Table 5.6 Applications of magnetoresistive effect

Principle	*Application*
Direct measurement of magnetic fields	Magnetic audio recording Reading machines for credit cards, magnetically coded price tags
Measuring magnetic field variation[a]	Measurement of linear and angular displacement Proximity switches Position measurement Angular velocity of ferrous gear wheels

[a] To accomplish this, it must be either a metallic object or an object with a metallic coating or an identifier placed in a constant magnetic field, or the moving element to be detected must incorporate a permanent magnet.

Piezoelectricity

Certain materials, especially the crystalline ones, produce an emf when deformed by an application of pressure along the specific axes. The phenomenon is known as *piezo-electricity*[16] or *piezoelectric effect* and is widely used for the construction of many transducers that involve the measurement of dynamic pressure.

Origin of piezoelectricity

In most crystals, the unit cell (the basic repeating unit) is symmetrical; in piezoelectric crystals, it is not. Normally, piezoelectric crystals are electrically neutral—the atoms inside them may not be symmetrically arranged, but their electrical charges, are perfectly balanced. A quartz (SiO_2) tetrahedron is shown in Fig. 5.9. When a pressure is applied to the tetrahedron (or a macroscopic crystal element) a displacement of the positive ion charge towards the centre of the negative ion charges occurs. Hence, the outer faces of such a piezoelectric element get charged under this pressure.

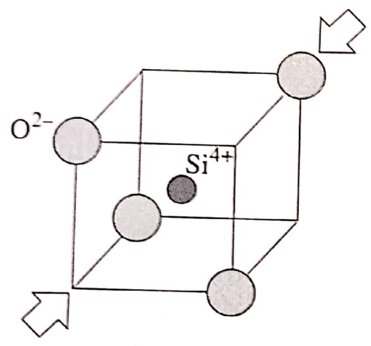

Fig. 5.9 Piezoelectricity generation in quartz. Arrows indicate the direction of application of pressure.

[16]Pronounced as piē'zō or pēā'zō (Webster's Universal Collegiate Dictionary, 1997). The prefix is a Greek word meaning *squeeze*.

Conversely, when an electric field is applied to a piezoelectric crystal, a mechanical strain is produced in it. This is sometimes called the *inverse piezoelectric effect.* If an alternating field is applied to such a crystal, the strain also varies periodically—but generally there is a phase lag between the applied field and the resulting strain, depending on the frequency of the applied field. At the natural frequency of vibration of the crystal, called the *resonance frequency*, the two are exactly in phase. This effect is utilised to construct resonant transducers and also to stabilise frequency in electronic clocks.

Piezoelectric materials

Generally, piezoelectric materials are classified into the following four categories:

Category	*Examples*
Naturally occurring single crystals	Quartz Tourmaline Topaz Cane Sugar Rochelle salt (potassium sodium tartrate tetrahydrate, $KNaC_4H_4O_6$, $4H_2O$)
Man-made crystals	Gallium Orthophosphate ($GaPO_4$) Langasite ($La_3Ga_5SiO_{14}$)— both quartz analogous crystals
Man-made polycrystalline ceramic materials	Barium Titanate ($BaTiO_3$) Lead Zirconate Titanate ($Pb[Zr_xTi_{1-x}]O_3$ where $0 < x < 1$)—more commonly known as PZT Lead Titanate ($PbTiO_3$) Potassium Niobate ($KNbO_3$) Lithium Niobate ($LiNbO_3$) Lithium Tantalate ($LiTaO_3$) Sodium Tungstate ($NaWO_3$)
Man-made polymers	PolyVinyliDene Fluoride (PVDF)

PZT is the most common piezoelectric ceramic in use today. Among the naturally occurring crystals, quartz is inexpensive. Tourmaline, a naturally occurring semi-precious form of quartz, has sub-microsecond response time and, therefore, very useful in the measurement of rapid transients.

PVDF exhibits piezoelectricity several times greater than quartz. Unlike ceramics, where the crystal structure of the material creates the piezoelectric effect, in polymers the intertwined long-chain molecules attract and repel each other when an electric field is applied.

The so-called natural crystals are already polarised and the piezoelectric element is usually a cut from the crystal in the direction of any of the electrical axes (called X-axes) or mechanical axes (called Y-axes)[Fig. 5.10(a)]. Figures 5.10(b) and (c) show how an X-cut piece of the hexagonal quartz crystal can be obtained.

Synthetic polycrystalline ceramic materials have to be baked under a strong dc electric field to provide polarisation. Thus, they have the advantage of being moulded into any shape or size.

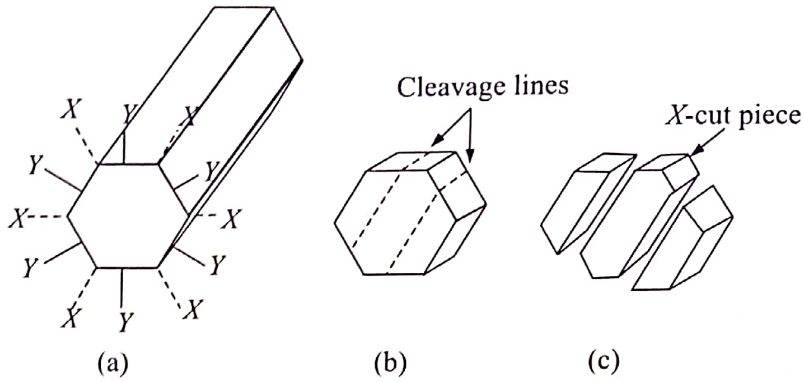

Fig. 5.10 Quartz crystal: (a) X and Y axes, (b) and (c) X-cutting

Curie temperature. The Curie temperature T_C is the temperature at which the piezoelectric material changes to a non-piezoelectric form. Before polarisation or above Curie temperature[17], PZT crystallites have symmetric cubic unit cells [Fig. 5.11(a)]. Below the Curie temperature, the lattice structure becomes deformed and asymmetric. The unit cells then exhibit spontaneous polarisation [Fig. 5.11(b)], i.e. the individual PZT crystallites become piezoelectric.

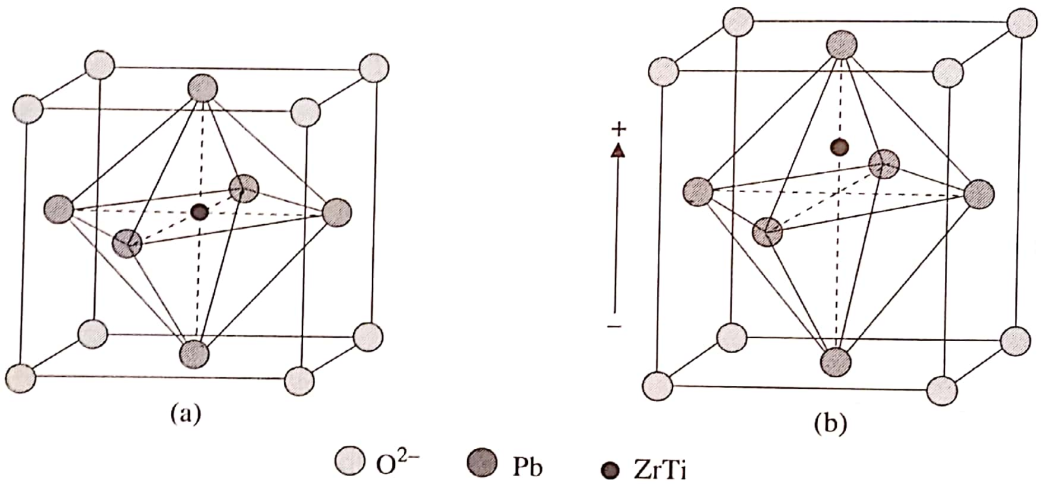

Fig. 5.11 PZT unit cell: (a) Perovskite-type PZT unit cell in the symmetric cubic state above the Curie temperature, and (b) tetragonally distorted unit cell below the Curie temperature.

Domains. Groups of unit cells with the same orientation of polarisation are akin to *Weiss domains* of ferromagnetism. The random distribution of the domain orientations in the ceramic material manifests no macroscopic piezoelectric behaviour [Fig. 5.12(a)]. Due to the ferroelectric[18] nature of the material, it is possible to force permanent alignment of the different domains using a strong electric field. This process is called *poling* [Fig. 5.12(b)]. Some PZT ceramics must be poled at an elevated temperature to acquire a remnant

[17] Named after brothers Pierre and Jacques Curie of France who discovered piezoelectricity in 1880.

[18] Dielectrics which show hysteresis effect for applied field and polarisation are called *ferroelectrics*. A ferroelectric is spontaneously polarised, i.e. it is polarised in the absence of an electric field. Since the dielectric behaviour of these materials is in many respects analogous to the magnetic behaviour of ferromagnetic materials, they are called *ferroelectric solids*.

polarisation. The ceramic then exhibits piezoelectric properties [Fig. 5.12(c)]. It will also change dimensions when an electric potential is applied (inverse piezoelectricity).

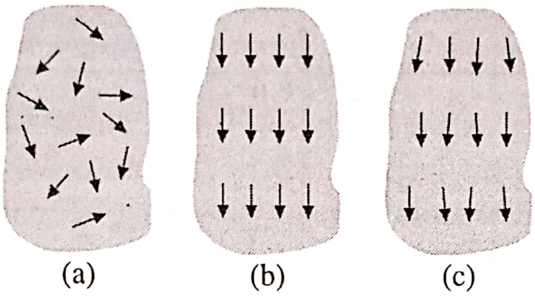

Fig. 5.12 Electric dipoles in domains: (a) unpoled ferroelectric ceramic, (b) during poling and (c) after poling (piezoelectric ceramic).

Modes of utilising piezoelectricity

In piezoelectric sensors, many modes of stressing the piezoelectric material can be used. Acting as precision springs, the different element configurations shown in Fig. 5.13 offer various advantages and disadvantages as detailed in Table 5.7.

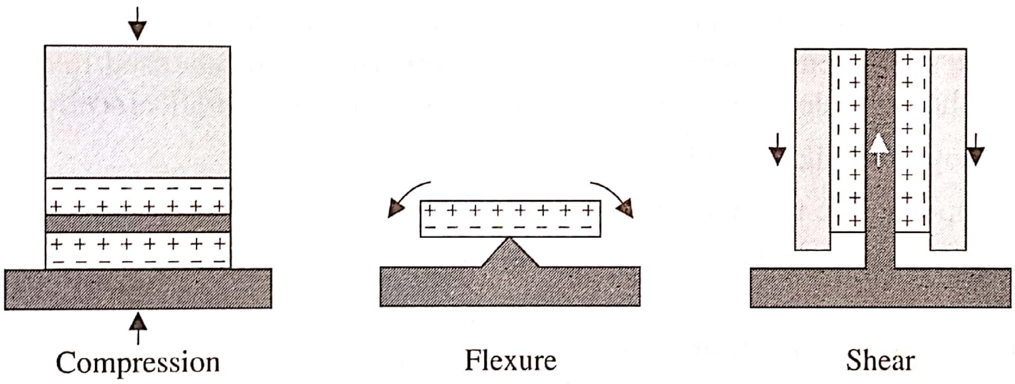

Fig. 5.13 Different modes of stressing the piezoelectric material. The white represents the piezoelectric crystals, while the arrows indicate how the material is stressed. Compression and shear modes typically have a seismic mass, which is represented by the grey colour.

Table 5.7 Advantages and disadvantages of different configurations

Configuration	*Advantages*	*Disadvantages*
Compression	High rigidity, making it useful for implementation in high frequency pressure and force sensors	Somewhat sensitive to thermal transients
Flexure	Simplicity of design	Narrow frequency range and low overshock survivability
Shear	Offers a well balanced blend of wide frequency range, low off-axis sensitivity, low sensitivity to base strain and low sensitivity to thermal inputs	Rather complicated design

Piezoelectric coefficients

Because of the anisotropic nature of piezoelectric ceramics, piezoelectric effects are dependent on direction. To identify directions, the axes 1, 2, and 3 are introduced, corresponding to X, Y and Z of the classical right-handed orthogonal axis set. The axes 4, 5 and 6 identify rotations (shear)—23, 31, 12. Figure 5.14 illustrates them.

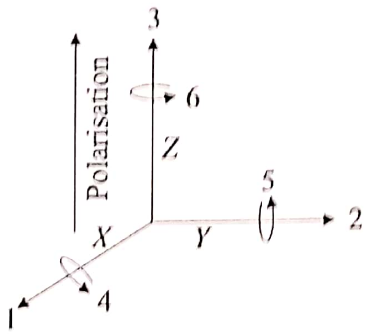

Fig. 5.14 Orthogonal system describing the properties of a poled piezoelectric ceramic. Axis 3 is the poling direction.

The direction of polarisation (axis 3) is established during manufacturing process by a strong dc field applied between two electrodes. For linear actuators[19] which involve translation, the piezo properties along the poling axis, along which the largest deflection generally takes place, are the most important.

Piezoelectric materials are characterised by d, g, h, e coefficients as well as a coupling parameter k. We will discuss them after we talk about the notations used in defining them.

Apart from the piezoelectric coefficients, piezoelectricity is also affected by

1. Electric properties like permittivity and pyroelectricity[20]
2. Elastic property like the Young's modulus
3. Thermal property like the Curie temperature

Notations. Piezoelectric constants are generally expressed with double subscripts. The subscripts link electrical and mechanical quantities. The first subscript indicates the direction of the stimulus while the second, the direction of the reaction of the system.

For example, d_{33} applies when the electric field is along the polarisation axis (direction 3) and the strain (deflection) is along the same axis. d_{31} applies if the electric field is in the same direction as before, but the deflection of interest is that along axis 1 (perpendicular to the polarisation axis).

In addition, piezoceramic material constants may be written with a *superscript* which specifies either a mechanical or electrical boundary condition. The superscripts are T, E, D and S are explained in Table 5.8.

---

[19]See at page 146.

[20]Pyroelectric materials are those which produce electric charge as they undergo a temperature change. Piezoelectric materials are also pyroelectric. When their temperature is increased, they develop a voltage that has the same orientation as the polarisation voltage. When their temperature is decreased, they develop a voltage having an orientation opposite to the polarisation voltage. This creates a depolarising field with the potential to degrade the state of polarisation of the part.

Table 5.8 Significance of superscripts used to specify piezoelectric material constants

Superscript	*Implication*	*Meaning*
T	Stress = constant	Mechanically free
E	Electric field = 0	Short circuited
D	Charge displacement (i.e. current) = 0	Open circuit
S	Strain = constant	Mechanically clamped

Note:

1. We use here S for strain and T for stress rather than the conventional symbols ε and σ only to avoid confusion with the permittivity symbol ε.
2. In a dielectric material the presence of an electric field $\mathbf{E}$ causes the bound charges in the material (atomic nuclei and their electrons) to slightly separate, inducing a local electric dipole moment. The electric displacement field $\mathbf{D}$ is defined as

$$\mathbf{D} \equiv \varepsilon_0 \mathbf{E} + \mathbf{P}$$

where ε_0 is the vacuum permittivity (also called permittivity of free space), and $\mathbf{P}$ is the (macroscopic) density of the permanent and induced electric dipole moments in the material, called the *polarisation density*.

3. In a linear, homogeneous, isotropic dielectric with instantaneous response to changes in the electric field, $\mathbf{P}$ depends linearly on the electric field, giving rise to the relation

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

where the constant of proportionality χ is called the *electric susceptibility* of the material. Thus

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

where ε $(= \varepsilon_0 \varepsilon_r)$ is the permittivity and ε_r $(= 1 + \chi)$ is the relative permittivity of the material.

4. In linear, homogeneous, isotropic media ε is a constant. However, in linear anisotropic media it is a matrix.

Now, let us define the different coefficients we have talked about.

d coefficient. The piezoelectric charge coefficient (aka *charge constant*), d_{ij}, is defined as follows:

Direct effect

$$d_{ij} = \left.\frac{\text{Charge density developed in } i\text{-direction}}{\text{Applied stress in } j\text{-direction}}\right|_{E=0} \quad \text{C/N} \quad \left[\text{from } \frac{\text{C/m}^2}{\text{N/m}^2}\right] \tag{5.20}$$

Inverse effect

$$d_{ij} = \left.\frac{\text{Developed strain in } j\text{-direction}}{\text{Applied electric field in } i\text{-direction}}\right|_{T=\text{const.}} \quad \text{m/V} \quad \left[\text{from } \frac{\text{m/m}}{\text{V/m}}\right] \tag{5.21}$$

Note: The directions i and j are inverted in the inverse effect—the j-direction is in the numerator in this case.

1. It bleeds the charge off the capacitor C_f at a low rate to prevent the amplifier from drifting into saturation.
2. It also provides a dc bias path for the negative input.

The values of R_f and C_f set the lower cutoff frequency of the amplifier given by

$$f_L = \frac{1}{2\pi R_f C_f}$$

The amplifier action maintains a 0 V across its input terminals so that the stray capacitance of the connecting cable poses no problem. The resistor R_i provides ESD[22] protection as well as it combines with the capacitors C_p and C_c to set the higher cutoff frequency given by

$$f_H = \frac{1}{2\pi R_i (C_p + C_c)}$$

The output is given by

$$V_o = -\frac{Q_p}{C_f} + \frac{V_{cc}}{2}$$

Thus, for no input the biasing puts the output voltage at $V_{cc}/2$. Which means, the output will swing around this dc level.

Example 5.2
Determine the pressure sensitivity of a quartz piezoelectric transducer of thickness 2.5 mm. Voltage sensitivity of quartz is 50×10^{-3} Vm/N.

Solution
Given $g = E_o/tp = 50 \times 10^{-3}$ Vm/N and $t = 2.5$ mm $= 2.5 \times 10^{-3}$ m. Therefore, pressure sensitivity $= E_o/p = gt = 125$ mV/kPa.

Example 5.3
A quartz piezoelectric transducer has the following specifications: area = 1 cm^2, thickness = 1 mm, Young's modulus = 9×10^{10} Pa, charge sensitivity = 2 pC/N, relative permittivity = 5 and resistivity = 10^{14} Ω-cm. A 20 pF capacitor and a 100 MΩ resistor are connected in parallel across the electrodes of the piezoelectric transducer. If a force $F = 0.02\sin(10^3 t)$ N is applied, calculate

(a) the peak-to-peak voltage generated across the electrodes

(b) the maximum change in crystal thickness

Solution
Given:

$$\text{Area of the piezoelectric transducer, } A = 1\ \text{cm}^0 = 10^{-4}\ \text{m}^0$$
$$\text{Thickness, } t = 1\ \text{mm} = 10^{-3}\ \text{m}$$
$$\text{Young's modulus, } Y = 9 \times 10^{10}\ \text{Pa}$$
$$\text{Charge sensitivity, } d = 0\ \text{pC/N} = 0 \times 10^{-10}\ \text{C/N}$$
$$\text{Relative permittivity, } \varepsilon_r = 5, \text{ therefore, } \varepsilon = \varepsilon_0\varepsilon_r = 4.405 \times 10^{-11}\ \text{F/m}$$
$$\text{Resistivity, } \rho = 10^{14}\ \Omega\text{-cm} = 10^{10}\ \Omega\text{-m}$$
$$\text{Parallel resistance, } R = 100\ \text{M}\Omega = 10^8\ \Omega$$
$$\text{Parallel capacitance, } C = 00\ \text{pF} = 00 \times 10^{-10}\ \text{F}$$

[22]ElectroStatic Discharge.

Therefore,

$$\text{Resistance of the piezoelectric transducer, } R_p = \rho A/t = 10^{11}\ \Omega$$
$$\text{Capacitance of the piezoelectric transducer, } C_p = \varepsilon A/t = 4.425 \times 10^{-12}\ \text{F}$$
$$\text{Equivalent resistance, } R_{eq} = R_p \parallel R \simeq 10^8\ \Omega$$
$$\text{Equivalent capacitance, } C_{eq} = C_p + C = 24.425 \times 10^{-12}\ \text{F}$$
$$\text{Time constant, } \tau = R_{eq}C_{eq} = 24.425 \times 10^{-4}\ \text{s}$$

The applied force is sinusoidal with an amplitude of 0.02 N, i.e. with a peak-to-peak value, $(F)_{\text{p-p}} = 0.04$ N and its angular frequency, $\omega = 10^3$ rad.

(a) Therefore, from Eq. (5.40), we get

$$(e_o)_{\text{p-p}} = \frac{d}{C_{eq}} \frac{1}{\sqrt{1 + (1/\omega\tau)^2}} (F)_{\text{p-p}}$$
$$= \frac{2 \times 10^{-12}}{24.425 \times 10^{-12}} \times \frac{1}{\sqrt{1 + 1/(10^3 \times 24.425 \times 10^{-4})^2}} \times 0.04\ \text{V}$$
$$\simeq 2.8\ \text{mV}$$

(b) Since, Young's modulus, $Y = \dfrac{\text{longitudinal stress}}{\text{longitudinal strain}} = \dfrac{F/A}{\Delta l/l}$, we have,

$$(\Delta l)_{\text{p-p}} = \frac{(F)_{\text{p-p}} l}{AY}$$
$$= \frac{0.04 \times 10^{-3}}{10^{-4} \times 9 \times 10^{10}}\ \text{m}$$
$$\simeq 4.4 \times 10^{-12}\ \text{m} = 4.4\ \text{pm}$$

Piezoelectric actuator

An actuator is a mechanical device for moving or controlling a mechanism or system. It is operated by a source of energy, usually in the form of an electric current.

In instrumentation, actuators are a subdivision of transducers. They are devices which transform an input signal (mainly an electrical signal) into motion. Specific examples include: electrical motors, pneumatic actuators, hydraulic actuators, linear actuators etc. Piezoelectric actuators are also used because piezoelectrics deform linearly with an applied electric field.

Commonly used stack actuators achieve a relative displacement of up to 0.2%. Displacement of piezoceramic actuators is primarily a function of the applied electric field strength E, the length L of the actuator, the forces applied to it and the properties of the piezoelectric material used. The material properties can be described by the piezoelectric charge constant d_{ij}. We know that this constant describes the relationship between the applied electric field and the mechanical strain produced.

The change in length, ΔL, of an unloaded single-layer piezo actuator can be estimated by the following equation:

$$\Delta L = S \cdot L \approx \pm E d_{ij} L$$

where S is the strain $= \Delta L/L$.

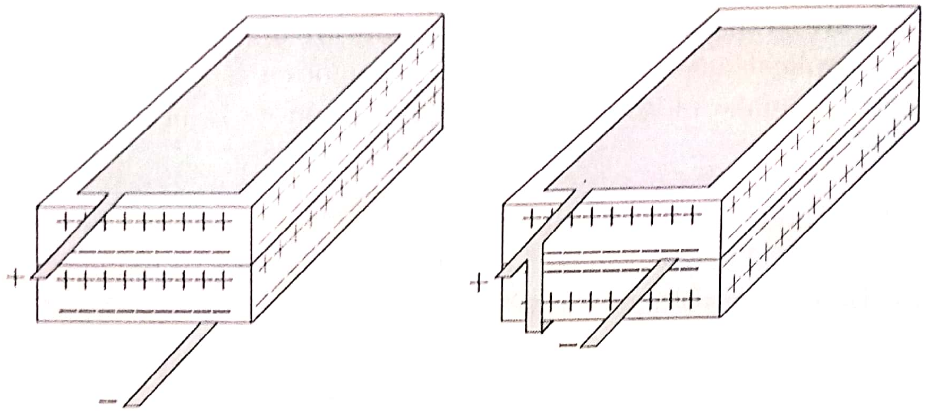

Fig. 5.22 Bimorphs: (a) serial and (b) parallel.

Parallel bimorph produces twice the capacitance as that of a series connection and in a sender-type transducer admits the full excitation voltage across each plate.

In either case the device relies on the d_{31} piezoelectric constant and that the strain is proportional to the square of the applied voltage.

Multimorph. Instead of two plates, monolithic, multi-layer type piezo benders, known as *multimorphs*, are available too. Similar to multilayer stack actuators, they run on a low operating voltage (60 to 100 V).

Bender type actuators provide large motion in a small package at the expense of stiffness, force and speed.

Advantages and disadvantages

From its discovery by the Curies in 1880, it took about 70 years before the piezoelectric effect was used for industrial sensing applications. Since then, its utilisation 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 like in medical, aerospace and nuclear instrumentation.

Advantages. The high modulus of elasticity of many piezoelectric materials is comparable to that of many metals and the maximum stress that they can withstand can be as high as 105×10^6 N/m^2. Even though piezoelectric sensors are electromechanical systems that react on compression, the sensing elements show almost zero deformation. The piezoelectric sensors are

1. Rugged
2. Have an extremely high natural frequency
3. An excellent linearity over a wide amplitude range
4. Insensitive to electromagnetic fields and radiation, enabling measurements under harsh conditions
5. Materials like gallium phosphate or tourmaline have an extreme stability over temperature enabling sensors to have a working range of 1000°C

Table 5.10 gives an idea about the relative standing of piezoelectric transducers vis-á-vis the strain sensitivity of other transducers.

Table 5.10 Comparison of sensitivity of sensing principles

Principle	*Sensitivity* (V/μm)	*Resolution* (μm)	*Dynamic range* (dB)
Piezoelectric	5.0	0.00001	160
Piezoresistive	0.0001	0.0001	128
Inductive	0.001	0.0005	126
Capacitive	0.005	0.0001	117

Disadvantages. In comparison to the advantages of piezoelectric transducers, disadvantages are only a few, namely

1. The major disadvantage is that they cannot be used for true static measurements. A static force will generate a fixed amount of charge 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 charge, thus yielding an inaccurate signal.
2. 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.

Applications

The piezo materials are available in a variety of shapes and sizes such as discs, plates, bars, rings, rods, tubes, etc. Some of their typical applications as transducers are as follows:

1. Vibration and shock measurement
2. Accelerometers
3. Ultrasound flow meters
4. Dynamic force and pressure measurement
5. NDT (non-destructive testing) transducers[23]

Other applications include

1. Stable oscillation frequency generators
2. High voltage generators tor gas lighters
3. Fuses for explosives
4. Nebulisers
5. SONAR
6. Deepwater hydrophones[24]
7. Actuators/translators
8. Ultrasonic cleaners, welders

[23] Ultrasound waves are passed through a material and received at different speeds relative to the density and elastic properties of the material, producing data that can be utilised to create a cross-sectional image.

[24] Device for converting sound waves into electrical signals, similar in operation to a microphone but used [illegible] underwater source, such as a submarine.