
“EXPLORING THE STUDY OF PIEZOELECTRIC EFFECT IN PZT CERAMICS FOR MODERN ELECTRONIC APPLICATIONS”

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Crossref DOI - <https://doi.org/10.63665/rh.v7i2.78>

Abstract :

Piezoelectric materials are widely referred to as "smart" materials due to their ability to convert mechanical pressure acting on them to electrical signals and vice versa. Piezoelectric materials exhibit essential properties that make them suitable for various engineering applications, including sensors and actuators in industrial work. This review article presents a thorough investigation of the basic principles of piezoelectric materials, as well as a systematic overview of their modelling for several kinds of applications. Current challenges in this area have been critically reviewed in a discussion. As a result, this review can provide a guideline for the scholars who want to use PEH's for their research.

The paper also systematically reviews the piezoelectric materials, operating principles, representative schemes, characteristics, and potential applications of each mainstream type of piezoelectric actuator. In order to categorise piezoelectric actuators into direct and indirect categories with multiple subcategories, we want to present a more nuanced and scientific viewpoint here.

Furthermore, this review investigates the relationships and mechanisms that underlie all types of piezoelectric actuators, as well as their advantages and disadvantages, and prospective development trends.

The complete content and detailed comparison may help the development of a comprehensive understanding of piezoelectric actuators, as well as the identification of practical applications and future research.

Keywords : piezoelectric materials; smart materials; piezoelectric energy harvester; Piezoelectric effect, amplified piezoelectric actuator, ultrasonic actuator; Piezoelectric polymer; Lead Zirconate Titanate (PZT).

Introduction :

Today, there is a large choice of piezoelectric materials to select from as a result of the research done on these materials (Figure 1).



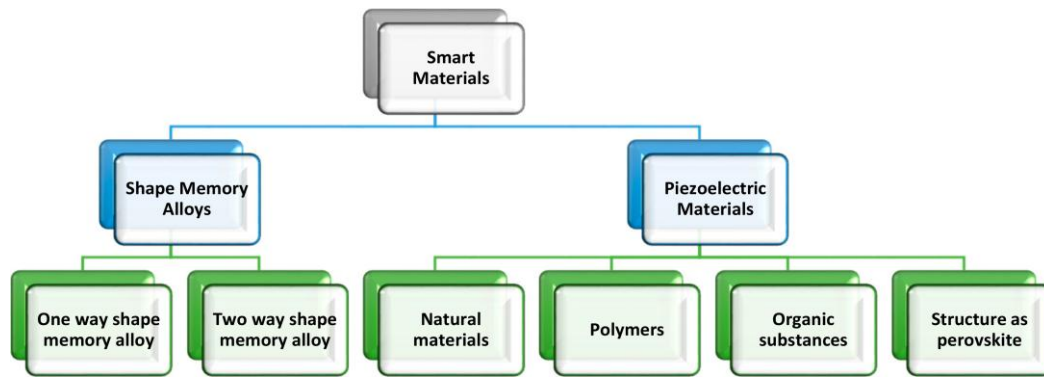


Figure 1. Most common smart materials.

The main categories of vibration-based energy harvesters are piezoelectric, electromagnetic, and electrostatic. As the structures need to be made using micromachining techniques, piezoelectric devices of smaller sizes—like MEMS size devices—benefit from power scaling with volume. In the literature the power densities that can be obtained with different energy sources, together with their benefits and drawbacks have been covered. Piezoelectric vibration energy harvesters are said to have a higher energy density for practical purposes. Over the last ten years PEHs have been widely researched.

Over the past five years, lead zirconate titanate (PZT) has gained popularity as a piezoelectric material for energy harvesting.

Piezoelectric Materials :

Piezoelectric materials are simple, inexpensive, lightweight, and easy-to-control smartmaterial for structural actuation application. It is renowned for its versatility in a wide range of applications in various structures; piezoelectric materials are easily moulded into a variety of shapes, including fibres, cylinders, thin films, and patches.

The piezoelectric material which is commonly used in automotive and aerospace engineering nowadays are: Lead Zirconate Titanate (PZT), Lead Titanate (LT), Sodium Potassium Niobate (SPN), Lead Magnesium Niobate (PMN), and Leadmetaniobate (LMN). Lead Zirconate Titanate (PZT), one of the five forms of piezoelectric material mentioned above, is one of the ferroelectric materials that is most commonly researched because of its many uses as a pyroelectric material that is regularly utilized for structural restoration [1].From the literature, we observed that PZT is being used for the repair of cracks, shape control, vibration control, and structural health monitoring [2].

Many piezoelectric materials have been created over the last century, but perovskite lead zirconate titanate which is a polycrystalline monolithic piezoelectric ceramic known as PZT is the most popular one and is often doped with niobium or lanthanum to form soft and hard piezoelectric materials. While PZT is the most prevalent material, it contains lead, necessitating a substantial and continuous research effort to find other formulations [3–6]. Recently, Gao et al. [7] developed a PNN PZT (0.55Pb (Ni_{1/3}Nb_{2/3}) O₃–0.135PbZrO₃–0.315PbTiO₃) ceramic with a remarkably high coupling coefficient much higher than conventional PZT ceramics. Piezoelectric ceramics are dense and brittle, despite their low

cost and strong coupling. The growing usage of piezoelectric ceramics in MEMS has led to the development of PZT thin films, which can be used on a small scale to provide flexibility and enhance coupling through the use of grain texturing and epitaxial thin films on substrates. [8–10].

Piezoelectric effect and piezoelectric materials :

1. Background :

The piezoelectric effect denotes the ability of certain materials to generate an electric charge in response to applied mechanical stress, whereas the inverse effect is the reverse, as shown in Fig. 3. Generally, the piezoelectric effect stems from the electromechanical coupling between the dielectric and elastic properties. Dielectric properties mainly refer to the relationship between electrical displacement and electric field, and elastic properties refer to the relationship between stress and strain. The IEEE standard on piezoelectricity [11] has been established for decades based on fundamental contributions from Voigt [12], Cady [13], Heising [14], Mason [15], Mindlin [16], Tiersten et al. [17,18], etc.

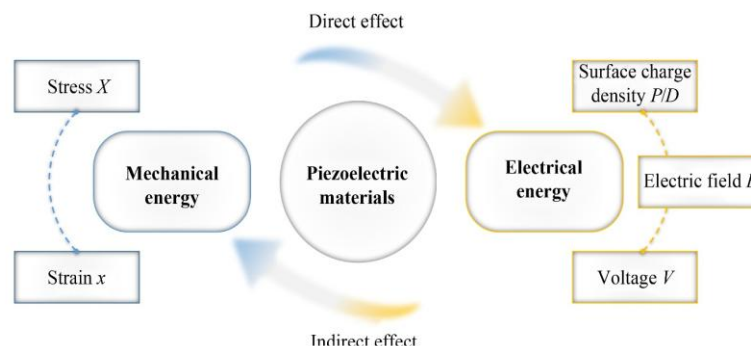


Fig. 3 Piezoelectric effect energy conversion relationship.

2. Piezoelectric materials can be classified into single crystals, piezoelectric ceramics, and polymers.

Table 3 summarizes the properties of various piezoelectric materials. As better specifications typically translate into higher costs and more physical fragility, single crystals can achieve the highest coefficient and a wider range of the piezoelectric constant through various doping techniques. Piezoelectric ceramics, the most widely used commercial piezoelectric materials, often have greater dielectric and piezoelectric constants, which strengthens the piezoelectric action. Polymers exhibit low piezoelectricity but they show better flexibility, low density, low acoustic impedance, and easy processing.

Table 3 Piezoelectric coupling coefficients of different piezoelectric inorganic and organic materials;

Compound	Material	Type	$d_{33}/(\text{pC}\cdot\text{N}^{-1})$		
			$d_{33}/(\text{pC}\cdot\text{N}^{-1})$	$d_{31}/(\text{pC}\cdot\text{N}^{-1})$	
Inorganic	α -Quartz	Single crystal	2.31	–	[20]
	LiNbO ₃		6	–1	[20]
	PMN-PT		2500	–	[23]
	PZN-PT		2455	–1204	[21]
	PIN-PT		1600	–	[22]
	AlN	Ceramic	5.5	–2.0	[24]
	BaTiO ₃		191	–79	[19]
	PZT-5A		374	–171	[25]
	PZT-5H		650	–320	[19]
Organic	PVDF	Polymer	25	–	[56]
	Polyimide		2.5–16.5	–	[53]

3. Lead Zirconate Titanate :

Lead zirconate titanate, also called **lead zirconium titanate** and commonly abbreviated as **PZT**, is an inorganic compound with chemical formula $\text{Pb}[\text{Zr}_x\text{Ti}_{1-x}]\text{O}_3$ ($0 \leq x \leq 1$). It is a ceramic perovskite material that shows a marked piezoelectric effect, meaning that the compound changes shape when an electric field is applied. It is used in a number of practical applications such as ultrasonic transducers and piezoelectric resonators. It is a white to off-white solid.

Around 1952, the Tokyo Institute of Technology developed the first lead zirconium titanate.

Lead zirconium titanate has a higher operating temperature and is more sensitive than barium titanate, a previously identified metallic-oxide-based piezoelectric material.

Because of its relative affordability, chemical inertness, and physical strength, piezoelectric ceramics are used in various applications.

(a) Electroceramic properties :

Lead zirconate titanate exhibits piezoelectric properties, generating a voltage across two of its surfaces when subjected to compression, which is useful for sensor applications, and undergoing a physical deformation when an external electric field is applied, also beneficial for actuator applications. The relative permittivity of lead zirconate titanate can range from 300 to 20000, depending upon orientation and doping. Being pyroelectric, this material develops a voltage difference across two of its faces under changing temperature conditions; consequently, lead zirconate titanate can be used as a heat sensor. Lead zirconate titanate is also ferroelectric, which means that it has a spontaneous electric polarization (electric dipole) that can be reversed in the presence of an electric field. The material features an extremely large relative permittivity at the morphotropic phase boundary (MPB) near $x = 0.52$.

Some formulations are ohmic until at least 250 kV/cm (25 MV/m), after which



current grows exponentially with field strength before reaching avalanche breakdown; but lead zirconate titanate exhibits time-dependent dielectric breakdown — breakdown may occur under constant-voltage stress after minutes or hours, depending on voltage and temperature, so its dielectric strength depends on the time scale over which it is measured. Other formulations have dielectric strengths measured in the 8–16 MV/m range.

In commercial applications, it is usually not used in its pure form; instead, it is doped with acceptors that generate oxygen (anion) vacancies or donors that produce metal (cation) vacancies, thereby facilitating domain wall motion inside the material.

In general, acceptor doping creates *hard* lead zirconate titanate, while donor doping creates *soft* lead zirconate titanate. Hard and soft lead zirconate titanate generally differs in their piezoelectric constants. Piezoelectric constants are proportional to the polarization or to the electrical field generated per unit of mechanical stress, or alternatively is the mechanical strain produced by per unit of electric field applied. In general, *soft* lead zirconate titanate has higher piezoelectric constant, but larger losses in the material due to internal friction. In *hard* lead zirconate titanate, domain wall motion is pinned by the impurities, thereby lowering the losses in the material, but at the expense of a reduced piezoelectric constant.

b) Varieties :

One of the commonly studied chemical compositions is $\text{PbZr}_{0.52}\text{Ti}_{0.48}\text{O}_3$. The increased piezoelectric response and poling efficiency near to $x = 0.52$ is due to the increased number of allowable domain states at the MPB. At this boundary, the 6 possible domain states from the tetragonal phase $\langle 100 \rangle$ and the 8 possible domain states from the rhombohedral phase $\langle 111 \rangle$ are equally favorable energetically, thereby allowing a maximum 14 possible domain states.

Like structurally similar lead scandium tantalate and barium strontium titanate, lead zirconate titanate can be used for manufacture of uncooled staring array infrared imaging sensors for thermographic cameras. Both thin film (usually obtained by chemical vapor deposition) and bulk structures are used. The formula of the material used usually approaches $\text{Pb}_{1.1}(\text{Zr}_{0.3}\text{Ti}_{0.7})\text{O}_3$ (called lead zirconate titanate 30/70). Its properties may be modified by doping it with lanthanum, resulting in **lanthanum-doped lead zirconium titanate (lead zirconate titanate, also called lead lanthanum zirconium titanate)**, with formula $\text{Pb}_{0.83}\text{La}_{0.17}(\text{Zr}_{0.3}\text{Ti}_{0.7})_{0.9575}\text{O}_3$ (lead zirconate titanate 17/30/70).

c) PZT Ceramics Properties :

Piezoelectricity : *PZT ceramics exhibit the ability to convert mechanical stress into electrical charge and vice versa, making them crucial for various sensing and actuation applications.*

- **Ferro electricity** : These ceramics can undergo a reversible change in spontaneous electric polarization when exposed to an external electric field, providing a foundation for their piezoelectric behaviour.



- **High Curie temperature** : PZT ceramics maintain their ferroelectric and piezoelectric properties at elevated temperatures, known as the Curie temperature, allowing for stable performance in a wide range of applications.
- **Electromechanical Coupling** : PZT ceramics have high electromechanical coupling coefficients, indicating their efficiency in converting electrical energy to mechanical motion and vice versa, making them suitable for precision applications.
- **Stability and Durability** : PZT ceramics are known for their stability and durability, ensuring reliable performance over an extended operational lifespan, particularly in demanding environments.

d) Key Characteristics :

- **Composition** : Solid solution of lead titanate (PbTiO_3) and lead zirconate (PbZrO_3) with formula $\text{Pb}[\text{Zr}_x\text{Ti}_{1-x}]\text{O}_3$.
- **Structure** : Tetragonal perovskite crystal structure.
- **Properties** : Excellent electromechanical coupling, ferroelectric, high piezoelectric coefficients, and good stability.
- **Types** : Can be "soft" (high piezoelectricity, lower losses) or "hard" (more stable under high stress, lower losses).

Manufacturing :

- Involves mixing raw powders (lead, zirconium, titanium oxides).
- Pressed and sintered (fired at high temperatures, 1250-1350°C) to form a ceramic body.
- Subjected to electrical "poling" (applying a strong electric field) to align its crystalline structure for piezoelectricity.

PZT Manufacturing :

Figure 1:



The process of manufacturing PZT powders consists of six distinct unit operations. High-purity raw materials are evaluated, selected and sourced throughout the world. Selection criteria, in addition to purity, include material activity and limits on specific deleterious impurities.

Once each material is selected and approved for use, it is precisely weighed, according to the formulation being manufactured, and transferred to wet mills. These ingredients are wet-milled together in their proper proportions to achieve a uniform particle size distribution. Precise control over particle size distribution is necessary to ensure appropriate material activity during the calcination.

Following the wet milling process, the product is dried and prepared for calcining. The product must be calcined in high-purity crucibles to guarantee no chemical contaminants are present in the final product. The calcining operation is carried out in air at about 1000°C, where the desired PZT phase is formed.

Uses :



Lead zirconate titanate is used in the fabrication of ultrasound transducers, sensors, actuators, high-value ceramic capacitors, and ferroelectric memory (FRAM) chips. It is also used in the manufacture of ceramic resonators for reference timing in electronic circuitry. Anti-flash goggles featuring PLZT protect aircrew from burns and blindness in case of a nuclear explosion. The PLZT lenses could turn opaque in less than 150 microseconds.

Soft (sensor) PZT ceramic powders are typically used when high coupling and/or high charge sensitivity are important, such as in flow or level sensors; ultrasonic non-destructive testing/evaluation (NDT/NDE) applications; or for accurate inspections of automotive, structural or aerospace products. Material characteristics include a high dielectric constant; high coupling; high charge sensitivity; high density with a fine grain structure; a high Curie point; and a clean, noise-free frequency response.

Hard (high power) PZT ceramic powders are used when high power characteristics are required, including applications such as the generation of ultrasonic or high-voltage energy in ultrasonic cleaners, sonar devices, etc. Important powder characteristics include a high piezoelectric charge constant (d_{33}); a higher mechanical quality factor that reduces mechanical loss and enables a lower operating temperature; a low dissipation factor that ensures cooler, more economical operation; high dielectric stability; and low mechanical loss under demanding conditions.

PZT Ceramics Applications Sensors :

PZT ceramics are widely used in various sensor applications, including pressure sensors, accelerometers and ultrasonic sensors, leveraging their piezoelectric properties for precise measurements.

- **Actuators :** These ceramics find applications in actuators for precise motion control in devices such as nanopositioners, micropositioners, and other electromechanical systems.

- **Ultrasonic Transducers** : PZT ceramics play a crucial role in ultrasonic transducers used for medical imaging, non-destructive testing, and cleaning applications.
- **Piezoelectric Devices** : PZT ceramics are essential components in piezoelectric devices like piezoelectric motors, buzzers, and speakers, where their ability to convert electrical energy to mechanical motion is exploited.
- **Sonar Systems** : PZT ceramics are utilized in sonar systems for underwater communication and detection due to their excellent sensitivity to acoustic signals.
- **Precision Mechanics** : In applications requiring precise positioning and fine-tuning, PZT ceramics are employed in devices like atomic force microscopes (AFM) and scanning tunneling microscopes (STM).
- **Energy Harvesting** : PZT ceramics can be used to convert mechanical vibrations or movements into electrical energy, offering potential applications in energy harvesting devices.
- **Medical Devices** : PZT ceramics are employed in medical devices such as ultrasound imaging probes, where their piezoelectric properties are utilized for generating and detecting ultrasonic waves.

Future Scope :

Future research on PZT ceramics can focus on eco-friendly material development, nanoscale integration, smart energy harvesting systems, AI-assisted sensor networks and advanced fabrication techniques, enabling next-generation electronic and biomedical devices.

Future research may focus on integrating Artificial Intelligence with PZT-based systems for intelligent material design, predictive maintenance, adaptive energy harvesting and smart sensing applications. AI-driven optimization and real-time analytics can significantly enhance performance, reliability, and efficiency of next-generation piezoelectric electronic devices.

References :

- Nogas-C'wikiel, E. Fabrication of Mn Doped PZT for Ceramic-Polymer Composites. *Arch. Metall. Mater.* **2011**, 56, 2–6. [[CrossRef](#)]
- Aabid, A.; Parveez, B.; Raheman, A.; Ibrahim, Y.E.; Anjum, A.; Hrairi, M.; Parveen, N.; Zayan, J.M. A review of piezoelectric materials based structural control and health monitoring techniques for engineering structures: Challenges and opportunities. *Actuators* **2021**, 10, 26. [[CrossRef](#)]
- Panda, P.K. Review: Environmental friendly lead-free piezoelectric materials. *J. Mater. Sci.* **2009**, 44, 5049–5062. [[CrossRef](#)]
- Priya, S.; Nahm, S. *Lead-Free Piezoelectrics*, 1st ed.; Springer: New York, NY, USA, 013.
- Uchino, K. *The Development of Piezoelectric Materials and The New Perspective*. In *Advanced Piezoelectric Materials: Science and Technology*, 2nd ed.; Uchino, K., Ed.; Woodhead Publishing: Sawston, UK, 2010; pp. 1–85.
- Marino, A.; Genchi, G.G.; Mattoli, V.; Ciofani, G. *Piezoelectric nanotransducers: The*



- future of neural stimulation. *Nano Today* **2017**, 14, 9–12. [[CrossRef](#)]
- Gao, X.; Wu, J.; Yu, Y.; Chu, Z.; Shi, H.; Dong, S. Giant Piezoelectric Coefficients in Relaxor Piezoelectric Ceramic PNN-PZT for Vibration Energy Harvesting. *Adv. Funct. Mater.* **2018**, 28, 1706895. [[CrossRef](#)]
 - Damjanovic, D. Ferroelectric, dielectric and piezoelectric properties of ferroelectric thin films and ceramics. *Rep. Prog. Phys.* **1998**, 61, 1267–1324. [[CrossRef](#)]
 - Messing, G.L.; Trolier-McKinstry, S.; Sabolsky, E.M.; Duran, C.; Kwon, S.; Brahmaroutu, B.; Park, P.; Yilmaz, H.; Rehrig, P.W.; Eitel, K.B.; et al. Templated Grain Growth of Textured Piezoelectric Ceramics. *Crit. Rev. Solid State Mater. Sci.* **2004**, 29, 45–96. [[CrossRef](#)]
 - Isarakorn, D. Epitaxial piezoelectric MEMS on silicon. *J. Micromech. Microeng.* **2010**, 20, 55008. [[CrossRef](#)]
 - 11.Meitzler A H, Berlincourt D, Welsh F S, Tiersten H F, Coquin G A, Warner W A. IEEE Standard on Piezoelectricity. ANSI/IEEE, 1987
 - Voigt W. *Crystal Physics Textbook*. Leipzig and Berlin: B. G. Teubner, 1910
 - Cady W G. *Piezoelectricity: An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals*. New York: McGraw-Hill Book Company, Inc., 1946
 - Heising R A. *Quartz Crystals for Electrical Circuits, Their Design and Manufacture*. New York: D. Van Nostrand Company, Inc., 1946
 - Mason W. *Hysteresis Losses in Solid Materials, Piezoelectric Crystals and Their Application in Ultrasonics*. New York: Van Nostrand, 1950
 - Mindlin R D. On the equations of motion of piezoelectric crystals. In: *Problems of Continuum Mechanics*. Philadelphia: SIAM, 1989, 282–290
 - Tiersten H F, Mindlin R D. Forced vibrations of piezoelectric crystal plates. *Quarterly of Applied Mathematics*, 1962, 20:107–119
 - Tiersten H F. *Linear Piezoelectric Plate Vibrations: Elements of the Linear Theory of Piezoelectricity and the Vibrations Piezoelectric Plates*. New York: Springer, 2013
 - Turner B L, Senevirathne S, Kilgour K, McArt D, Biggs M, Menegatti S, Daniele M A. Itrasound-powered implants: a critical review of piezoelectric material selection and applications. *Advanced Healthcare Materials*, 2021, 10(17): 2100986
 - Luan G D, Zhang J D, Wang R Q. *Piezoelectric Transducers and Arrays*. Revised ed. Beijing: Peking University Press, 2005 (in Chinese).
 - Zhang R, Jiang B, Cao W W, Amin A. Complete set of material constants of 0.93Pb(Zn_{1/3}Nb_{2/3})O₃-0.07PbTiO₃ domain engineered single crystal. *Journal of Materials Science Letters*, 2002, 21(23): 1877–1879
 - Guo Y P, Luo H S, He T H, Pan X M, Yin Z W. Electric-field induced strain and piezoelectric properties of a high curie temperature Pb(In_{1/2}Nb_{1/2})O₃-PbTiO₃ single crystal. *Materials Research Bulletin*, 2003, 38(5): 857–864
 - Park S E, Shrout T R. Ultrahigh strain and piezoelectric behaviour in relaxor based ferroelectric single crystals. *Journal of Applied Physics*, 1997, 82(4): 1804–1811
 - Liu Y, Cai Y, Zhang Y, Tovstopyat A, Liu S, Sun C L. Materials, design, and characteristics of bulk acoustic wave resonator: a review. *Micromachines*, 2020,



11(7): 630

- Berlincourt D A, Curran D R, Jaffe H. Piezoelectric and piezomagnetic materials and their function in transducers.
- Ramadan K S, Sameoto D, Evoy S. A review of piezoelectric polymers as functional materials for electromechanical transducers. Smart Materials and Structures, 2014, 23(3): 033001
- Chen Q X, Payne P A. Industrial applications of piezoelectric polymer transducers. Measurement Science & Technology, 1995, 6(3): 249

