# INTRODUCTION TO PIEZOELECTRIC SENSORS

## INTRODUCTION

Over the past 50 years piezoelectric sensors have proven to be a versatile tool for the measurement of various processes. Today, they are used for the determination of pressure, acceleration, strain or force in quality assurance, process control and development across many different industries.

Piezoelectric sensors rely on the piezoelectric effect, which was discovered by the Curie brothers in the late 19th century. While investigating a number of naturally occurring materials such as tourmaline and quartz, Pierre and Jacques Curie realized that these materials had the ability to transform energy of a mechanical input into an electrical output. More specifically, when a pressure [piezo is the Greek word for pressure] is applied to a piezoelectric material, it causes a mechanical deformation and a displacement of charges. Those charges are highly proportional to the applied pressure [Piezoelectricity].

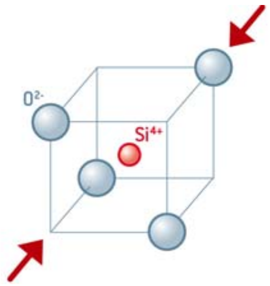


**Figure 1:** Piezoelectricity of quartz

*A quartz ($SiO_2$) tetrahedron is shown. When a force is applied to the tetrahedron (or a macroscopic crystal element) a displacement of the cation charge towards the center of the anion charges occurs. Hence, the outer faces of such a piezoelectric element get charged under this pressure.*

Many creatures use an interesting application of piezoelectricity. Bones act as force sensors. Once loaded, bones produce charges proportional to the resulting internal torsion or displacement. Those charges stimulate and drive the build up of new bone material. This leads to the strengthening of structures where the internal displacements are the greatest. With time, this allows weaker structures to increase their strength and stability as material is laid down proportional to the forces affecting the bone.

From the Curies' initial discovery, it took until the 1950's before the piezoelectric effect was used for industrial sensing applications. Since then, the utilization of this measuring principle has experienced a constant growth and can nowadays be regarded as a mature technology with an outstanding inherent reliability. It has been successfully used in various critical applications as for example in medical, aerospace and nuclear instrumentation.

The rise of piezoelectric technology is directly related to a set of inherent advantages. The high modulus of elasticity of many piezoelectric materials is comparable to that of many metals and goes up to $10^5$ N/mm$^2$. Even though piezoelectric sensors are electromechanical systems that react on compression, the sensing elements show almost zero deflection. This is the reason why piezoelectric sensors are so rugged, have an extremely high natural frequency and an excellent linearity over a wide amplitude range. Additionally, piezoelectric technology is insensitive to electromagnetic fields and radiation, enabling measurements under harsh conditions. Some materials used (especially galliumphosphate or tourmaline) have an extreme stability over temperature enabling sensors to have a working range of 1000°C.

| **Principle** | **Strain Sensitivity (V/µ*)** | **Threshold (µ*)** | **Span to threshold ratio** |
|---|---|---|---|
| Piezoelectric | 5.0 | 0.00001 | 100.000.000 |
| Piezoresistive | 0.0001 | 0.0001 | 2.500.000 |
| Inductive | 0.001 | 0.0005 | 2.000.000 |
| Capacitive | 0.005 | 0.0001 | 750.000 |

**Table 1:** Comparison of sensing principles

*Comparison of different sensing principles according to Gautschi. Numbers give only a tendency for the general characteristics.*

The single disadvantage of piezoelectric sensors is that they cannot be used for true static measurements. A static force will result in a fixed amount of charges on the piezoelectric material. Working with conventional electronics, not perfect insulating materials, and reduction in internal sensor resistance will result in a constant loss of electrons, yielding an inaccurate signal. Elevated temperatures cause an additional drop in internal resistance; therefore, at higher temperatures, only piezoelectric materials can be used that maintain a high internal resistance.

Anyhow, it would be a misconception that piezoelectric sensors can only be used for very fast processes or at ambient conditions. In fact, there are numerous applications that show quasi-static measurements while there are other applications that go to temperatures far beyond 500°C.

## PRINCIPLE OF OPERATION

Depending on the way a piezoelectric material is cut, three main types of operations can be distinguished 1. transversal 2. longitudinal 3. shear.

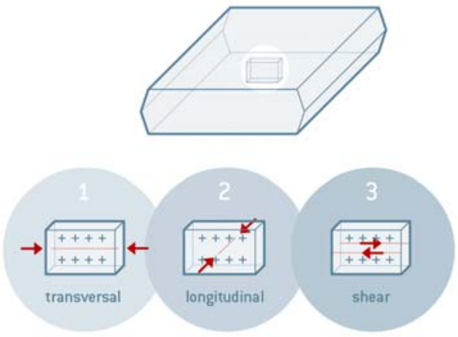


**Figure 2:** Gallium phosphate sensing elements

*A gallium phosphate crystal is shown with typical sensor elements manufactured out of it. Depending on the design of a sensor different "modes" to load the crystal can be used: transversal, longitudinal and shear (arrows indicate the direction where the load is applied). Charges are generated on both "x-sides" of the element. The positive charges on the front side are accompanied by negative charges on the back.*

**Transverse effect:** A force is applied along a neutral axis and the charges are generated along the $d_{11}$ direction. The amount of charge depends on the geometrical dimensions of the respective piezoelectric element. When dimensions a, b, c apply:

$$C_y = -d_{11} \times F_y \times b/a$$

where a is the dimension in line with the neutral axis and b is in line with the charge generating axis.

**Longitudinal effect:** The amount of charges produced is strictly proportional to the applied force and is independent of size and shape of the piezoelectric element. Using several elements that are mechanically in series and electrically in parallel is the only way to increase the charge output. The resulting charge is:

$$C_x = d_{11} \times F_x \times n$$

where

$d_{11}$ = piezoelectric coefficient [pC/N]

Fx = applied Force in x-direction [N]

n = number of elements

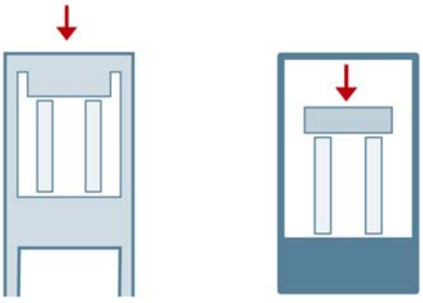
**Shear effect:** Again, the charges produced are strictly proportional to the applied forces and are independent of the element's size and shape. For n elements mechanically in series and electrically in parallel the charge is:

$$C_x = 2 \times d_{11} \times F_x \times n$$

In contrast to the longitudinal and shear effect, the transverse effect opens the possibility to fine tune sensitivity depending on the force applied and the element dimension. Therefore, Piezocryst's sensors almost exclusively use the transverse effect since it is possible to reproducibly obtain high charge outputs in combination with excellent temperature behaviour.

## SENSOR DESIGN

Based on piezoelectric technology various physical dimensions can be measured, the most important include pressure and acceleration. Figure 3 shows schematic configurations of those sensors in the transverse configuration. In both designs, the elements are thin cuboids that are loaded along their longest extension. For pressure sensors, a thin membrane with known dimensions and a massive base is used; assuring that an applied pressure specifically loads the elements in one direction. For accelerometers, a seismic mass is attached to the crystal elements. When the accelerometer experiences a motion, the invariant seismic mass loads the elements according to Newton's second law of motion F=ma.



(a) (b)

**Figure 3:** Schematic sensor design of pressure (a) and acceleration sensors (b)

*In both piezoelectric pressure sensors (a) and piezoelectric accelerometers (b), the crystal elements are used in transversal mode. The main difference in the working principle between these two cases is the way forces are applied to the sensing elements. In a pressure sensor a thin membrane is used to guide the force to the elements, in accelerometers the forces are applied by an attached seismic mass.*

Sensors often tend to be sensitive to more than one physical dimension. Therefore, it sometimes becomes necessary to compensate for unwanted effects. For instance, sophisticated pressure sensors often use acceleration compensation elements. Those compensations are based on the fact that the measuring elements may experience both, pressure and acceleration events. A second measuring unit is added to the sensor assembly that only experiences acceleration events. By carefully matching those elements, the acceleration signal (coming from the compensation element) is subtracted from the combined signal of pressure and acceleration (coming of the measuring elements) to derive the true pressure information.

## MATERIALS

Two main groups of materials are used for piezoelectric sensors: piezoelectric ceramics and single crystal materials. The ceramic materials (e.g. PZT ceramic) have a piezoelectric constant / sensitivity that is roughly two orders of magnitude higher than those of single crystal materials and can be produced by an inexpensive sintering processes. Unfortunately, their high sensitivity is always combined with a lack of long term stability. Therefore, piezoelectric ceramics are very often used wherever the requirements for measuring precision are not too high. The less sensitive single crystal materials (quartz, tourmaline and gallium phosphate) have a much higher – when carefully handled, almost infinite – long term stability. Additionally, some of them show excellent temperature behavior (especially gallium phosphate and tourmaline).

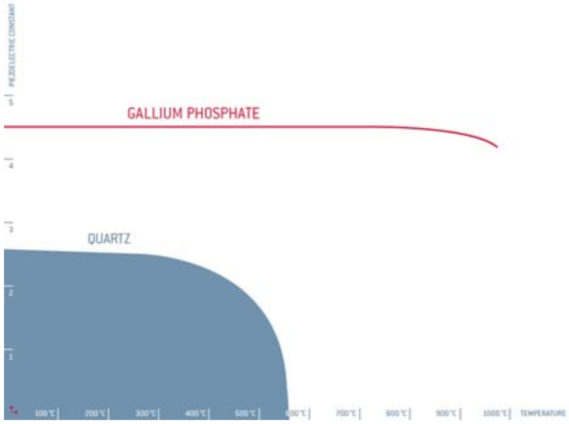


**Figure 4:** Piezoelectric coefficient vs. temperature

*Piezoelectric coefficient of* $GaPO_4$ *and quartz are shown versus temperature. Gallium phosphate offers better temperature characteristics and better temperature behavior for many of its material constants including the piezoelectric coefficient, which is a measure for sensitivity.*

## CONCLUSION

Piezoelectric sensors offer a unique set of capabilities that cannot be found in other sensing principles. As discussed, the inherent temperature stability, the amplitude range and the signal quality make it very interesting, in particular where no static information is needed.