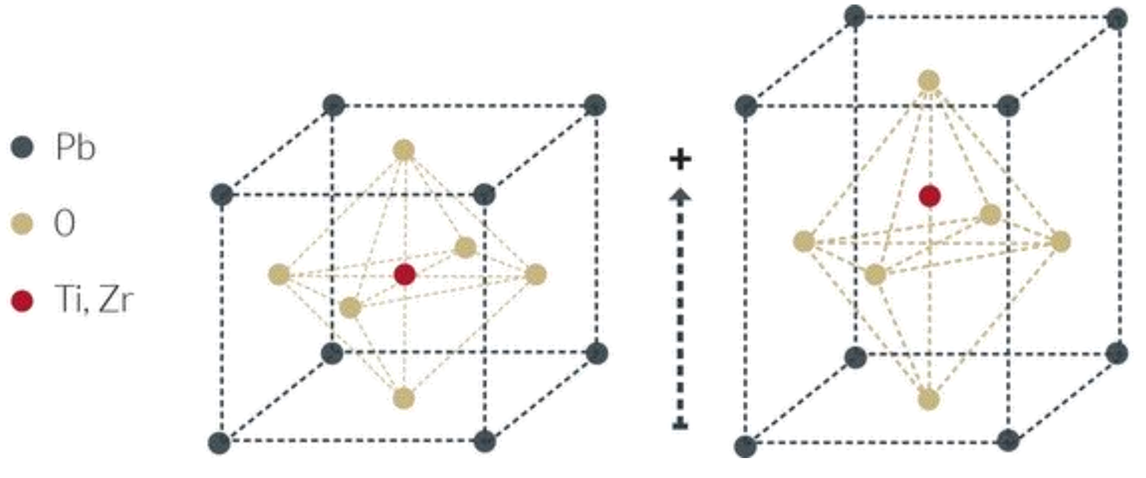
Piezoelectricity is the property of some materials to develop electric charge on their surface when mechanical stress is exerted on them. An applied electric field produces a linearly proportional strain in these materials. The electrical response to mechanical stimulation is called the direct piezoelectric effect, and the mechanical response to electrical simulation is called the converse piezoelectric effect.

Different piezoelectric materials

Piezoelectricity is the property of nearly all materials that have a non-centrosymetric crystal structure. Some naturally occurring crystalline materials possessing these properties are quartz and tourmaline. Some artificially produced piezoelectric crystals are Rochelle salt, ammonium dihydrogen phosphate and lithium sulphate. Another class of materials possessing these properties is polarized piezoelectric ceramic.

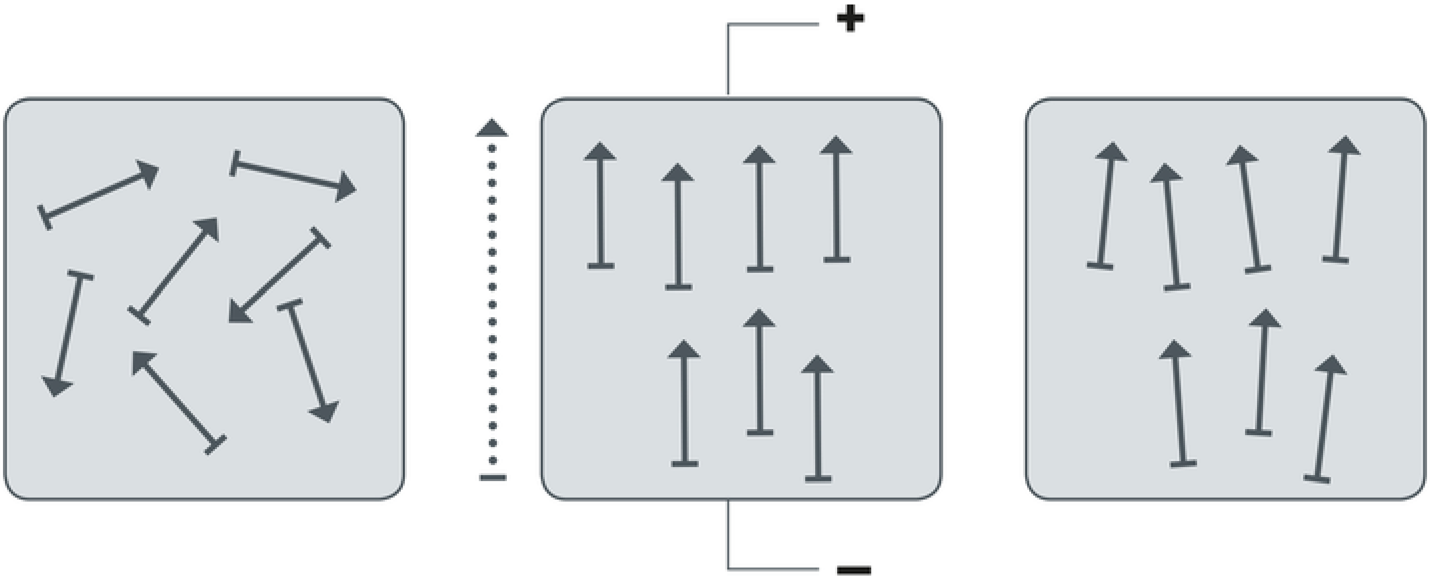
In contrast to the naturally occurring piezoelectric crystals, piezoelectric ceramics are of a “polycrystalline” structure. The most commonly produced piezoelectric ceramics are lead zirconate titanate (PZT), barium titanate and lead titanate. Ceramic materials have several advantages over single crystal, especially the ease of fabrication into a variety of shapes and sizes. In contrast, single crystals must be cut along certain crystallographic directions, limiting the possible geometric shapes.

PZT crystal structure



PZT have crystal structures belonging to the perovskite family with the general formula AB03. In the figure, the ideal, cubic perovskite structure is shown. PZT crystallites are centro-symmetric cubic (isotropic) above the Curie temperature and exhibit tetragonal symmetry (anisotropic structure) below the Curie temperature.

Poling process



Before poling, a piezoelectric ceramic material consists of small grains (crystallites), each containing domains in which the polar direction of the unit cells is aligned. These grains and domains are randomly oriented; hence, the net polarization of the material is zero, i.e. the ceramic does not exhibit piezoelectric properties. The application of a sufficiently high DC field (called poling process) will orient the domains in the field direction and lead to a remanent polarization of the material.

HARD DOPED AND SOFT DOPED PIEZOCERAMIC MATERIAL

Although there are several types of piezoelectric ceramic materials available today, most can be placed into one of two general categories: "Hard" materials and "soft" materials. The perovskite structure is very tolerant to element substitution (doping) – therefore the terms "hard doped" and "soft doped" are used. Even small amounts of a dopant (~1%) may cause huge changes in the properties of a material.

Characteristics of hard doped piezoceramic material

Hard materials are suitable for dynamic/on-resonance applications, where the high quality factor determines the amplification of the deflection at resonance. Hard materials can withstand high level of electrical excitation and mechanical stress, and are not easy poled or depolarised except at elevated temperature. However, this stability is accompanied by small piezoelectric constants (i.e. low strain). If intending to use piezoelectric actuators in dynamic operation for instance, e.g. for ultrasonic cleaning, it is strongly recommended to use actuators based on a hard piezoceramic material, which has a factor 10 lower dielectric losses than "soft" materials.

Characteristics of soft doped piezoceramic material

Soft ceramics feature high sensitivity and permittivity and are well suited for static or semi static applications, where large deflections are required. They produce larger displacements because their piezoelectric constants are higher. However, when operated in dynamic mode at high field such soft piezoceramic material types suffer from high dielectric losses and high dissipation factors, which may lead to overheating over an extended period of operation.

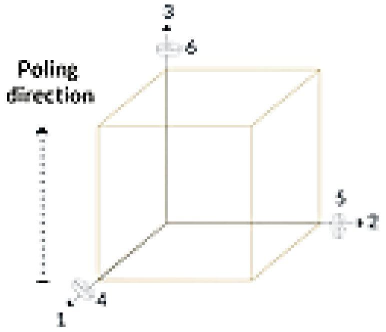
Below you can see a comparison of the characteristics of the hard and soft doped piezoceramic material.

Type of ceramic	Soft piezoceramic material	Hard piezoceramic material
Piezo constants (Strain in Static)	High	Low
Dielectric constants (capacitance)	High	Low
Dielectric losses (self-heating)	High	Low
Coercive field (depolarization)	Low	High
Quality factors (strain at resonance)	Low	High

CONSTITUTIVE EQUATIONS

Because of the anisotropic nature of piezoelectric ceramics, properties are different depending on direction. To identify directions in a piezoelectric ceramic element, three axes are used. These axes, termed 1, 2, and 3, are analogous to X, Y, and Z of the classical three-dimensional orthogonal set of axes.

Piezoelectric coefficients and directions



Schematic diagram of dipole effect induced in piezoelectric material

The polar, or 3 axis, is taken parallel to the direction of polarization within the ceramic. This direction is established during manufacturing process by a high DC voltage that is applied between a pair of electroded faces to activate the material. In many cases these electrodes are also used in operation, so the field is always applied in direction 3. Directions 1 and 2 are physically similar so they can be defined arbitrarily, perpendicular to direction 3. The axes termed 4, 5 and 6 correspond to tilting (shear) motions around axes 1, 2 and 3 respectively.

In shear elements, these poling electrodes are later removed and replaced by electrodes deposited on a second pair of faces. In this event, the 3 axis is not altered, but is then parallel to the electroded faces found on the finished element. Operating field is therefore applied in direction 1. In such devices, the wanted mechanical stress or strain is shear around axis 5.

Piezoelectric materials are characterized by several coefficients. Piezoelectric coefficients with double subscripts link electrical and mechanical quantities. The first subscript gives the direction of the electric field associated with the voltage applied, or the charge produced. The second subscript gives the direction of the mechanical stress or strain.

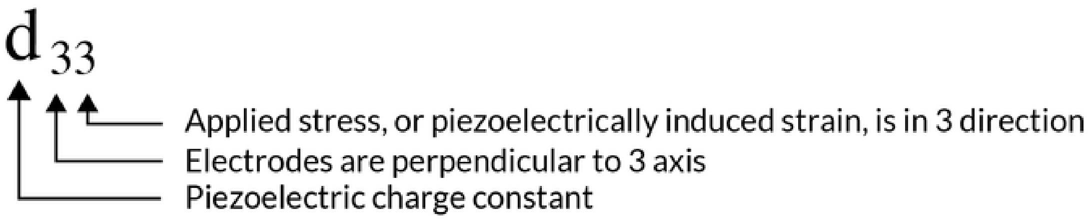
The piezoelectric constants relating the mechanical strain produced by an applied electric field are termed the piezoelectric deformation constants, or the “d” coefficients. They are expressed in meters per volt [m/V]. Conversely, these coefficients which are also called piezoelectric charge constants may be viewed as relating the charge collected on the electrodes to the applied mechanical stress. The units can therefore also be expressed in Coulombs per Newton [C/N].

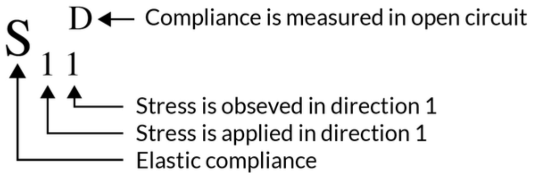
In addition, several piezoelectric material constants may be written with a “superscript” which specifies either a mechanical or an electrical boundary condition. The superscripts are T, E, D, and S, signifying:

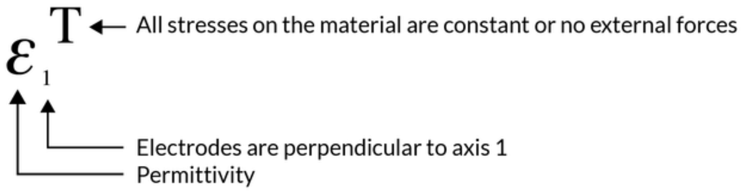
- T=constant stress=mechanically free
- E=constant field=short circuit
- D=constant electrical displacement=open circuit
- S=constant strain=mechanically clamped

All matrix variables used in the piezoelectric constitutive equations are described in our list of symbols used on the website.

Here are three examples of parameters used in the piezoelectric equations together with an explanation of their notation:







Basic piezoelectric equations

There are different ways of writing the fundamental equations of the piezoelectric materials, depending on which variables are of interest. The two most common forms are (the superscript t stands for matrix-transpose):

$$S = s^{E} \cdot T + [d]^{t} \cdot E \qquad S = s^{D} \cdot T + [g]^{t} \cdot D$$

$$D = d \cdot T + \varepsilon^{T} \cdot E \qquad E = -g \cdot T + [\varepsilon^{T}]^{-1} \cdot D$$

These matrix relationships are widely used for finite element modelling. For analytical approaches, in general only some of the relationships are useful so the problem can be further simplified. For example this relationship, extracted from line 3 of the first matrix equation, describes strain in direction 3 as a function of stress and field.

$$S_3 = s^E_{13}\cdot(T_1+T_2)+s^E_{33}\cdot T_3+d_{33}\cdot E_3$$

Limitations of the linear constitutive equations

There are a number of limitations of the linear constitutive equations. The piezoelectric effect is actually non-linear in nature due to hysteresis and creep.

Furthermore, the dynamics of the material are not described by the linear constitutive equations. Piezoelectric coefficients are temperature dependant. Piezoelectric coefficients show a strong electric field dependency.

The linear constitutive equations above are applicable for low electric field only!

These non-linearities are described in more details in Properties of piezoceramic material at high field.

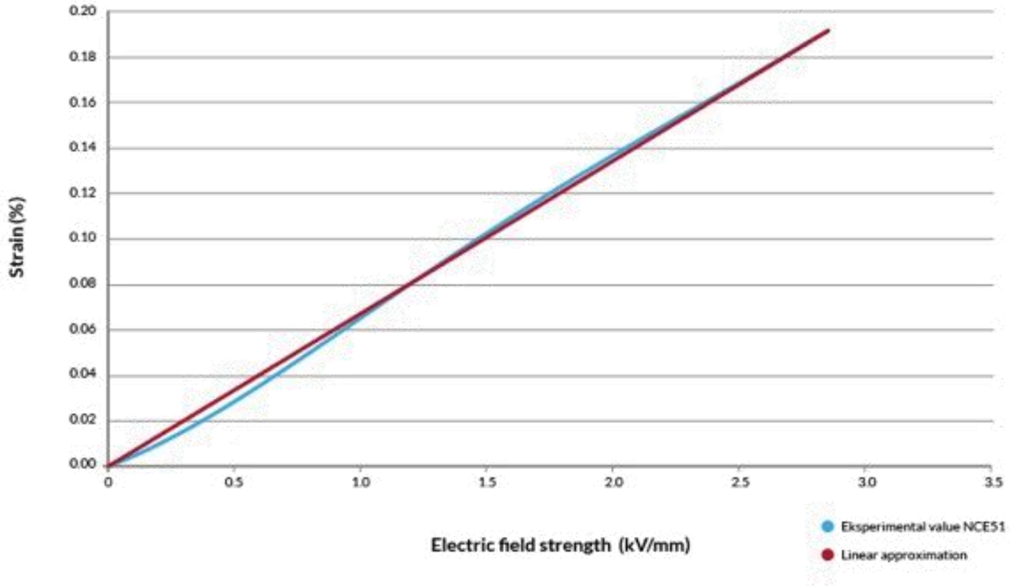
PROPERTIES OF PIEZOCERAMIC MATERIAL AT HIGH FIELD

Piezoelectric materials exhibit non-linearity, hysteresis and creep. This page provides typical material data to understand and compensate these effects.

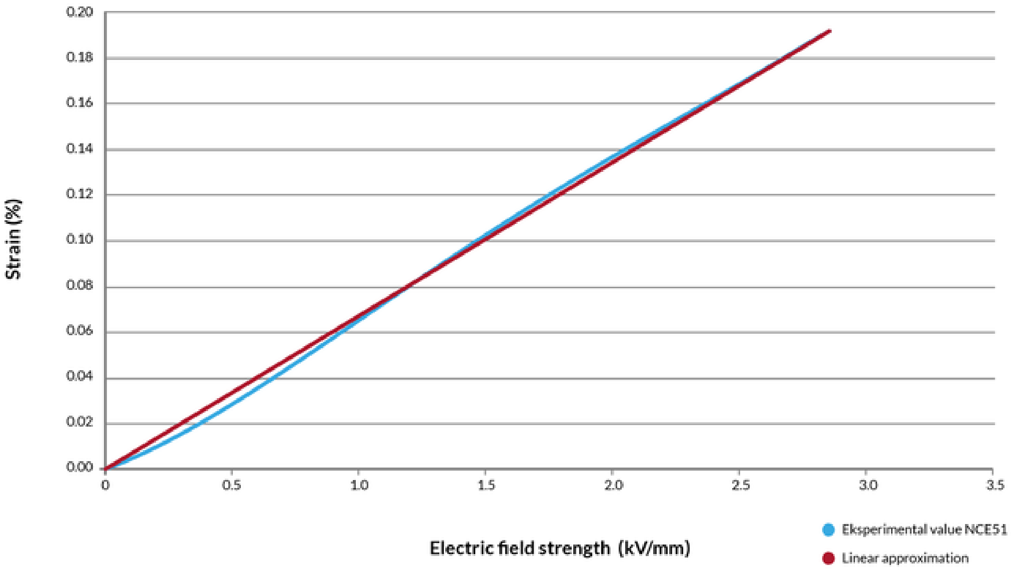
Linearity: actuators, stacked actuators and benders

The stroke versus applied voltage relationship for piezo electric actuators is not perfectly linear as predicted by the piezoelectric equations. Typical performances are shown in the following figures. As it can be seen, the extension vs voltage curve is actually slightly S-shaped. At low voltage, the curve for increasing voltage is concave upward and the shape is close to quadratic.

The example below shows the displacement during charging of an actuator using NCE57. More detailed curves can be found in the "hysteresis" section. Non-linearity implies that stroke at 1kV/mm is less than expected from the linear extrapolation using stroke at the maximum recommended field (3kV/mm).



Non-linearity for NCE51



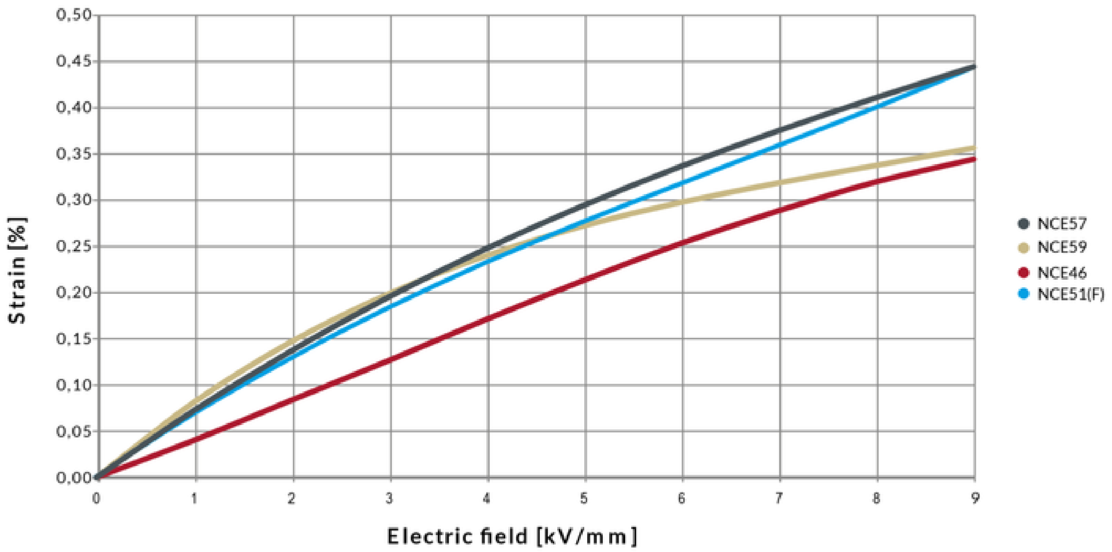
Non-linearity for NCE51

Very high electric field material data - actuators, stacked actuators and benders

In some applications, it is desirable to archive maximum strain from the piezo electric element only by applying a very high electric field. In some cases the maximum recommended field strength of 3kV/mm may be exceeded e.g. for short-term use applications or static applications. Operating field of 4kV/mm is normally acceptable, however testing is recommended.

The figure below shows how strain evolves with electric field for our different materials up to a maximum electricl field strength of 9kV/mm. The drawback of applying a very high electric field is that the actuator lifetime is reduced drastically.

The data in the figure are only of informative character and we recommend to contact our R&D before designing actuators based on very high electric field.



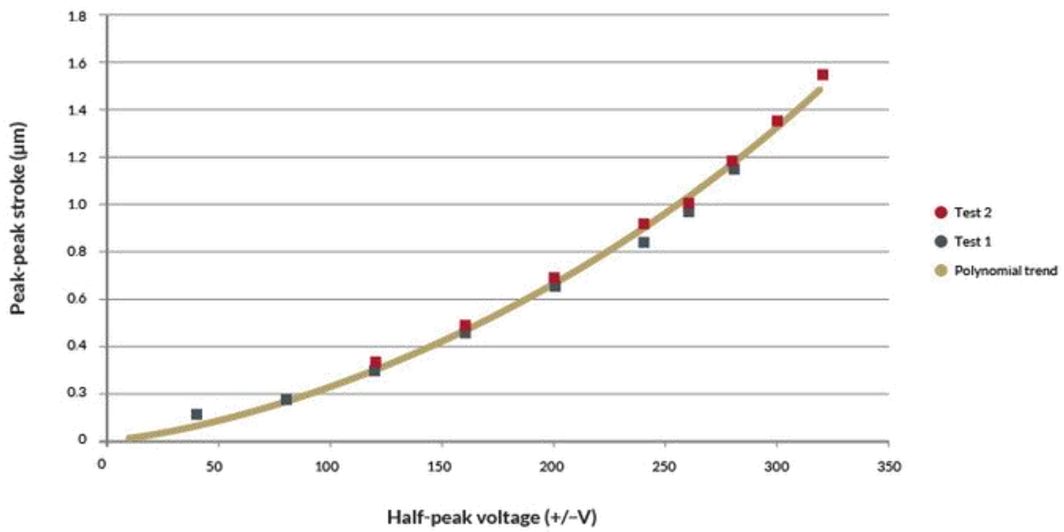
Strain vs. electric field for NCE46, NCE51F, NCE57 and NCE59

Linearity - shear plates

The peak to peak stroke versus peak applied voltage relationship for shear plates is not linear. Typical measurements are shown in the following figure. As it can be seen, the displacement increases when the actuator is used close to the maximum recommended voltage.

The polynomial trend follows the experimental relationship. With δ being the displacement, t the height of the actuator and E the applied electric field (Voltage/height):

$$\delta = 2.88 \cdot 10^{-15} \cdot t \cdot E^2 + 5.0 \cdot 10^{-10} \cdot t \cdot E$$



Experimental data and trend for two Noliac shear plates (CSAP02)

Hysteresis - actuators, stacked actuators and benders

All piezoelectric materials exhibit a mechanical hysteresis as the strain does not follow the same track upon charging and discharging. The hysteresis is expressed as the maximum strain divided by the maximum difference between the two tracks as can be seen in the figure below. Hysteresis tends to decrease with ageing. If hysteresis is a problem for a specific application, it is common to use a feedback loop to compensate it. Feedback signal can be position, force or dielectric charge.

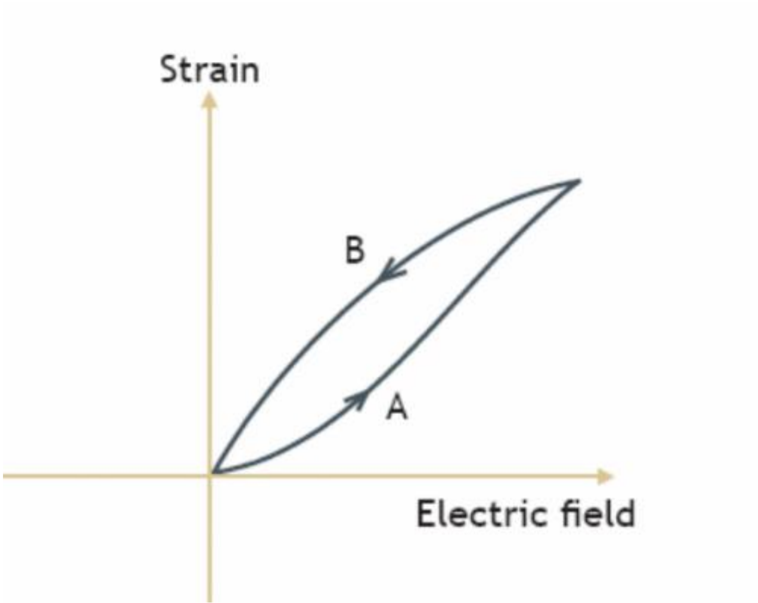


Figure showing the principle relationship between strain and electric field strength.

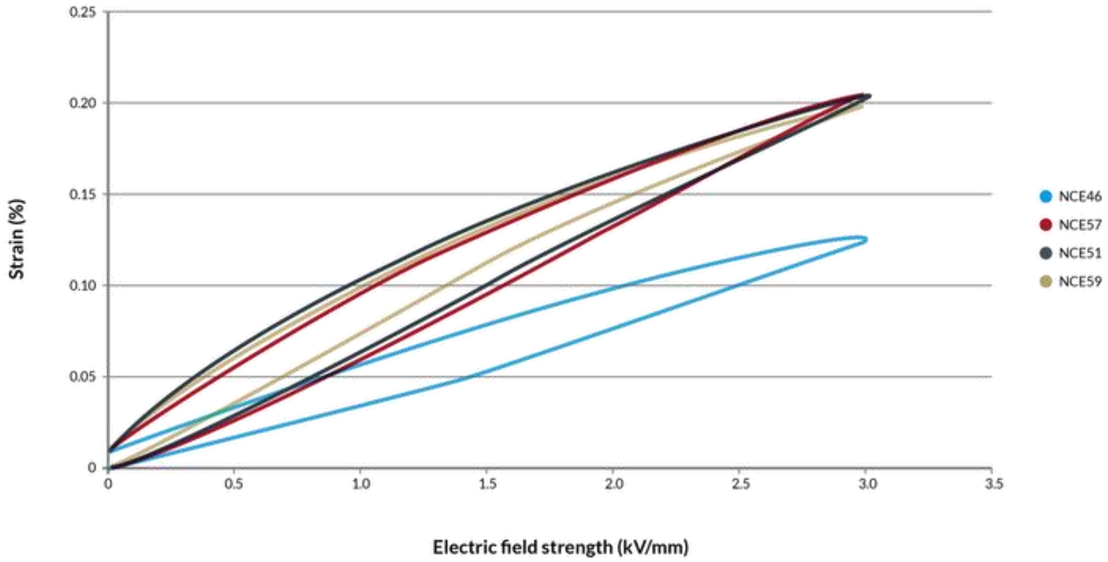


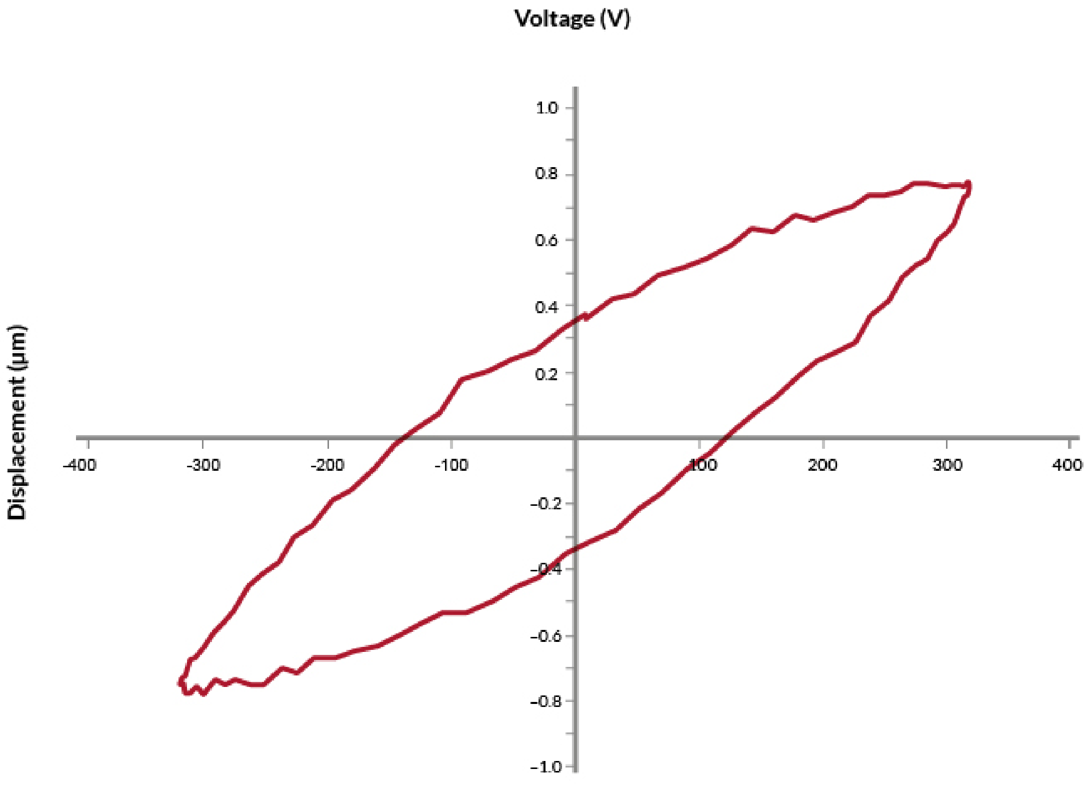
Figure showing the relationship for four different materials.

The mechanical hysteresis depends on the type of ceramics and can vary from 4% to 20 %.

Material	Hysteresis (%)
NCE46	20
NCE51/51F	19
NCE57	19
NCE59	13

Hysteresis - shear plates

Due to their high non-linearity, shear plates exhibit much higher hysteresis than other actuator types. Hysteresis at full voltage amplitude is in the order of 35%. Reducing the amplitude of the voltage will reduce hysteresis.



Displacement vs. voltage for a Noliac shear plate CSAP02 (experimental data)

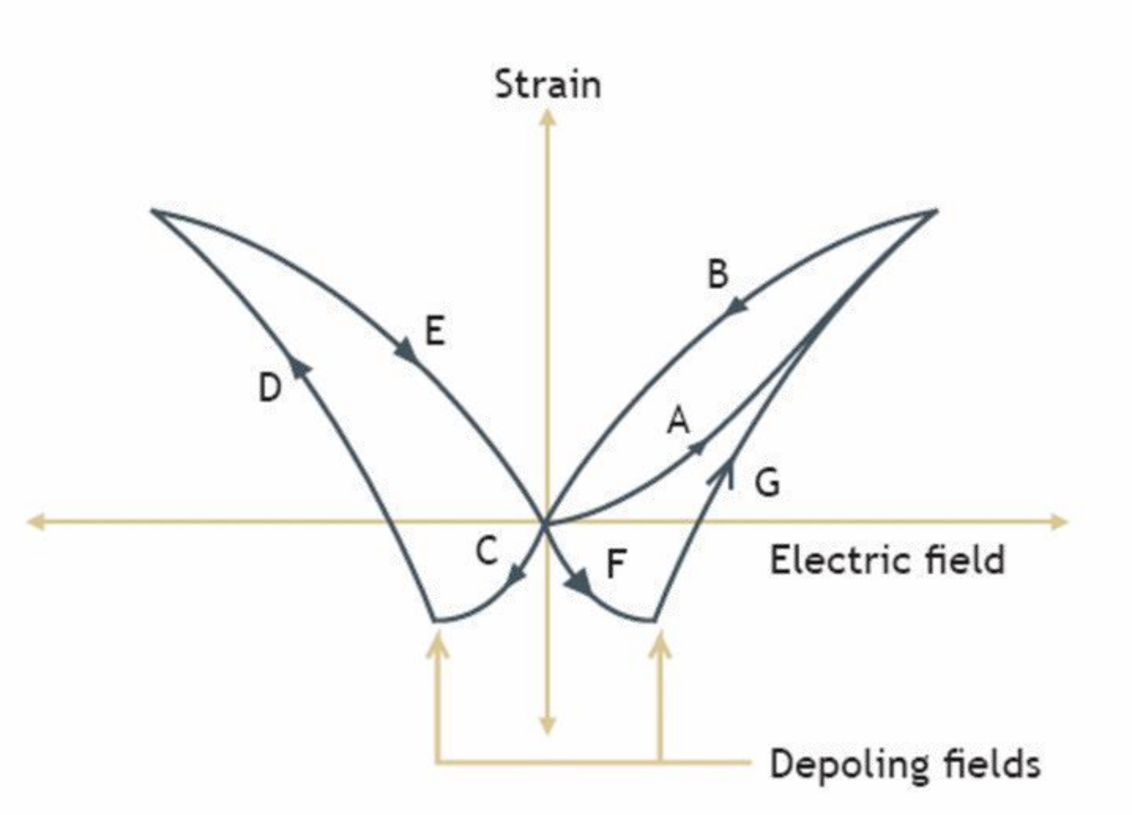
Operation under reverse bias - actuators, stacked actuators and benders

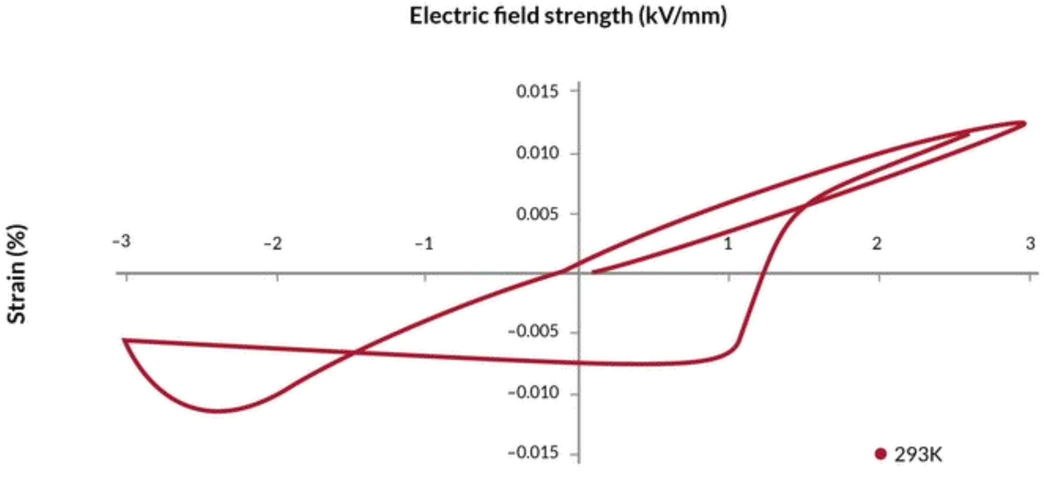
In addition to the normal hysteresis curve AB when the applied voltage is positive, the butterfly diagram CDEFG defines the behaviour of the material through a complete cycle of positive and negative operating electric fields. Negative electric fields produce negative strain along curve C until the depoling field (coercive field) where the extension suddenly turns positive following the curve D. The process is repeated along curves EFG when the electric field is made positive again. The "butterfly" diagram provides a complete characterization of the depoling and repoling process.

Most hard piezoelectric materials can only be fully poled or depoled at elevated temperatures so once poled, they can tolerate high reverse fields without difficulty.

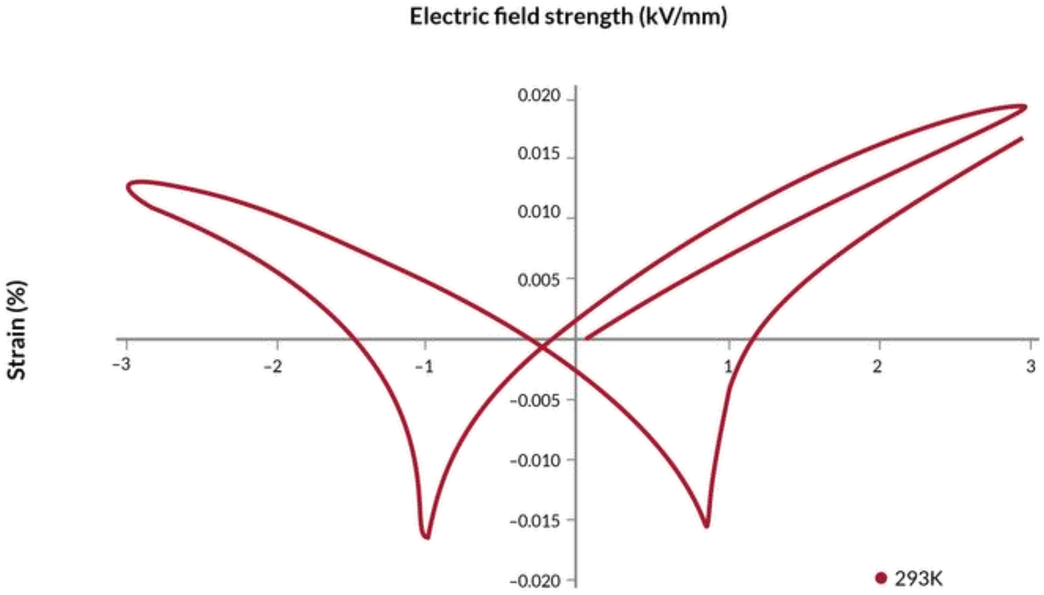
Noliac do not recommend operation under reverse field. However, in some applications this can bring some additional strain. The drawbacks are the lower linearity, increased hysteresis and losses. In addition temperature must be monitored as the coercive field varies with temperature (refer to "thermal properties").

Soft piezoelectric materials are easily depoled when subjected to an electrical field opposite to the poling direction. The effect of cycling between positive and negative voltages for various piezoelectric materials is shown in the following figures below the diagram showing the principle:

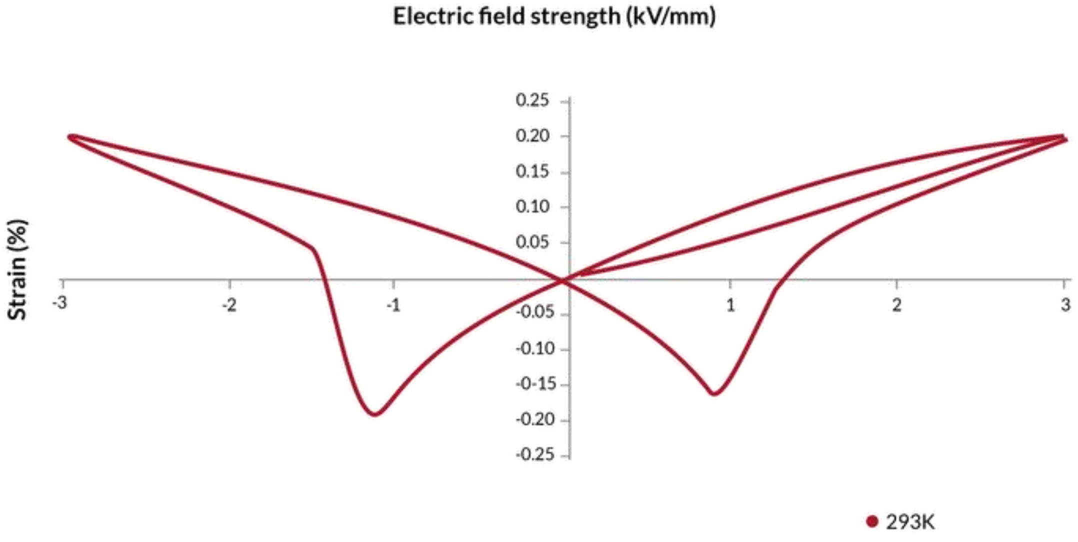




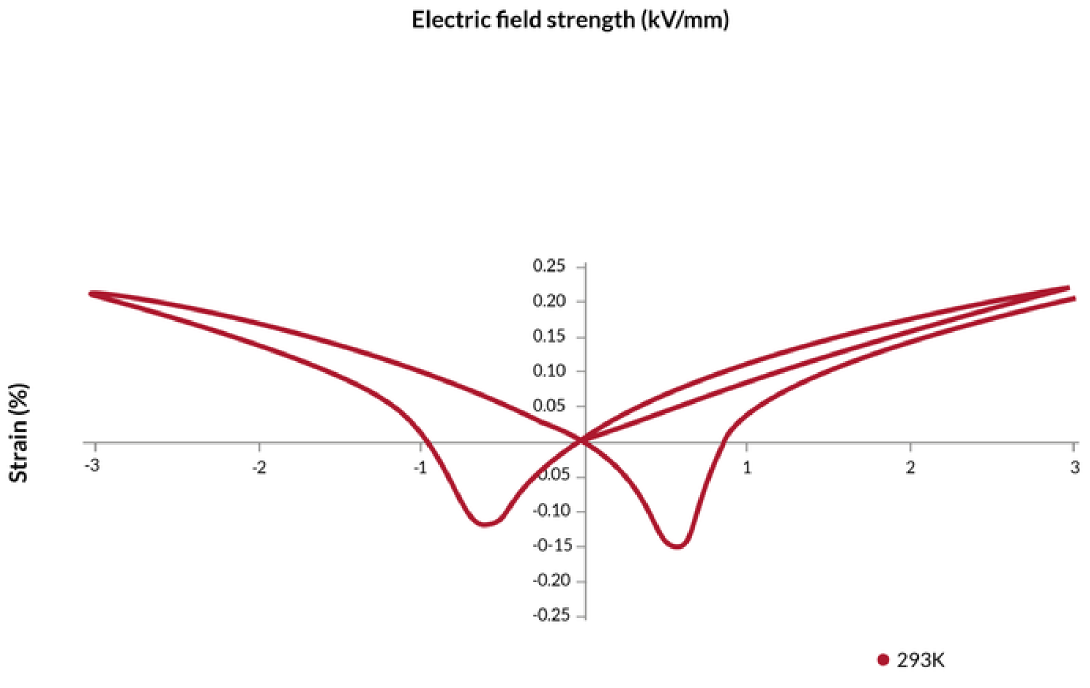
Strain vs. electric field for NCE46



Strain vs. electric field for NCE51



Strain vs. electric field for NCE57

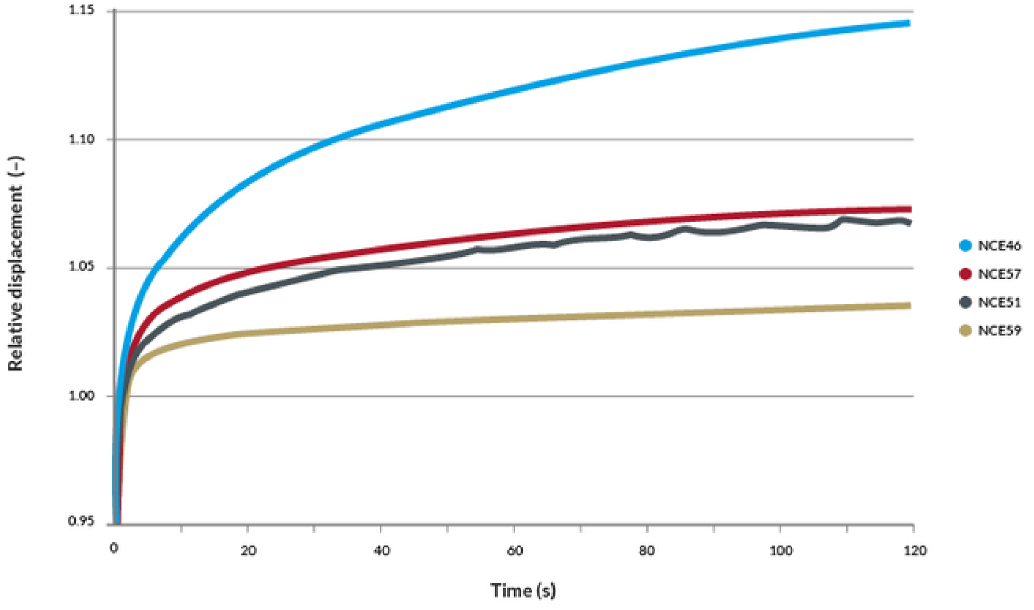


Strain vs. electric field for NCE59

Creep

Piezoelectric materials exhibit a creep effect i.e. the material continues to expand for some time upon application of voltage. Correspondingly the material does not immediately return to the initial strain level after return to 0V.
While creeping, the material continues to draw charge at very low levels. The creep effect for different actuator materials is compared in the following figure, where the maximum electric field is established after 1s, corresponding to the baseline for displacement (relative displacement = 1).

Creep always occurs in the same direction as the dimensional change produced by the voltage step. The effect is logarithmic so the additional expansion between 10s and 100s will be similar to the expansion obtained between 1s and 10s. For linear/stacked actuators, typical values are 4% per decade for NCE51/51F and 9% per decade for NCE46. Values are 2-3 times higher for bending actuators. Creep is related to the long-time average that the actuator has experienced in its life.



Creep for NCE46, NCE51, /NCE57 and NCE59

THERMAL PROPERTIES OF PIEZOCERAMIC MATERIAL

The electric and piezoelectric properties are affected by temperature variations. Each piezoelectric material is affected differently by temperature changes, according to the method of manufacture and chemical composition of the material.

Maximum temperature

Piezoelectric materials should be used well below their Curie temperature for the poling to be stable. Any conditions that raise the temperature close to the Curie temperature will cause the piezoelectric material to become partially or completely depolarised and severely degrade performance. For applications that require operation at elevated temperature a material with a sufficiently high Curie temperature must be chosen. Maximum recommended operating temperatures are specified for each product. It is important to monitor temperature, in particular for dynamic applications where self-heating can occur.

Minimum temperature

Our materials can be used at cryogenic temperatures and have been demonstrated down to 4mK. For these applications a specific preparation (wires, adhesive etc.) is required.

Read about your possibilites for ultra-high vacuum

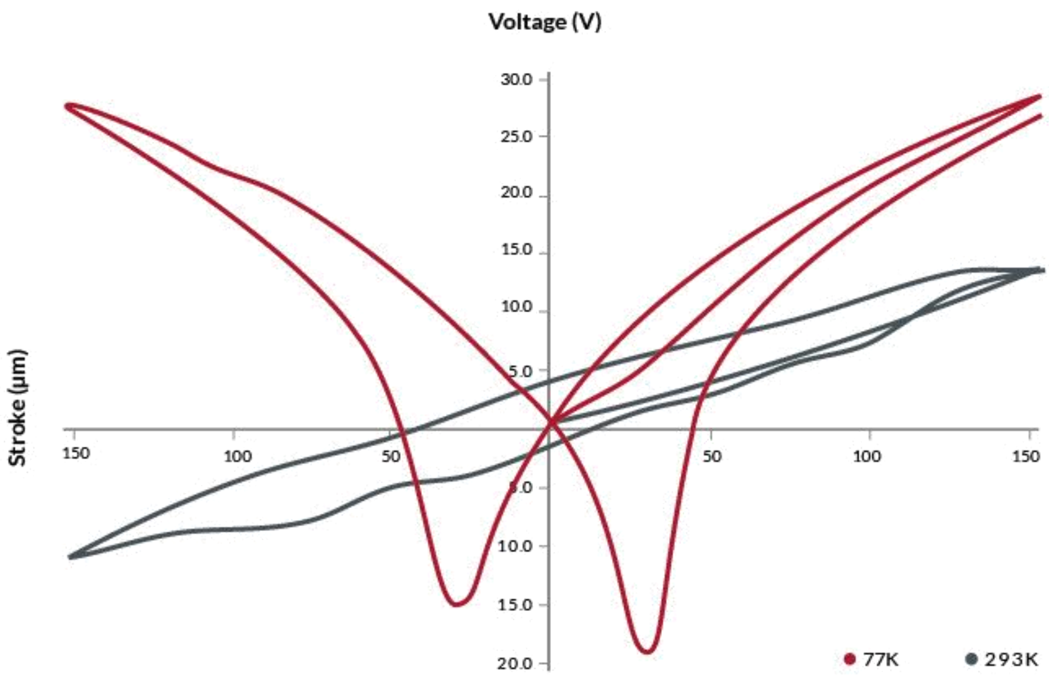
The mechanical and electrical properties of piezoelectric ceramic are greatly reduced at cryogenic temperatures. When piezoelectric actuators are cooled down to cryogenic temperatures, the piezoelectric ceramic behaves like a very hard piezoelectric material featuring:

- Strong reduction of electrical capacitance
- Reduction of loss factor
- Reduced strain coefficients d33 and d31
- Strong increase of the coercive field.

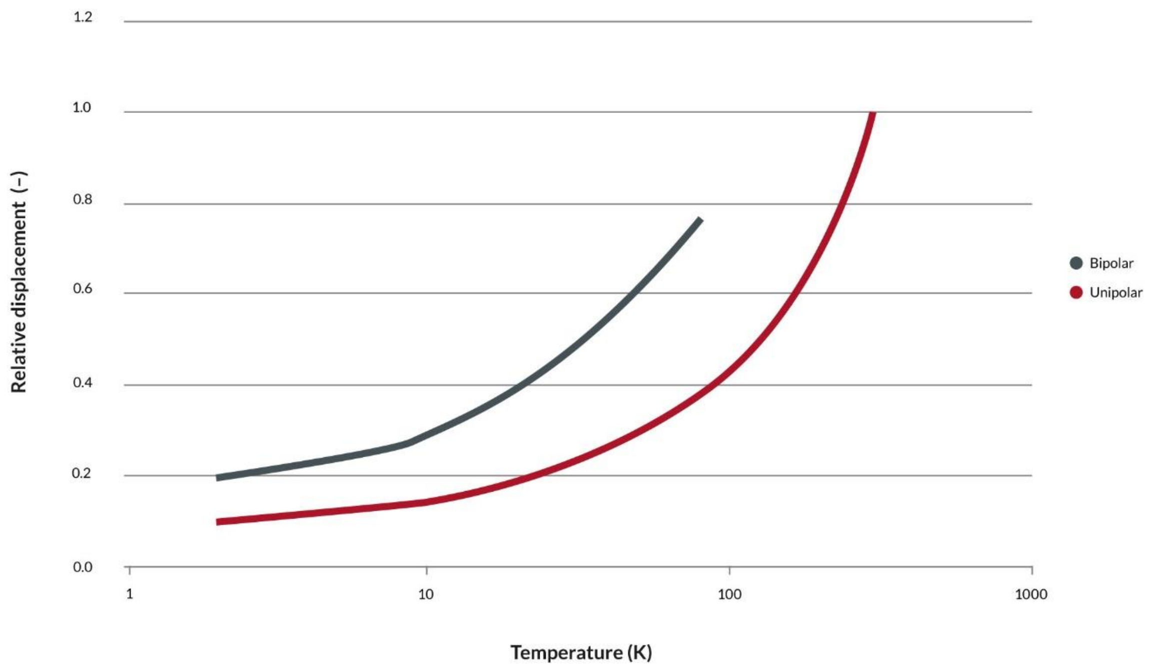
The last point means, that at low temperatures a piezoelectric actuator becomes extremely stable against electrical depoling. Therefore, a much wider bipolar operation compared to room temperature is possible. Thereby, the loss in stroke for low temperature can be partially compensated for.

Below you can see an example of cryogenic measurements at two different temperatures showing the relationship between stroke and voltage. As it can be seen, the strain at 77 K is approximately reduced to half size at room temperature. Due to the strong increase of the coercive field, it can also be observed that the actuator exhibits a fairly linear voltage-displacement characteristic at negative voltage. The piezoelectric actuator becomes extremely stable against electrical depoling and the loss in stroke at low temperature can be partially compensated by using a wide bipolar operation.

A less known parameter is the thermal expansion coefficient for ceramics, important to consider when designing devices where piezoelectric actuators will be part of a composite structure and where the other elements of constructions are e.g metals. The thermal expansion coefficient for ceramics is similar to many ceramics and glasses and is typically in the range of 10-5 to 10-6/°C. A major difference with common materials is that the thermal expansion coefficient is anisotropic with respect to the poling direction.



Example of cryogenic measurements at two different temperatures



The evolution of maximum displacement vs. temperature for NCE57

HOW TO CHOOSE A CERAMIC MATERIAL

The table below gives an overview of the characteristics of the different ceramic materials.

	Medium soft doped piezoceramic material (NCE51)	Hard doped piezoceramic material (NCE46)
High strain (static or semi-static application)	++	-
Low hysteresis	-	-
Low creep effect	-	--
Low dielectric constant (low capacitance)	+	++
High Mechanical quality factor (resonance frequency application)	-	++
Low Dielectric dissipation factor (low self-heating)	-	++
High temperature application	++	++