

# A Comprehensive Review of Piezoelectric Sensors and Actuators: Challenges of Temperature-Dependent Materials

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**Abstract** - Piezoelectric sensors and actuators play an important role as structural health monitors for both aerospace and automotive systems, yet the application of such devices under extreme conditions is restricted by the basic compromise between sensitivity and thermal stability. This review aims to address the problem of the application of piezoelectric devices under extreme conditions, i.e., temperatures as high as 1000 °C, by conducting a meta-analysis of existing published articles between 2015 and 2026, focusing on the temperature-dependent properties of Lead Zirconate Titanate (PZT), Lanthanum Gallium Silicate (LGS), Lithium Niobate (LiNbO<sub>3</sub>), and Yttrium Calcium Oxyborate (YCOB). The review is mainly focused on the role of crystal structure, ferroelectric, and non-ferroelectric properties, as they apply to the four different materials under review. The results of the analysis show that while PZT has high sensitivity due to domain wall mobility, electromechanical coupling is also high, yet the performance drops abruptly as the temperature approaches the Curie point, while the non-ferroelectric single crystals, i.e., LGS and YCOB, show excellent structural stability, i.e., no phase transitions occur up to 1000 °C, yet the signal output is lower, while LiNbO<sub>3</sub> shows good performance under high-temperature conditions, yet electrical conductivity is increased, thus degrading the signal output. This shows that there is a basic dilemma between ferroelectric ceramics, i.e., good sensitivity, yet poor thermal endurance, while single crystals show good thermal endurance, yet the signal output is lower, thus indicating that the way forward is to enhance the polarization retention, signal-to-noise performance under high-temperature conditions, thus applicable for extreme environments, as well as for medical applications such as high-intensity ultrasound therapy, as it is applicable under extreme conditions.

**Keywords** - Piezoelectric, Sensors, Actuators, Temperature-dependent materials

## I. INTRODUCTION

As technology has progressed in electronic markets, there has been a notable rise in interest for energy harvesting in the recent years. The growing global population has led to an increased energy demand [1]. Piezoelectric sensors and actuators have attracted considerable interest due to their distinct capability to transform electrical energy into mechanical energy and vice versa. Recent progress in piezoelectric sensors and actuators encompasses the creation of flexible and wearable devices, including wireless

communications technologies, and miniaturization for applications at the micro- and nanoscale technologies [2]. High-Temperature piezoelectric sensors are essential in aerospace, automotive, energy sector because it is very reliable, lightweight, and economical under extreme conditions where LGS, LiNbO<sub>3</sub>, AlN and above all YCOB are used with a consistent performance at high temperature [3]. However, the usefulness of these materials is largely influenced by temperature-related issues such as hysteresis, change of dielectric properties, and decomposition of electrodes. It is important to understand and address these temperature-related problems in the pursuit of reliable and efficient piezoelectric devices including sensors, actuators, and so on.

## II. STATEMENT OF THE PROBLEM

Piezoelectric sensors and actuators devices have been prominently incorporated in various modern engineering practices, such as precision devices, robots, aerospace technology, health monitoring, and micro-electromechanical systems, due to their high sensitivity, quick response, and miniaturized design. Nevertheless, the performance of piezoelectric devices is significantly affected by fluctuations in temperatures. Various key piezoelectric properties such as piezoelectric coefficients, dielectric constants, elastic stiffness, and stability of polarization are inherently modified with changes in temperatures, thereby affecting overall performance.

While various studies have already been conducted and published on piezoelectric devices, the existing literature is mainly peripheral, focusing on the impact of temperature individually rather than offering comprehensive study on various materials and applications. Since existing studies are mainly based on examining the performance of the device under ideal conditions rather than considering the inevitable change due to changes in temperature, it is high time to perform a comprehensive study critically examining the temperature-based problems and offers new insights for effective development of piezoelectric materials suitable for high-end technology applications.

### III. RESEARCH OBJECTIVES

General Objective:

To provide a comprehensive understanding of the effects of temperature on the reliability and performance of piezoelectric sensors and actuators.

Specific Objectives:

- To analyze the impact of thermal fluctuations on the electromechanical performance of PZT, LGS, LiNbO<sub>3</sub>, and YCOB.
- To categorize the material degradation modes and electrode failures occurring in extreme thermal environments.
- To evaluate the current state of compensation methods and material alternatives used to mitigate temperature-dependency in high-end technology.

### IV. RESEARCH QUESTIONS

1. What are the piezoelectric properties particularly the electromechanical coupling and  $d_{33}$  coefficient factor of PZT, LGS, LiNbO<sub>3</sub> and YCOB are found to vary as they are brought to their respective Curie temperature or decomposition points?
2. What are the major technical issues such as thermal depolarization oxygen vacancy migration and electrode to substrate degradation that impair the stability of sensors in high temperature applications?
3. In the current literature (2015–2026), what are the critical trade-offs between high-sensitivity lead-based ceramics (PZT) and thermally stable but lower-output single crystals (YCOB/LGS)?

### V. SIGNIFICANCE OF THE STUDY

This review indicates the relevance of knowledge on temperature-dependent materials of piezoelectric materials in relation to different applications. It helps to develop stronger, more powerful and more environmentally resilient piezoelectric systems by detecting knowledge gaps. Lastly, it provides an all-encompassing source where researchers and engineers can refer to in order to design, select and optimize piezoelectric devices in mission critical applications.

### VI. SCOPE AND DELIMITATIONS

This review focuses on the performance and thermal stability of high-temperature piezoelectric materials, specifically Lead Zirconate Titanate (PZT), Lanthanum

Gallium Silicate (LGS), Lithium Niobate (LiNbO<sub>3</sub>), and Yttrium Calcium Oxyborate (YCOB). The study covers temperature ranges from ambient conditions up to 1000°C, focusing on their roles in sensing (vibration, pressure) and actuation (precision positioning). The analysis includes technical challenges such as thermal depolarization, dielectric loss, and electrode degradation in aerospace and automotive contexts.

This study does not cover cryogenic (low-temperature) piezoelectric behavior or materials used strictly for non-mechanical energy storage, such as standard capacitors. It will not involve original laboratory experimentation; instead, it is delimited to a critical meta-analysis of peer-reviewed literature and technical reports published between 2015 and 2026.

### VII. REVIEW OF RELATED LITERATURE

As piezoelectric materials such as Lead Zirconate Titanate (PZT), Lanthanum Gallium Silicate (LGS), Lithium Niobate (LiNbO<sub>3</sub>), and Yttrium Calcium Oxyborate (YCOB) approach their Curie temperatures ( $T_C$ ) or decomposition temperatures, the properties of piezoelectric materials behave differently and largely depend on crystalline structure and piezoelectric processes. Piezoelectricity is the linear dependence between the mechanical stress and electrical polarization that is exhibited in non-centrosymmetric crystals [4], [5]. This is measured by the electromechanical coupling factor ( $k$ ) and the piezoelectric charge coefficient ( $d_{33}$ ) which are important in a number of applications such as sensors, actuators and transducers [6], [4], [7].

#### Lead Zirconate Titanate (PZT)

Ferroelectric PZT, is a type of ceramic and a sharp increase in piezoelectric characteristics occurs just prior to its Curie temperature after which it rapidly deteriorates [5]. Ferroelectric substances have spontaneous polarization, which can be reoriented by an external electric field, and this is also directly connected with their piezoelectric behavior [8] [9]. The ferroelectric domains of PZT become freer and an increasing temperature result in the extensive enhancement of the piezoelectric coefficient ( $d_{33}$ ) and electromechanical coupling factor ( $k$ ) [10], [11], [12], [13]. As an example, a  $d_{33}$  of 1165 pC/N and a longitudinal mode electromechanical coupling factor  $k_{33}$  of 0.86 with a Curie temperature of 197 °C in textured ceramics, a type of PZT that can be obtained with (x) set to 0.36PNN-xPZ-(0.64-x)PT [11]. Similarly, Li<sub>2</sub>CO<sub>3</sub> doped PNN-PZT ceramics have demonstrated a  $d_{33}$  of 692 pC/N at low sintering temperature [14]. This improvement can be explained by the augmenting polarization rotation euphoria proximate to the morphotropic phase boundary (MPB) and nearer to  $T_C$  leading to augmented response to external stimuli [15]. However, above  $T_C$ , PZT experiences a phase change to a paraelectric state which does not have any spontaneous polarization and the piezoelectric properties become effectively zero at once [10], [9]. This transition between ferro and paraelectric causes thermal depolarization, an essential but challenging to experimentally determine characteristic [10], [16]. Some

PZT-based ceramics have reached high  $d_{33}$  of 680 pC/N and high Curie temperature of 330 °C, such as Sm-modified  $\text{Pb}(\text{In}_{1/2}\text{Nb}_{1/2}\text{O}_3\text{-PbZrO}_3\text{-PbTiO}_3$  ternary ceramics, which attempts to expand their temperature range of operation [15]. Furthermore, PZT-5A ceramics have been used in ultrasonic transducers for high-temperature non-destructive evaluation (NDE) applications, operating effectively up to 150 °C with a  $d_{33}$  of 395 pC/N and a coupling factor  $k_t$  of 0.51, and remaining operational up to 300 °C [17]. Despite its excellent room-temperature properties, the inherent  $T_C$  of PZT limits its use in extreme high-temperature environments [18].

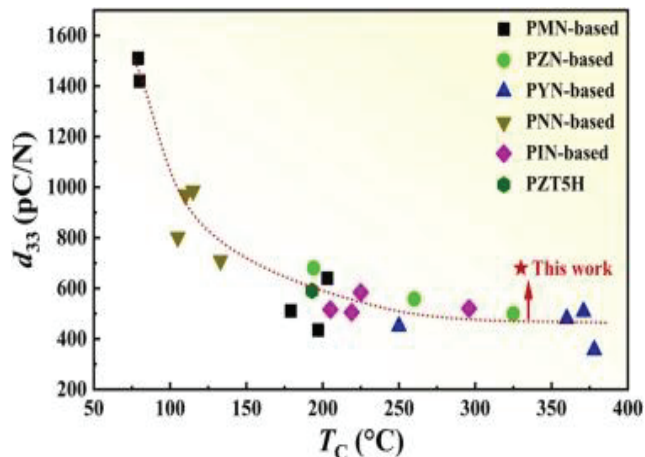


FIGURE 1. Temperature dependence of  $d_{33}$  for PIN-PHT-xSb ceramics. [15]

### Lanthanum Gallium Silicate (LGS)

In contrast, Langasite (LGS,  $\text{La}_3\text{Ga}_5\text{SiO}_{14}$ ) and Lithium Niobate ( $\text{LiNbO}_3$ ) are non-ferroelectric piezoelectric crystals. These materials do not possess a Curie temperature in the same sense as ferroelectrics, meaning they do not exhibit a sharp ferroelectric-to-paraelectric phase transition [5]. Instead, their piezoelectric properties degrade more gradually with increasing temperature. For LGS, the piezoelectric properties remain relatively stable up to approximately 900 °C, with degradation primarily due to increased phonon scattering and thermal expansion mismatch [19], [5]. LGS crystals are known for their high-temperature stability and are considered for high-temperature sensor applications [19]. The decomposition point of LGS is above 1470 °C [5]. Acoustic loss, a key factor in performance, has been studied in LGS up to high temperatures, indicating its robustness [19].

### Lithium Niobate

Lithium Niobate ( $\text{LiNbO}_3$ ) is another high-temperature piezoelectric material known for its high Curie temperature (approximately 1150 °C or 1483 K) [20] [18] [21]. Its piezoelectric properties, including the elastic, piezoelectric, and dielectric coefficients, have been characterized extensively from 25 °C to 900 °C [20]. Although  $\text{LiNbO}_3$  is very promising material with strong piezoelectric characteristics and high  $T_C$ , its working temperature is usually constrained to approximately 600 °C at high temperatures because the material is becoming more electrically conductive and suffers photorefractive damage at high temperatures, reducing device performance [22] [21]

[5]. The study of Acoustic loss of  $\text{LiNb}_{1-x}\text{Ta}_x\text{O}_3$  solid solutions at temperature up to 900 °C has been conducted which gives some insight into the behavior of acoustic loss at high temperatures [22]. The degradation that occurs at temperature exceeding 300 °C is usually monotonic as compared to that which occurs in ferroelectric materials [5].

### Yttrium Calcium Oxyborate (YCOB)

Another non-ferroelectric piezoelectric crystal is the Yttrium Calcium Oxyborate ( $\text{YCa}_4\text{O}(\text{BO})$  [5] It shows no finished change over to its congruent melting point of about 1500 °C [23] [5]. Consequently, its  $d_{33}$  and electromechanical coupling factor exhibit relatively mild, almost linear temperature reductions up to 1000 °C [23] [5]. This is mainly gradual degradation by anharmonic lattice effects and not phase change [5]. High-temperature piezoelectric sensing applications YCOB crystals also exhibit high stability in electrical properties without annealing even after exposure to high temperatures (900–1100 °C) in a low oxygen partial pressure atmosphere [23]. The electroelastic behavior of YCOB has also been tested during irradiation conditions that can be seen to indicate its toughness in adverse situations [24]. Its  $d_{33}$  values are usually lower than that of PZT, an example of which is a  $\text{Ba}_2\text{TiSi}_2\text{O}_8$  (BTS) crystal, which has similar properties as some borate crystals, giving  $d_{33}$  of 2.9 pC/N and 4.0 pC/N [25].

### Thermal Depolarization

A few interrelated technical issues, including thermal depolarization, oxygen vacancy migration, and electrode-to-substrate deterioration, seriously impair the dependability of sensors used in high-temperature settings, especially those that reach 1000 °C [26], [27]. These problems are especially common in oxide-based sensors and solid-state electrochemical sensors, which are essential for applications that need steady performance in extremely hot or cold environments [26], [27].

For ferroelectric and piezoelectric sensing devices in particular, thermal depolarization poses a significant difficulty [26]. Thermal depolarization appears as a change in the pyroelectric coefficient with different heating and cooling rates in materials such as  $\text{Nd}_2\text{Ti}_2\text{O}_7$  (Neodymium titanate) ceramics, which are known as high  $T_C$  ferroelectrics [26]. For example, the pyroelectric coefficient ranges from 88-90  $\mu\text{C}/\text{m}^2\text{K}$  at 5°C/min to 28-30  $\mu\text{C}/\text{m}^2\text{K}$  at 30°C/min and then dropped to 10-12  $\mu\text{C}/\text{m}^2\text{K}$  at rates between 30°C/min and 80°C/min [26]. When thermal energy exceeds the coercive energy barrier, remnant polarization is lost, resulting in irreversible signal drift and decreased sensitivity [28]. For instance, characteristics near the interface and catalytic efficiency are affected by the thermal depolarization of polarized calcium phosphate [28]. Thermal activation energy contributes to electrical degradation in multilayer ceramic capacitors; activation energies of approximately 1.5 eV have been noted for automatic prototype MLCCs [29].

### Oxygen Vacancy Migration

Another significant component causing sensor deterioration at high temperatures is oxygen vacancy migration [26] [30]. Oxygen vacancies are point defects in oxide-based materials that have a major impact on device performance and material properties [31]. These vacancies become much more mobile at high temperatures, which can have several negative consequences, including aging, ionic conductivity, and lattice distortion [30] [32]. For example, real-time in-operando tracking in ferroelectric hafnium zirconium oxide has demonstrated that oxygen vacancy migration takes place during pre-wake-up and results in phase shifts during fatigue and **wake-up** [30]. The reported pyroelectric currents in  $\text{Nd}_2\text{Ti}_2\text{O}_7$  ceramics are also influenced by oxygen vacancy migrations [26]. At heterointerfaces, these migrating vacancies may also encourage interdiffusion and phase decomposition [33]. For instance, the mobility of oxygen vacancies in multilayer ceramic capacitors based on  $\text{BaTiO}_3$  is linked to activation energies of roughly 1.0 eV [29]. For ferroelectric  $\text{Hf}_{0.5}\text{Zr}_{0.5}\text{O}_2$  thin films, oxygen vacancy manipulation, such as through  $\text{TiO}_2$  stack interface engineering, can lower the coercive field and perhaps increase reliability [34]. The functionality of solid oxide fuel cell electrolytes at intermediate temperatures depends critically on the creation and migration of oxygen vacancies close to misfit dislocations in oxide heterostructures such as  $\text{SrTiO}_3/\text{BaZrO}_3$  [33] [35]. Defect engineering can alter the mechanism of insulating degradation by introducing positively or negatively charged oxygen vacancies, as in the case of doping  $\text{MgO}$  or  $\text{ZrO}_2$  in  $\text{Al}_2\text{O}_3$ , respectively [36]. As seen in  $\text{CuO}$  nanowires, stress-induced reversible oxygen vacancy migration can occasionally even happen at **transformations** [37].

The long-term stability of high-temperature sensors is seriously threatened by electrode-to-substrate deterioration [38] [39]. Thermally driven interdiffusion, interfacial reactions, and delamination brought on by discrepancies in thermal expansion coefficients (CTE) are some of the mechanisms that contribute to this degradation [38] [39]. One common degradation process that affects photovoltaic modules' long-term performance and dependability is delamination [40]. One of the main reasons for performance loss in solid oxide cells (SOCs) is electrode-electrolyte delamination brought on by the CTE mismatch during thermal cycling [38]. Increased contact resistance, a lack of adhesion, and ultimately electrical open-circuit failure can result from this [39]. The significance of substrate-electrode compatibility for high-temperature applications in highlighted by printed sensors, such as multipoint thermocouples and resistance temperature detectors (RTDs) made on steel and ceramic substrates utilizing plasma spray techniques [41]. Two-step annealing can improve the high-temperature stability of Indium Tin Oxide (ITO) - Indium Oxide thermocouples and solve interfacial stability problems [42]. High-temperature pressure sensors' packaging problems can be resolved by using borosilicate glass wafers that have been anodically bonded to SOI wafers, filled with conductive silver paste, and then sintered to enable operation at temperatures higher than 150 °C [43]. Additionally, Multiphysics modeling shows that active layer cracking and electrode/electrolyte interface delamination have a major

impact on the electrochemical performance degradation in SOCs [39]. High adhesion is required for the integration of thick/thin film sensors into component systems, particularly for dual-layer sensors intended for high-temperature applications, like NTC thermistors stable up to 1300 °C [44].

### High Temperature

Sensor degradation at high temperatures is caused by a number of reasons in addition to these main obstacles. These include the rapid oxidation or corrosion of metallic electrodes or leads, the evaporation of volatile molecules, and the sliding of grain boundaries [45]. At high-temperatures, temperature drift may jeopardize the stability of magnetic sensors [46]. Strong thermal effects that introduce bias in strain readings are a problem for high-temperature strain sensors, such as those that use cascaded Fabry-Perot cavities and fiber Bragg gratings on sapphire fibers [47]. Even though these sensors can function at temperatures as high as 1150 °C, accurate strain measurement depends on appropriate temperature adjustment [47]. High-temperature sensing up to 750 °C is demonstrated using silicon carbide-on-insulator (SiCOI) thermoresistive sensors with strong linearity and low hysteresis; however, the underlying material stability is still crucial [48]. The limits of conventional sensors that operate below 200 °C can be addressed by graphene high-temperature sensors, which are shielded by a single silicon nitride layer and can expand their range to extremely high temperatures [49].

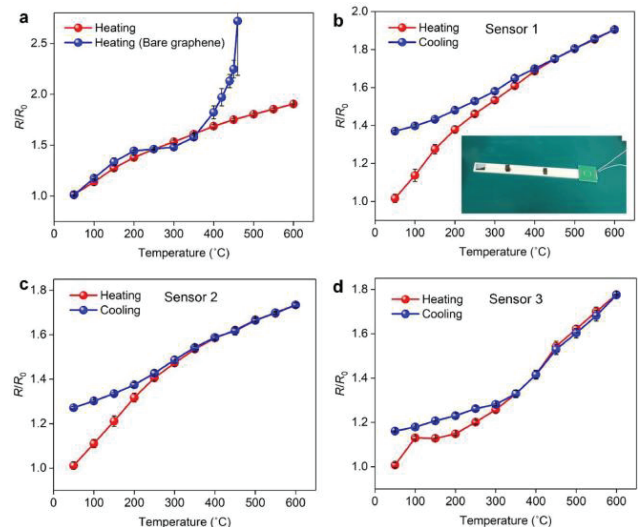


FIGURE 2. Thermal hysteresis of the micro graphene high temperature [49].

Strategies for mitigating these degradations are the development of high-temperature sensor technology depending on mechanisms. Defect engineering techniques include doping to pin vacancies, using diffusion-barrier interlayers (e.g.,  $\text{TiN}$ ,  $\text{CeO}_2$ ), and the creation of nanostructured stable electrodes [34] [36]. Furthermore, creating thermomechanical matched architectures reduces the stress caused by CTE mismatches [38]. Ceramics materials  $\text{La}_2\text{Ti}_2\text{O}_7$  with high Curie temperatures ( $T_C \sim 1460$

°C) show guarantee for high-temperature accelerator sensors and doping them with elements Zn can further alter their charge carrier transport behavior and high-temperature electrical properties [27]. High sensitivity at high temperatures is provided by microwave resonator-based pressure sensors that use diaphragm-assisted open-ended hollow coaxial cable resonators [50]. High temperature resistance and self-compensation capabilities are demonstrated by self-compensating absolute micro-pressure sensors made from raw porcelain substrates and functional layers of silver paste [51].

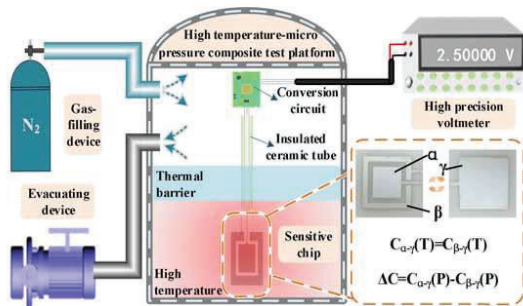


FIGURE 3. Design and fabrication of the high-temperature self-compensating absolute micro-pressure [51].

Ultimately, a thorough understanding of these degradation routes and the use of cutting-edge materials science and engineering techniques to counteract them are necessary to guarantee the long-term dependability of sensors at temperatures as high as 1000 °C.

### Critical Trade Offs

A number of interdependent performance axes, including piezoelectric coefficient ( $d_{33}$ ), thermal stability, mechanical quality factor ( $Q_m$ ), electromechanical coupling, environmental compliance, and sensitivity-output balance, are crucial trade-offs between thermally stable but lower-output single crystals like Yttrium Calcium Oxyborate (YCOB) and Languisite (LGS) and high-sensitivity lead-based ceramics, particularly Lead Zirconate Titanate (PZT) [52] [53] [54] [55]. These materials are essential for energy harvesting, actuation, and sensing applications; their unique benefits and drawbacks vary based on performance and operating conditions [52] [56] [57] [58].

### Piezoelectric Performance vs. Thermal Stability

Because of their exceptional piezoelectric performance, PZT ceramics have long been regarded as the gold standard for piezoelectric sensors. Typically,  $d_{33}$  values range from 200 to 600 pC/N, and for porous PZT-5H single crystals, they can reach 1550 pC/N [53] [59]. They are extremely sensitive for a variety of applications because of their high piezoelectric coefficient, which enables the effective conversion of mechanical stress into electrical impulses or vice versa [60]. PZT's remarkable characteristics are frequently engineered by doping and modifying its composition to the morphotropic phase boundary (MPB). For example, a specific PZT based ceramics have obtained strong electromechanical coupling factors ( $k_t$  up to 0.55) [61]

, through compositions like 0.1 PYN-(1-x)PZ-xPT - outstanding piezoelectric coefficients ( $d_{33}$  of ~450 pC/N), and a high Curie temperature ( $T_C \sim 398$  °C) [62]. PZT's thermal depolarization at high temperatures, however, is a major drawback that limits its operating range. It typically functions well at moderate temperatures but degrades at about 150-200 °C [52] [53] [55]. The material's intrinsic thermal instability and Curie temperature ( $T_C$ ) are linked to this degradation, which may result in permanent loss of piezoelectric characteristics and signal degradation [63] [64].

Single-crystal materials, such as YCOB and LGS, on the other hand, have better thermal stability and can perform at considerably higher temperatures-often as high 800-1000 °C [24] [23]. Because it exhibits robust electrical characteristics even after annealing at temperatures between 900 and 1100 °C under low oxygen partial pressure, YCOB, for example [23]. To improve thermal characteristics even more, Sc-doped YCOB crystals have been created [8]. These materials have much lower piezoelectric coefficients ( $d_{33}$ ), usually in the range of 3-10 pC/N, despite having exceptional thermal robustness and very little hysteresis [24]. This reduced output influences the overall signal-to-noise ratio by requiring more intricate signal amplification and processing in sensor devices.

### Mechanical Quality Factor and Electromechanical Coupling

The electromechanical coupling coefficient and mechanical quality factor ( $Q_m$ ) are crucial for evaluating piezoelectric materials. Hard PZT variations are appropriate for high-power, narrowband applications due to high  $Q_m$  values, stability against high electric fields, and reduced piezoelectric coefficients. Often achieved through acceptor doping. Recently, under high temperatures and stress conditions, some PZT-based ceramics have shown exceptional high-power performance [65]. Although there is an inherent trade-off that makes it difficult to achieve both high  $Q_m$  and high  $d_{33}$  at the same time, recent developments have showed promise in overcoming this through acceptor-modified invisible-boundary techniques, achieving high  $Q_m \sim 1096$  and  $d_{33} \sim 337$  pC/N [66].

Despite their thermal stability, YCOB and LGS typically have lower electromechanical coupling coefficients ( $k_t < 0.2$ ) [24]. When compared to PZT, this feature restricts their sensitivity and bandwidth in high-frequency or low-amplitude applications. Their potential for high-temperature sensing applications in challenging situations, such as nuclear power plants, is further highlighted by the assessment of the electro elastic characteristics of YCOB and GdCOB crystals exposed to high-energy irradiation, replicating harsh environments [24].

### Environmental and Regulatory Compliance

One major issue with PZT is its lead content that includes 60w% hazardous PbO, which breaches RoHS and REACH laws [53] [67] [68]. Lead oxide's volatility during sintering poses additional manufacturing difficulties since its loss can result in atomic-scale flaws like head and oxygen vacancies that alter the material's characteristics. Due to its toxicity, it is unsuitable for environmentally sensitive applications such as wearable electronics and biomedical implants [53] [69].

Efforts to modify PZT chemically through methods like cold sintering aim to improve its properties and address specific manufacturing issues [70].

Conversely, YCOB and LGS are lead-free materials, which makes them safer and more suitable for the environment where lead toxicity is an issue [24] [8]. Their radiation hardness and chemical inertness make them perfect for application in implanted sensor, nuclear, and aerospace technologies [24]. Due to the desire for lead-free substitutes, a great deal of research has been done on materials such as Barium Calcium Zirconium Titanate (BCZT) as possible substitutes for PZT in energy harvesting applications. Performance is frequently compared using simulations using programs like COMSOL Multiphysics [67]. Similarly, the strain temperature stability and piezoelectric characteristics of ceramics based on potassium sodium niobate (KNN) without lead have significantly improved [71] [72] [73] [74].

### Trade-off Summary and Future Directions

The decision between PZT and single crystals like YCOB/LGS involves a fundamental trade-off: high sensitivity and output (PZT) versus exceptional thermal

stability and environmental compatibility (YCOB/LGS) [52] [53] [54] [55]. PZT excels in applications requiring high piezoelectric response, but its operational temperature range is limited, and its lead content poses health and environmental risks [53]. Although YCOB and LGS are lead-free and provide unmatched thermal stability, their lower piezoelectric coefficients result in poorer output and sensitivity, frequently necessitating more complex electrical amplification [24].

Current research is focused on bridging this gap through several strategies:

1. **Lead free piezoelectric ceramics:** A lot of work is being done to create lead-free substitutes that perform as well as or better than PZT [53] [54] [75]. To obtain high piezoelectricity and wide operating temperature ranges, materials such as  $\text{BiFeO}_3\text{-BaTiO}_3$  ceramics,  $\text{Bi}_{0.5}(\text{Na}_{0.40}\text{K}_{0.10})\text{TiO}_3$  and  $(\text{Na,K})\text{NbO}_3$ -based materials are being researched. [73] [76] [77] [78]. For instance, it has been suggested that a synergistic design approach flattens the Gibbs free energy density profile, frequently by allowing several phases to coexist, to improve piezoelectricity in lead-free materials [75].

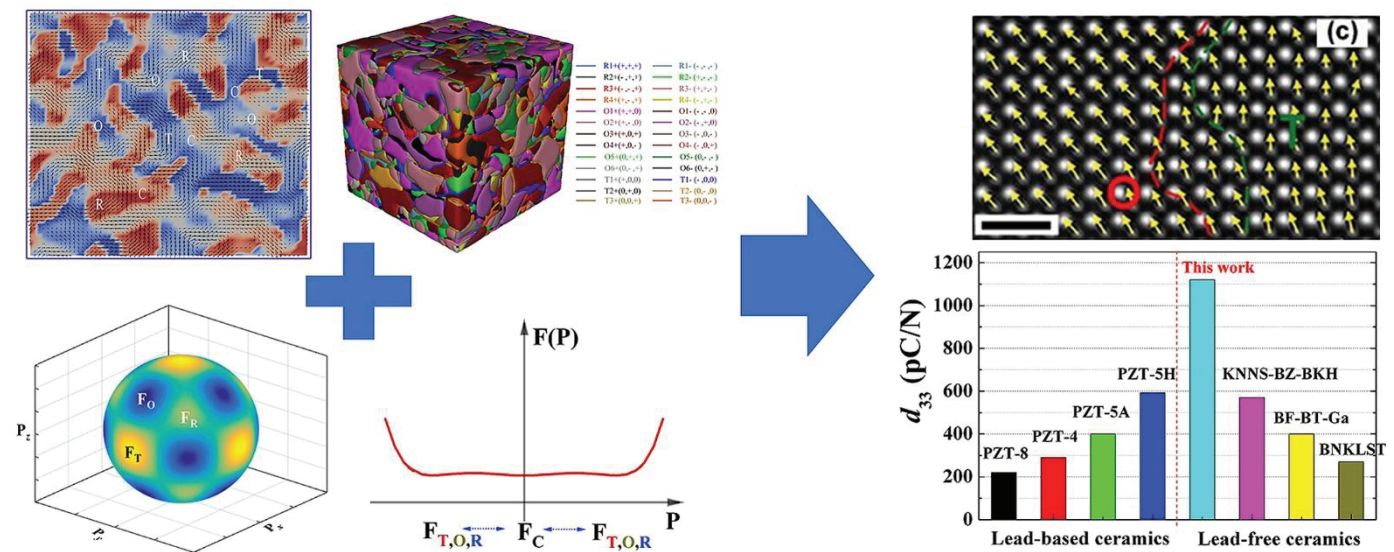


FIGURE 4. Synergistic Design Strategy for Lead-Free Piezoelectric [75]

2. **Porous and composite structures:** PZT can improve piezoelectric energy harvesting performance and give wearable devices flexibility when incorporated into porous structures or composites with polymers like PVDF and CNTs [79] [80]. By combining the low acoustic impedance of polymers with the strong piezoelectric activity of ceramics, these composites can increase efficiently.

3. **Domain engineering and compositional modification:** new material systems and strategies involving lead vacancies, morphotropic phase boundaries, and specific dopants (e.g., Sm, Nb,  $\text{Fe}_2\text{O}_3$ ,  $\text{BiYO}_3$ ) are being investigated for PZT-based ceramics in order to simultaneously achieve

superior temperature stability, broad usage temperature ranges, and high piezoelectricity [63] [64] [81] [82].

4. **High-temperature specific materials:**  $\text{Bi}_{12}\text{SiO}_{20}$  (BSO) is one alternative single crystal that is being researched for high-temperature piezoelectric vibration sensors. It has been shown that crystal cuts optimized for low piezoelectric losses and high longitudinal piezoelectric coefficients are possible [9]. Furthermore, ceramics based on  $\text{CaBi}_2\text{Nb}_2\text{O}_9$  are being developed to attain both good resistivity and large piezoelectric coefficients at high temperatures [83].

Ultimately, even though lead-based and lead-free piezoelectric materials have advanced significantly, it is still

very difficult to fully match PZT's high output and YCOB's thermal robustness at the same time [53] [54]. The ideal material selection is determined by the particular application, taking into account environmental factors, mechanical robustness, thermal stability, and high sensitivity [52] [53] [55].

### Application and Future Directions

High-temperature piezoelectric sensors are essential for accurate monitoring of dynamic mechanical conditions in critical equipment across aerospace, automotive, nuclear power, and energy generation systems [84] [85] [9] [86]. For instance, piezoelectric ultrasonic transducers find applications in non-destructive evaluation (NDE), medical imaging, and petroleum exploration, but require high-performance materials that can withstand elevated temperatures [17]. Dynamic pressure sensors, which measure pressure changes in liquids or gases at high temperatures (above 700 °C), are also being developed using materials like AlN [87].

The requirement for durable materials is further highlighted by the difficulties in creating piezoelectric devices for space conditions, which are characterized by intense radiation and temperatures [88]. Additionally, piezoelectric ceramic sensors are used in traffic Weighing-In-Motion (WIM) systems, where it is essential that they maintain a steady output in a range of temperature conditions [89].

Insufficient cross-material comparison studies under realistic thermal cycling, a lack of unified thermal aging models, and a restricted integration of thermal compensation mechanisms in device design are some of the existing shortcomings that future research attempts to solve [52]. Two important areas of research to improve the resilience and dependability of high-temperature piezoelectric devices are enhanced electrode metallization and multi-physics modeling (thermo-electro-mechanical coupling). Enabling the creation of more durable, high-performing, and ecologically friendly piezoelectric devices for demanding technological applications is the ultimate objective.

## VIII. CONCLUSION

Piezoelectric materials like PZT, LGS, LiNbO<sub>3</sub>, and YCOB have been found to have highly varying temperature-dependent characteristics based on their unique crystal structures and piezoelectric mechanisms. Ferroelectric PZT has been found to have highly favorable piezoelectric coefficients with a strong positive effect on d<sub>33</sub> and electromechanical coupling factors as the Curie temperature is approached due to increased domain wall mobility. However, this is offset by a strong negative effect due to abrupt degradation beyond the TCT<sub>CTC</sub> temperature due to thermal depolarization and a ferroelectric-paraelectric phase transition, which severely restricts its use in high-temperature environments.

Non-ferroelectric single crystals like LGS, LiNbO<sub>3</sub>, and YCOB do not have phase transitions in their working temperature ranges, leading to gradual degradation of

piezoelectric properties. LGS and LiNbO<sub>3</sub> have stable properties in wide temperature ranges, with LGS having excellent stability up to 900 °C and LiNbO<sub>3</sub> having a high Curie temperature with operational difficulties due to increased electrical conductivity at high temperatures. YCOB has excellent high-temperature stability with functional piezoelectric properties up to 1000 °C and beyond, although with very low piezoelectric signals.

These materials, therefore, demonstrate a fundamental trade-off between high sensitivity and poor thermal stability in ferroelectric ceramics and high thermal stability with low signal output in non-ferroelectric single crystals. This, therefore, leads to a material selection dilemma for piezoelectric sensors and actuators in high-temperature environments.

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