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Ferroelectric Sensor Materials: A short review

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Abstract

Among many plausible sensor applications, ferroelectric materials provide a broad variety of options. Miniaturization, higher resolution and accuracy, use in harsh environments, advanced processing techniques, and better materials are the directions in which the industry is heading right now. The rapid expanding category of ferroelectric sensors encompasses a wide variety of devices that utilize piezoelectric, electro-strictive, pyroelectric, dielectric, and conduction phenomena. It is used in a wide variety of contexts including manufacturing, transportation, aircraft, medicine, communications, and environmental tracking. In this brief overview, the physical phenomena that underlie the most common types of ferroelectric sensors like the infrared sensors, pressure sensors, ultrasonic transducers for medical imaging and material testing, and a wide range of devices based on the exponential temperature dependence of resistivity are discussed. Bulk ceramics, multi-layer ceramics, single crystals, polymersand ceramic-polymer composites have been used as the sensor materials.

Keywords: Ferroelectric sensor, IR sensor, Transducer, Thermistor, Multi-layer ceramics, Single crystal

Introduction

In order to detect changes in pressure, temperature, or mechanical strain, ferroelectric sensors make use of the unique features of ferroelectric materials [1-3]. Due to their novel characteristics and broad range possible applications, these sensors have attracted a lot of interest in recent years [4-6]. The extreme sensitivity of ferroelectric sensors provides one of its most significant advantages. Since the polarization of ferroelectric materials may shift in response to even minute modifications in the physical stimulus that is provided, so extremely accurate measurements are possible with these materials[7]. In addition, the response time of these sensors is extremely quick, which qualifies them for the usage in applications that need high levels of speed.Further, the wide working temperature range of ferroelectric sensors is another benefit[8]. They are appropriate for the use in tough situations since they can operate in a wide range of temperatures from cryogenic to high heat. Pressure sensing, temperature sensing, and mechanical strain sensing are just a few of the uses for ferroelectric sensors[9]. They have been used to gauge tyre pressure in the automotive sector and aircraft wing deflection in the aerospace sector. They have also been used to monitor blood pressure in the medical sector and acceleration and vibration in the industrial sector[10-11]. In addition to their numerous benefits, ferroelectric sensors have certain

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drawbacks. The lack of readily available appropriate ferroelectric materials is one of the major problems. In addition, compared to other kinds of sensors, the price of these sensors are relatively expensive. Ferroelectric sensors are an emerging technology with a wide range of possible uses. They may be used in a number of applications for their high sensitivity, quick response time, and wide operating temperature range[12]. So, further study is required to increase the accessibility of appropriate ferroelectric materials. Ferroelectric sensors have found widespread use in pressure sensing applications. Measurements of pressure are essential in several commercial, medical, and aeronautical fields[13-17]. They have a high degree of precision in measuring pressure and may provide continuous, up-to-the-minute data on the system's health[18].Innovative ferroelectric materials and enhanced sensor design have been the focus of recent studies with an objective to increase the performance of ferroelectric devices. For instance, the lead-free ferroelectric materials like $(K,Na)NbO_3$ and $BaTiO_3$ have been the subject of investigation for pressure sensing applications[19]. Traditional ferroelectric materials containing lead have been phased out because of their toxicity, and these materials may be able to take their place. The use of ferroelectric thin films integrated on silicon substrates is a unique approach that has been created to give a low-cost, compact, and high-performance pressure sensor recently[20]. The improvement of their performance and the introduction of new uses have resulted from the discovery of innovative ferroelectric materials and methodologies for sensor design [21-23]. Further investigation and development for improving the performance and decreasing the prices of ferroelectric sensors is anticipated to further boost their application in the future. In this short review, we will first go over the physics behind the most common types of ferroelectric sensors and the materials used in them. We will then move on to the most common types of other sensors, such as infrared sensors, pressure sensors, ultrasonic transducers for medical imaging and material testing, and a wide range of devices based on the exponential temperature dependence of resistivity. The area of sensor devices is discussed with an emphasis on recent advances and prospective new discoveries.

Major types of types ferroelectric sensors and Infrared sensors

Infrared (IR) sensors have become an indispensable tool in various fields including thermal imaging, remote sensing, and gas detection. Due to their high sensitivity, rapid response, and stability, ferroelectric IR sensors have stood out among the many varieties of IR sensors [24]. The ferroelectric materials have their fast polarization and readily altered between two distinct states by the application of an electric field. For this reason, capacitors, memory, and sensors all benefit by using ferroelectric materials [25]. Ferroelectric IR sensors are used in thermal imaging to identify the temperature distribution of an item by measuring the intensity of IR radiation produced by the object [26]. Ferroelectric IR sensors are used in gas sensing to identify the presence of gas molecules by measuring the absorption of IR radiation by the gas, and also are used in remote sensing to detect and quantify the IR radiation emitted by astronomical objects such as stars, planets, and galaxies [27]. Ferroelectric infrared (IR) sensors provide a number of benefits over other types of IR sensors, including high sensitivity, rapid response, and stability [28]. These characteristics make the ferroelectric IR sensors suitable for a range of applications, such as thermal imaging, gas detection, and remote sensing. Ferroelectric infrared (IR) sensors have a bright future, with continuous research focused at enhancing their performance and broadening their applications.

Pressure Sensor

A ferroelectric pressure sensor is a type of pressure sensor that measures pressure using the piezoelectric capabilities of ferroelectric materials [29]. The sensor operates by applying pressure to a ferroelectric material, creating a change in the material's polarization and so producing a quantifiable voltage output. Since the voltage output is proportional to the applied pressure, precise and accurate measurementsare possible. Automotive systems, industrial process control, medical devices, and aerospace systems are just a few of the uses of ferroelectric pressure sensors [13]. They are well-known for their excellent sensitivity, stability, and precision, as well as their resistance to severe conditions and high temperatures.

Ultrasonic Transducers

Ultrasonic transducers are devices that transform high-frequency sound waves into electrical energy and vice versa. They are utilized in different sectors, including medical, engineering, and industrial processes[30]. Ultrasonic transducers are the inspection tools that may be used in a wide variety of applications because of its versatility and precision. Even though they have several drawbacks, several industries nevertheless find them to be a useful non-destructive tool with great precision [31]. The advantages of ultrasonic transducers may be highlighted as follows:

- Ultrasonic transducers can investigate the internal structure of a material, locate fractures, and measure thickness with extreme accuracy.
- Ultrasonic transducers produce high-frequency sound waves that go through the substance being evaluated without causing any harm.
- Ultrasonic transducers come in many different frequencies, which makes them useful for different tasks.
- Ultrasonic transducers provide a thorough inspection due to the capacity of its sound waves to go through the materials.
- On the other hand, the main discrepancies of ultrasonic transducers are constrained by the acoustic characteristics of the substance they are evaluating, making it more challenging to check specific materials. When compared to other inspection techniques, the cost of the ultrasonic transducers rather expensive[32]. Ultrasonic transducer setup is difficult and complicated, requiring specific skills and tools.

Devices based on the exponential temperature dependence of resistivity

Thermistors are the type of devices that are used extensively in a broad variety of applications because of their exponential temperature dependency of resistivity[33]. Because of the temperature dependent resistance variation, a thermistor is particularly well-suited for the use in temperature sensing and regulation applications. Thermistors are widely used for temperature monitoring because of their low cost, rapid response time, and active response in broad temperature range. Thermistors are commonly used in car engines, HVAC systems, and consumer electronics[34]. Because of the poor precision of thermistors, which is one of its drawbacks, these temperature sensing devices are typically employed in conjunction with one or more additional temperature detecting devices. In general, thermistors provide a solution that is both dependable and cost-effective for applications involving temperature sensing and control.

Sensor Materials

Bulk Ceramics

Ferroelectric materials are known as the ferroelectric ceramics that are well-suited for the use in a wide range of sensing applications due to their high dielectric constant, high piezoelectric coefficient, high mechanical quality factor, and variety of forms and sizes [35]. For a number of reasons including their potential as ferroelectric sensor materials, bulk ceramics have gained a lot of interest in recent years. With a variety of uses as ferroelectric sensors, bulk ceramics are a significant class of ferroelectric materials. Therefore, bulk ceramics will continue to be essential in the creation of cutting-edge ferroelectric sensors for a variety of applications [36].Some of the bulk ceramics useful in sensor devices are:

- Lead ZirconateTitanate (PZT): Because of its high piezoelectric coefficient and dielectric constant, PZT is a popular bulk ceramic material for ferroelectric sensors[37].
- Barium Titanate ($BaTiO_3$): As a result of its strong piezoelectric coefficient and high dielectric constant, $BaTiO_3$ is a widely used bulk ceramic material in sensing applications[38].
- Lithium Niobate ($LiNbO_3$): Because of its high piezoelectric coefficient, the bulk ceramic $LiNbO_3$ is well-suited for the use in a wide variety of sensing applications including pressure and force detection[39].

Bulk ceramics are most beneficial for sensing applications, since the mechanical deformation of the material is directly proportional to the electrical output, sensing applications, such as pressure and force sensors find the bulk ceramics to be an excellent choice due to their high piezoelectric coefficients. Because of their high dielectric constant, bulk ceramics have a large capacitance, which makes them suitable in capacitive sensing applications, in which the sensor's capacitance varies in relation to the variations in the dielectric constant of the surrounding environment [40]. As a result of their high mechanical quality factor, bulk ceramics are well-suited for temperature-sensitive sensing applications, since their mechanical response is constant throughout a broad temperature range. Because of its malleability, bulk ceramics may be fashioned into micro- and nano-sensors of varying sizes and forms[41].

Multi-layer Ceramics

As the novel ferroelectric ceramics, the multi-layer ceramics are gaining interest as a potential solution for high-performance sensor applications[42]. Focusing on the production methods, sensing mechanisms, and performance assessment, several studies examine the current developments in the field of multi-layer ceramics as ferroelectric sensor materials. Sensors like pressure, humidity, temperature, and acceleration sensors may all benefit from the multi-layer ceramics' exceptional and adjustable electrical, mechanical, and thermal capabilities[43, 44]. The optimization of the structure of multi-layer ceramics, the enhancement of their sensing capabilities, and the creation of novel applications have all been emphasized by several research groups as present difficulties and future prospects in this multi-layer ceramics. Multi-layer ceramics, which are made up of alternating layers of different ferroelectric materials, can display distinctive and adjustable electrical, mechanical, and thermal characteristics, making them excellent for a wide range of sensors. Pulsed laser deposition (PLD), sol-gel, and solid-state reaction methods are just a few of the manufacturing techniques that may be used to produce multi-layer ceramics[45]. Using PLD, the multilayer ceramics of excellent crystallinity and purity may be grown by precisely controlling the layer thickness and composition. Sol-gel is a low-cost method for synthesizing the multi-layer ceramics with homogenous and nanostructured layers. The synthesis of multilayer ceramics with large grain size and good mechanical stability is possible via the use of the straight-forward process of solid-state reaction.

Interaction between ferroelectric layers and an external stimulus is credited as the sensing mechanism of multi-layer ceramics. As a result of the stimulation, the spontaneous polarization of the ferroelectric layers may shift, which in turn may alter the multi-layer ceramics' electrical, mechanical, or thermal characteristics. As an illustration, external pressure may alter the capacitance of multi-layer ceramics used in pressure sensors by altering the spontaneous polarization of the ferroelectric layers. The capacitance of humidity sensors is sensitive to changes in the dielectric constant of the multi-layer ceramics used in the sensors, which can be influenced by the high relative humidity. Sensitivity, stability, linearity, repeatability, and reaction time are only few of the variables that may be used to assess multi-layer ceramics' efficacy as ferroelectric sensor materials[46]. Changes in capacitance, dielectric constant, or polarization are all good indicators of how sensitive multilayer ceramics are to external stimuli.

Single Crystals

As a type of ferroelectric material, single crystals have improved electrical, mechanical, and thermal properties [47]. There are several positive aspects of using single crystals as ferroelectric sensor materials. When it comes to ferroelectric sensors, single crystals have various benefits over other materials. Firstly, single crystals have a stronger polarization compared to polycrystalline or amorphous materials, which leads to higher sensitivity in ferroelectric sensors. In addition, single crystals are superior to polycrystalline materials for high-precision measurements because they generate less electrical noise [48]. In addition, single crystals are superior to polycrystalline materials in terms of their mechanical strength and thermal stability, which further make them a good choice for usage in extreme conditions. Despite these benefits, single crystals have several disadvantages. Firstly, they are more challenging and costly to manufacture as compared to the polycrystalline or amorphous materials. Furthermore, the grain sizes of single crystals are often smaller, making them more prone to flaws, which can lead to decreased reliability and performance [49]. In order to make single crystals more widely accessible for the usage in a variety of applications, additional study is needed to solve their constraints, such as their high cost and sensitivity to faults.

Polymers

Polymer sensor materials have recently been recognized as a potentially useful tool in a variety of sensing contexts [50]. For example, these materials' special features make them useful in gas sensing, biosensing, and environmental monitoring. Compared to more conventional sensing materials, polymer sensors have many benefits, including low cost, simple manufacture, and adjustable characteristics. It is possible to create polymer sensor materials by a number of different routes, including solution-based techniques, electrospinning, and molecular imprinting[51]. With a solution-based technique, a polymer and sensing agent are dissolved in a solvent and then deposited onto a substrate. Electrospinning is a technique for making polymer fibers that may be used as a sensing material, and it employs an electric field. To do molecular imprinting, a template molecule must be constructed, after which a polymer with desired properties can be synthesized. Sensor materials made from polymers vary in their characteristics based on the polymer and the synthetic route taken to create them. However, high sensitivity, selectivity, and stability are all characteristics shared by these materials [52]. Due to their favorable characteristics, they may be implemented in sensing applications where the ability to detect minute changes in the surrounding environment is essential. Also, the mechanical characteristics of polymer sensor materials are well-suited for application in flexible and wearable sensors. Gas sensing, chemical sensing, and biosensing are just few of the many uses for polymer sensor materials. Carbon monoxide, nitrogen oxide, and hydrogen may all be detected by gas sensing. Chemicals like pesticides, explosives, and illegal narcotics may all be detected by chemical sensing. The detection of proteins, DNA, and cells is part of biosensing [53].

Ceramic-polymer composites

Due to their remarkable detecting qualities and prospective applications in a wide range of sectors, including environmental monitoring, biomedical diagnostics, and industrial process control, ceramic-polymer composite sensors have attracted considerable interest in recent years. The ceramic-polymer composite sensors take use of the best features of both ceramics and polymers to generate a material with excellent sensitivity, selectivity, and stability towards a wide range of analytes [54]. Here, we take a look at what scientists know about ceramic-polymer composite sensors right now, from how they're made to what kinds of uses have been found for them. Different methods such as sol-gel, electrospinning, and dip-coating can be used to create ceramic-polymer composite sensors. In the sol-gel method, a gel is first created from a precursor solution before being heated to turn the material into a ceramic. Electrospinning is a method for producing polymer fibers by subjecting a polymer solution to an electric field [55]. On applying a uniform coating of ceramic or polymer to a substrate, the dip-coating method is commonly employed. The manufacturing method used for a given sensor will be determined by its final use and the qualities it must possess. The fabrication of ceramic-polymer composite sensors relies heavily on the material choices made during the design phase. Titanium dioxide (TiO_2), zinc oxide (ZnO), and tungsten oxide (WO_3) are common ceramic materials utilized in these sensors due to their large surface area and gas-sensing characteristics [56]. Most of these sensors are made from polymer materials like polyethylene glycol (PEG), polystyrene (PS), or polyvinyl alcohol (PVA) because of their adaptability, low cost, and ease of processing. Enhanced sensor qualities, such as sensitivity and selectivity, are possible thanks to the use of composite sensors made of ceramics and polymers. Multiple types of sensing, including gas sensing, strain detecting, and temperature sensing, may benefit from the use of ceramic-polymer composite sensors. Carbon monoxide (CO), nitrogen dioxide (NO_2), and methane (CH_4) are just some of the gases that gas sensors can detect and measure [57]. Strain sensing is beneficial for monitoring structural health and finding fractures or deformations in buildings and bridges because it utilizes sensors that can detect changes in mechanical strain or deformation in a material. When it comes to temperature sensing, the sensors' ability to monitor temperature fluctuations makes them a valuable tool in a variety of manufacturing processes that necessitate tightly regulated temperatures. As a very active research subject, the creation of ceramic-polymer composite sensors has several promising future avenues to explore. The creation of sensors to detect volatile organic compounds (VOCs), which are hazardous to human health and the environment, is an area of research that has garnered considerable attention. Ceramic-polymer composite sensors are being integrated into wearable devices for health monitoring and illness detection, which is another area of interest. Finally, industrial and aerospace applications have an interest in the advancement of sensors that can function under extreme conditions [58].

Conclusion

Ferroelectric materials offer a wide range of potential uses as sensors. The current trends in the sector are towards miniaturization, increased resolution and precision, application in difficult settings, cutting-edge processing processes, and improved materials. Diverse sensors based on piezoelectric, electro-strictive, pyroelectric, dielectric, and conduction phenomena are included in the rapidly growing area of ferroelectric sensors. The applications of this technology are vast, spanning industries as diverse as automobiles, aeroplanes, medicine, communications, and environmental monitoring. Polymer sensor materials are versatile and functional. Sensitivity, selectivity, and stability make these materials ideal for sensing. Solution casting, electrospinning, and layer-by-layer assembly can synthesize polymer sensor materials. These materials are also used for biosensing. As polymer sensor materials are studied, their synthesis, properties, and usage may improve. Ceramic-polymer composite sensors are a promising new class of materials due to their excellent sensing and wide range of applications by the use of the right building approach. Ceramic-polymer composite sensors are helpful for gas, strain, and temperature sensing, according to recent investigations. Future research should focus on VOC sensors, wearable health monitors, and extreme-condition sensors.

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