Smart Ferroelectric Materials for Sensors and Mechatronic Device Applications

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Abstract --- **Ferroelectric single crystals, ceramics, polymers and composites can convert changes in mechanical and thermal energies into electrical signals as well as exhibiting the converse effect. This dual functional ability enables them to sense changes in their environment and actuate a desired response, which allow them to be regarded as smart (or intelligent) materials. The present paper reviews the piezoelectric and pyroelectric properties, poling behavior and transducer properties of selected numbers of ferroelectric materials studied in our laboratory. These include PMN-PT single crystals, ceramic/polymer 1-3 composites, 0-3 nanocomposites and ferroelectric films prepared by various methods. The uses of these materials in sensor and mechatronic device applications are also discussed.**

I. Introduction

The concept of creating a form of materials and structures by providing the necessary functions of sensing, actuating, control and intelligence similar to a living being is the motivation for studying "smart materials". [1,2] Smart materials are functional materials for a variety of engineering applications and usually are part of some smart systems. For example, smart medical systems treating diabetes with blood sugar sensors and insulin delivery pumps; smart airplane wings achieving greater fuel efficiency by altering their shape in response to air pressure and flying speed; smart tennis rackets having rapid internal adjustments for overhead smashes and delicate drop shots and smart water purification systems for sensing and removing noxious pollutants. Many smart systems have been developed for automobiles, and there are many more to come.

Smart materials can be conveniently subdivided into passively smart materials that respond to external change without assistance, and actively smart materials that utilize a feedback loop enabling them to both recognize the change and initiate an appropriate response through an actuator circuit. [1] Barium titanate PTCR (positive temperature coefficient of resistance) thermistors are passively smart materials capable of self-protection against over-current. Actively smart materials include vibration-damping systems for outer-space platforms and electrically-controlled automobile suspension systems.

In this paper, emphasis is placed on introducing the various smart materials studied in our laboratory which include ferroelectric single crystals of lead magnesium niobate-lead titanate (PMN-PT), ceramic/polymer 1-3 composites, 0-3 nanocomposites and ferroelectric films prepared by various methods. On-going projects on the uses of these materials in sensor and mechatronic device applications are also presented.

II. PMN-PT Single Crystals

The superior piezoelectric properties of relaxor-based ferroelectric single crystals such as $Pb(Zn_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PZN-PT) and $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PMN-PT) have attracted worldwide attention.[3,4] These crystals have ultrahigh piezoelectric coefficient (d_{33} > 1800 pC/N) and electromechanical coupling coefficient (k_{33} > 0.9), (for comparison, the commonly used piezoceramic lead zirconate titanate (PZT) has d_{33} ~300-500 pC/N and k_{33} ~ 0.6), and strain levels up to 0.5% with minimal hysteresis. It is thus believed that they will become the new generation materials for transducers and actuators. We have a collaborative project with the Shanghai Institute of Ceramics, Chinese Academy of Sciences (SICCAS) on PMN-PT single crystals in which

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the crystals provided by SICCAS are characterized and then used in transducer developments. High frequency medical transducer for intravascular ultrasonography (IVUS) is one type of transducer under investigation. The crystal transducers will be developed jointly with a company in USA to be used in their IVUS systems. We will also grow these crystals in our laboratory and study the structural-property relationship using TEM and SEM. These crystals are also very promising actuator materials to be incorporated into various smart systems for industrial applications.

III. CERAMIC/POLYMER 1-3 COMPOSITES

1-3 composites consisting of piezoelectric ceramic rods embedded in a polymer matrix (Fig. 1) have found many fruitful applications in medical and underwater ultrasound.[5,6] Compared to ceramics, they have much lower acoustic impedance, hence energy can couple better to human tissue and water. They have higher hydrostatic d_h coefficient for underwater hydrophone application and good acoustic isolation between elements when used in ultrasonic arrays for medical imaging. Analogous to a photonic bandgap material, 1-3 composites have stopband resonances and if designed properly, acoustic waves will not be able to propagate in the plane of a composite disk and all the input energy can only radiate in a forward direction, hence eliminating the artifacts caused by the planar coupling effect and enhance the efficiency of the transducer. We have studied the resonance characteristics of 1-3 composites and are designing ultrasonic transducers using these materials. [7,8]

Recently, 1-3 composites have found useful applications in ultrasonic wire bonding. By using these materials, spurious resonance modes are suppressed and the thickness mode resonance has lower Q, which improves the stability of the transducer during bonding operations. [9] It has also opened up opportunities for designing transducers with higher frequencies or with multiple frequencies. A sensor that provides feedback signal to indicate the bond quality can also be installed [10] and a "smart" bonding transducer can be produced. Another on-going project is to fabricate high-frequency 1-3 composites for IVUS application. A sol-gel process is used to prepare piezoceramic fibres with diameter ranging from 30 μm to 50 μm. Aligned fibres are inserted into a low-viscosity epoxy enclosed in a plastic cylinder mold. By using different amounts of fibres, composites with different ceramic volume fractions are produced. The composites are then sliced into disk-shaped samples and, after poling, used in IVUS transducer fabrication.

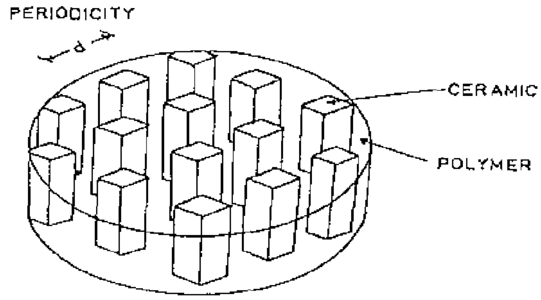

Fig. 1. Schematic diagram of ceramic/polymer 1-3 composite.

IV. CERAMIC/POLYMER 0-3 COMPOSITES

0-3 ceramic/polymer composites consisting of ceramic powder imbedded in a polymer matrix have also been studied extensively (Fig. 2). If both the ceramic and the polymer phases are ferroelectric, interesting properties are produced by poling the two phases in specific ways.[11] As the piezoelectric coefficients of the ceramic and copolymer phases have opposite signs while the pyroelectric coefficients have like signs, when both phases are poled in the same direction, the pyroelectric activity of the two phases reinforces while their piezoelectric activity partially cancels. This is very useful for pyroelectric sensor application since the low piezoelectric activity in the sensing element can minimize the vibration induced noise in the sensor. When the ceramic and polymer phases are poled in opposite directions, their piezoelectric activity reinforces while the pyroelectric activity partially cancels. This makes the 0-3 composite a suitable hydrophone material. [12] In order to use the 0-3 composites for integrated sensor applications, nanosized ceramic powders are produced by sol-gel processes and the powders are then incorporated into a polymer matrix to produce 0-3 nanocomposites. We have fabricated and characterized single-element pyroelectric sensors with different configurations and 8 × 1 integrated pyroelectric array sensors with readout electronics (Fig. 3). The performance of these sensors has proved to be superior to their counter part with ferroelectric polymer elements. We are planning to fabricate 2-dimensional integrated nanocomposite arrays in collaboration with other research groups.

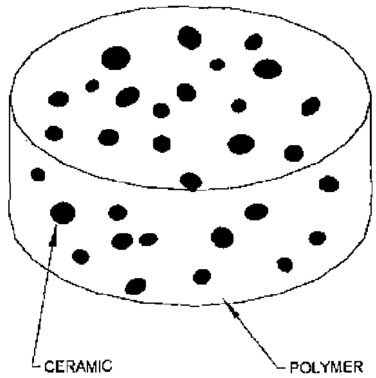

Fig. 2. Schematic diagram of ceramic/polymer 0-3 composite.

V. FERROELECTRIC FILMS

The possibility of using ferroelectric thin films (thickness ~ several tens of nm) in memory applications have attracted considerable interests and there are many reports on the production and characterization of potentially useful thin films such as lead zirconate titanate (PZT) barium strontium titanate (BST) and strontium bismuth tantalate (SBT). On the other hand, development on microelectromechanical systems (MEMS) has called for the use of thicker (thickness > 1 μm) ferroelectric films. In our laboratory, we have on-going projects on fabricating thin films by laser ablation, magnetron sputtering and by sol-gel routes. Thicker films can also be produced by a modified sol-gel process, or by doctor-blade tape casting etc. The devices under investigation include ultrasonic motors, multilayered piezoelectric transformers and actuators. Potential industrial applications have been identified and designs of these devices will be developed to cater for specific needs.

VI. CONCLUSION

This brief overview describes the research and development activities undertaken in the "Centre for Smart Materials" at the Hong Kong Polytechnic University. It is envisaged that more industrial applications will be identified and the Centre will become a resource for researchers and engineers who are interested in pursuing the applications of "Smart Materials".

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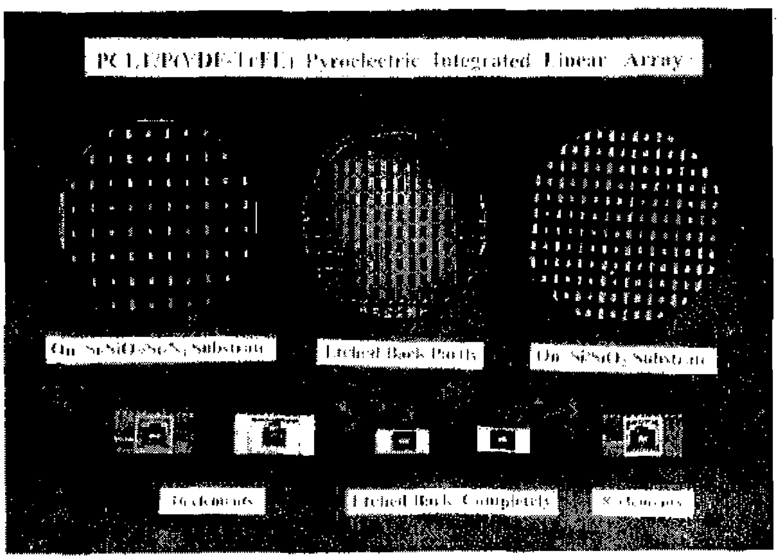

Fig. 3. PCLT/P(VDF-TrFE) pyroelectric integrated linear array.

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