Rare-Earth Doped Piezoelectric Materials

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Abstract
The mechanical industry, medical imaging, electronic information, ultrasonic devices, and other fields use piezoelectric materials including ceramics, crystals, and films extensively. Generally, improving the electric characteristics of piezoelectric materials involved adding oxide dopants or introducing new solid solutions to produce the morphotropic phase boundary. Due to their multifunctional performances combining piezoelectric and photoluminescence properties, rare-earth element doped piezoelectric materials have received a lot of attention recently. These materials have potential applications in the fields of optoelectronics, electronics, automatic control, machinery, and ultrasonics. On rare-earth doped piezoelectric ceramics, single crystals, and films, a summary of recent research and viewpoints was given.

Keywords: Rare-Earth, Piezoelectric Materials, Lanthanide

Introduction
Rare-earth (RE) elements have exceptional optical, electrical, magnetic, and nuclear capabilities and rich structures and energy levels, which have been used to improve the properties of functional materials and widen their applications. Due to their capacity for the reciprocal conversion of mechanical and electric energy, piezoelectric materials—one of the key functional materials—play a vital role in the disciplines of medicine, acoustics, machinery, and electronics. Piezoelectric materials' compositions, microstructures, and lattice flaws like oxygen vacancies all have an impact on how well they conduct electricity.
As a result, substantial research has been done to improve the characteristics of piezoelectric materials by adding additional solid solutions or oxide dopants. Due to their distinct ionic radius and differing chemical valence, the rare-earth ion doping may replace the original ions and result in the development of vacancies, which may influence the electric characteristics by distorting the crystal lattices. The family of rare earth elements consists of 17 members, including 15 lanthanides (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu), Sc, and Y. According to the described works, Figure 1 depicts the rare-earth element doped piezoelectric materials and their associated characteristics.
Due to particular rare-earth ions very lengthy metastable states and ladder-shaped 4f energy level, some piezoelectric materials with specific rare-earth doping can display blatant photoluminescence features. The primary energy flow directions during lanthanide luminescence sensitization. After absorbing energy, the electrons in the singlet (S0) ground state leap to the singlet (S1) excited state. Additionally, the excitation energy of the (S1) state is first transmitted by intersystem crossing to the triplet state (T) and then to the 4f states. Finally, it is possible to record the appropriate lanthanide ion emission [1].

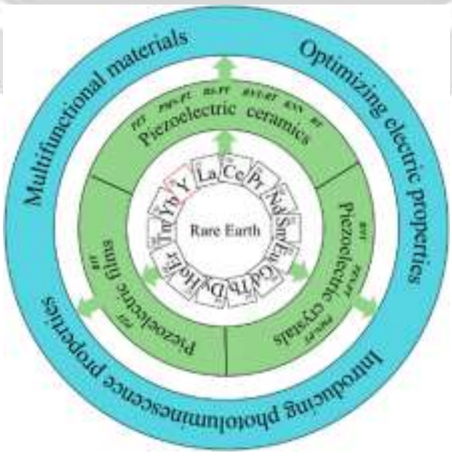

Figure 1. Relationship between the rare Earth, piezoelectric materials, and properties.

Researchers from China, the United States, and Australia have discovered that the rare-earth element samarium may significantly enhance the performance of piezoelectric crystals. The team details its research and the effectiveness of the changed crystals in their study that was published in the journal Science. Recently, piezoelectric devices have gained a lot of attention as scientists investigated if they might be used to generate energy from unorthodox sources, such as the movement of people's shoes or the bending of clothing when attached to them. Because they can transform mechanical vibrations into electrical signals, they are practical to utilize.

They also appear in less well-known sensors, including those found in ultrasound equipment. The best material for the purpose thus far has been a perovskite oxide crystal known as PMN-PT. A piezoelectric device requires a substance inside of it that responds to vibrations in order to function. Researchers have been exploring for new materials and strategies to enhance PMN-PT crystal performance in an effort to increase the performance of piezoelectric devices. In this new endeavor, the researchers opted for the latter strategy and assert that they were able to quadruple its performance.

Samarium was added to the mixture when PMN-PT was developed (using a modified Bridgman technique), and the researchers discovered that this produced a PMN-PT crystal that was far better at producing an electric charge. More specifically, they discovered that all that was required was the addition of one samarium atom for every 1000 parent crystals. They point out that the typical pC/N generated by standard PMN-PT crystals ranges from 1200 to 2500. The improved version can produce 3400 to 4100 pC/N, according to testing [2].

The scientists also discovered that adding samarium to the crystals increased their heterogeneity while generally improving other crystal characteristics. Additionally, doing so allowed the crystals to expand, which may have led to cost savings. According to the researchers, sensors with enhanced crystals would have more sensitivity and higher resolution. They would be more effective as well. Due to their exceptional electric and luminescent performance, rare-earth ion doped piezoelectric materials have garnered a lot of attention; nevertheless, there aren't many evaluations available in this area of study. The majority of studies concentrate on a certain kind of piezoelectric material or fabrication technique.

The bulk materials for piezoelectric perovskites without lead. In lead-free materials, the links between phase boundaries, domain topologies, and electrical characteristics were examined. The development of lead-free, textured, piezoelectric ceramics with improved piezoelectricity. the development of additively manufactured piezoelectric materials. It is reviewed and explained how rare-earth doping affects the electrical and optical characteristics of piezoelectric ceramics, crystals, and films [3-5].

Electrical Properties

The electrical and optical properties of the piezoelectric materials may be dramatically impacted by rare-earth doping. Among the rare-earth doped ceramics described, Sm doped PMN-PT ceramics were found to have the greatest piezoelectric constants (1510 pC/N), which may be related to the insertion of aliovalent Sm3+ dopant on the A-site of the perovskite structure with a comparable ion radius. The lanthanide rare Earth ion Sm^{3+} is the smallest of all, and it may entirely fill the A-site of the PMN-PT solid solution before replacing the Pb ion.

The local structural disorder is mostly to blame for the considerable impact Sm doping PMN-PT has on its electrical characteristics. Additionally, PMN-PT ceramics that have been doped with Eu^{3+} show outstanding piezoelectric characteristics. It has also been demonstrated that rare Earth ions with an ionic radius similar to the A-site ions of the perovskite ferroelectric materials may be employed to increase piezoelectric performance since Eu^{3+} and Sm^{3+} ions have similar ionic radii and valence states. However, Sm doping decreased PMN-PT's 89 °C Curie temperature, which would restrict its use in high temperature applications. For improving piezoelectric constant, RE-doped lead-based and lead-free-based materials with comparatively high Curie temperatures were investigated. In order to increase performances by controlling the local structural disorder of piezoelectric materials with a low Curie temperature, additional study will be required in the future. As a result, it is challenging to generate samples with both an outstanding piezoelectric constant and a high Curie temperature [6-8].

Optical Properties

There was discussion of the optical performances in addition to the electric qualities. One advantage of rare-earth doping is the ability to produce translucent samples with high transmittance. Some piezoelectric materials' transmittance when doped with rare earth elements. It has been discovered that in a particular wavelength range, the transparency of the mentioned piezoelectric materials approaches 60%. The major element impacting transmittance in ceramics is the grain boundary scattering loss. Rare-earth elements may dissolve uniformly into the perovskite lattice without going over the solubility limit, improving the ceramic's density, transparency, and other qualities.

However, if the rare-earth concentration rises, too many rare-earth ions may gather at the grain borders, which would cause Rayleigh scattering loss since the grain boundaries and matrix have different refractive indices. Additionally, crystal flaws, ion vacancies, and poor crystallinity caused by defects all have the potential to reduce transparency. The development of multifunctional optical devices may thus be considerably aided by optimizing these parameters to further increase the transparency of rare-earth doped piezoelectric materials. On

the other hand, because of the rare-earth ions' ladder-shaped 4f energy level, rare-earth doped piezoelectric materials can produce a distinctive emission spectrum after being stimulated. The rare-earth doped materials can produce some acute down-conversion emissions when stimulated between 300 and 500 nm. Red (617 nm) and orange (563 nm) emissions are typically acquired by Eu^{3+} doping and Sm^{3+} doping, respectively. Pr^{3+} doping can produce green emissions at 545 nm and red emissions at 617 nm. Additionally, under the excitation of 980 nm, certain strong up-conversion emissions can be produced in rare-earth doped materials.
Er^{3+} doped samples exhibit green (500 nm) and red (670 nm) emissions, whereas Tm^{3+}/Yb^{3+} co-doped samples exhibit blue (480 nm) and red (652 nm) emissions. Pr^{3+}/Yb^{3+} co-doped materials produced green (529 nm), orange (623 nm) and red (649 nm) emissions. The application possibilities for piezoelectric materials can be greatly increased by the newly disclosed photoluminescence performance.
In particular, the materials' ability to convert long-wavelength light, which is invisible to the human eye, into visible light will have significant applications in the fields of information science and technology, including laser, display, and anti-counterfeiting. It will also open up new research areas in biomedicine or photoacoustic multi-mode images. The electrical performance and luminescent performance of the rare-earth doped piezoelectric materials are, however, greatly influenced by a number of factors, such as doping concentration, sintering temperature, chemical composition, and preparation technique. The development of multifunctional materials and devices greatly depends on adjusting these parameters to attain both good electrical and optical capabilities [9, 10].

Conclusions

Rare-earth doping has a major impact on the electric and photoluminescence characteristics of piezoelectric materials. Therefore, rare-earth doping is a useful technique for creating materials with many functions. The following research and development trends are anticipated for rare-earth doped piezoelectric materials. It is vital to produce environmentally friendly, high-performing lead-free piezoelectric materials to replace conventional lead-based ceramics in order to meet the demands of environmental protection and the sustainable growth of human civilization. To attain outstanding electric qualities, the future development trend is to locate the right lead-free piezoelectric materials and the right rare-earth oxide concentration. Due to its excellent electric characteristics, rare-earth doped piezoelectric single crystals outperform conventional piezoelectric ceramics in applications requiring high energy conversion efficiency and huge strains. In order to address the needs of ever-more-demanding applications, single crystal growth conditions and characteristics will be optimised in future development. A sort of integrated multifunctional optical-mechanical-electric material is the rare-earth doped piezoelectric material. This kind of novel material provides significant benefits in sensing, detecting, and information transmission because of the special features of rare-earth ions and piezoelectric materials.

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