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Review Article

$Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ (PMN-PT) Material for Actuator Applications

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Due to its large piezoelectric and electrostrictive responses to an applied electric field the $(1-x)Pb(Mg_{1/3}Nb_{2/3})O_3$–$xPbTiO_3$ (PMN-PT) solid solution has been widely investigated as a promising material for different actuator applications. This paper discusses some of the recent achievements in the field of PMN-PT piezoelectric and electrostrictive actuators manufactured from PMN-PT single crystals, bulk ceramics, or thick films. The functional properties of PMN-PT materials and some representative examples of the investigated PMN-PT actuator structures and their applications are reported.

1. Introduction

In recent years, the fabrication of ferroelectric materials has been extensively studied, with a particular emphasis on micro- and nanodevices. Ferroelectric and piezoelectric films are mostly based on lead oxide compounds, mainly $Pb(Zr,Ti)O_3$ (PZT) solid solutions. An alternative to PZT are the relaxor-based systems, that is, the $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (in short form PMN-PT) material. PMN-PT-based materials are characterized by a high dielectric permittivity, high piezoelectric properties, high electrostriction, and are suitable for applications in multilayer capacitors, actuators, sensors, and electro-optical devices [1, 2].

Piezoelectric and electrostrictive actuators can be used in a wide range of applications, such as micropositioners, to precisely control the positioning in low- to very-heavy-load applications, miniature ultrasonic motors, and adaptive mechanical dampers [3–5]. In mechanical systems, these actuators can generate forces or pressures under static or high-frequency conditions and so activate a suitable mechanical device [6]. Bimorph, bending-type actuators are employed for applications that require a large displacement output, that is, fluid control devices [4, 7], robotic systems [4], and swing CCD (charge-coupled device) mechanisms [7, 8]. In an optical system, an actuator can be used to move a mirror or another optical switch [9, 10], and so forth. Depending on the application, specific constructions of the piezoelectric and electrostrictive actuators are designed, mainly with the appropriate bulk piezoceramic elements. However, recently, there has been a growing interest in micro- and nanometre-sized piezoelectric and electrostrictive actuators, which are particularly attractive for advanced applications in novel research fields, such as micromechanics, robotics, and microfluidics. The active piezoelectric elements integrated into microelectromechanical systems (MEMS) or nanoelectromechanical systems (NEMS) should be a few tens of μm or nm thick, respectively. For that reason, thick- and thin-film piezoelectric actuators are considered as a promising solution for future electromechanical systems and smart-structure technologies. In this paper, the results of investigations of PMN-PT material and possible actuator applications are reviewed. In the first section, the functional properties of the PMN-PT material (single crystals, ceramics, as well as films) are discussed, and in the second section, some examples of PMN-PT actuators are summarized.

2. Functional Properties of the PMN-PT Material System

The morphotropic phase boundary (MPB) in the PMN-PT system is located close to the $x = 0.35$ composition. These MPB compositions of the PMN-PT material remain the

Table 1: The elastic and piezoelectric properties of 0.67PMN-0.33PT single crystals, 0.655PMN-0.345PT ceramics and 0.65PMN-0.35PT thick films on Al_2O_3 substrates.

Coeff.	Unit	Crystals 0.67PMN−0.33PT orientation [001] [16]	Ceramics 0.655PMN−0.345PT [36]	Thick-films 0.65PMN−0.35PT [32]	Ceramics PZT-8 [37]
s_{11}^E	10^{-12} (m^2N^{-1})	69.0	13.5	23.1	11.5
s_{33}^E	10^{-12} (m^2N^{-1})	119.6	14.5	24.8	13.5
s_{12}^E	10^{-12} (m^2N^{-1})	−11.1	−4.8	−8.20	−3.7
s_{13}^E	10^{-12} (m^2N^{-1})	−55.7	−5.9	−10.1	−4.8
s_{44}^E	10^{-12} (m^2N^{-1})	14.5	31.0	53	31.9
s_{66}^E	10^{-12} (m^2N^{-1})	15.2	36.6	62.5	35.0
d_{31}	10^{-12} ($C\,N^{-1}$)	−1338	−223	−100	−97
d_{33}	10^{-12} ($C\,N^{-1}$)	2820	480	140–190 [21, 22, 32, 38, 39]	255

subject of intense research, while the functional properties of the material depend on the phase composition. It is worth mentioning that the strong piezoelectric properties of PMN-PT solid solutions are related to the "polarization rotation" between the adjacent rhombohedral and tetragonal phases through one (or more) intermediate phase(s) of low symmetry, that is, a monoclinic (orthorhombic or triclinic) phase [11, 12]. As a consequence, the observation of a low-symmetry phase, typically a monoclinic one, may suggest strong electromechanical responses.

The PMN-PT ceramics and a single crystal of the composition on the MPB can have piezoelectric coefficients d_{33} as high as 700 pC/N [13, 14] and 1500–2800 pC/N [1, 15, 16], respectively. The commonly used poling electric fields for the PMN-PT material vary from 2 to 3.5 kV/mm [13, 14, 17–22]. On the other hand, the PMN-PT material with compositions $x = 0 - 0.1$ shows relaxor behaviour [23–25] and are known as good electrostrictive materials [26–29]. Likewise, the electrostrictive effect of the MPB compositions was also reported to be relatively high [30, 31]. Due to the large responses of the PMN-PT material to the applied electric field, this material is suitable for actuators. The response of the bending structure with PMN-PT layers to the electric field can be written as

$$S_1(E) = d_{31}E_3 + M_{31}E_3^2, \tag{1}$$

where S is the strain, E (V/m) is the electric field, d (m/V) is the piezoelectric coefficient, and M (m^2/V^2) is the electrostrictive coefficient. Therefore, the characteristics of the actuators made by using PMN-PT differ from those of the linear piezoelectric actuators (e.g., PZT actuators), mainly because of the high electrostrictive effect in the PMN-PT material. This effect takes place particularly at larger electric fields. However, under low applied el. fields, that is, lower than 1.5 kV/cm for the MPB compositions [32, 33], the major effect is the piezoelectric effect. Hence, at low el. fields, not just PZT, but also PMN-PT actuators show a linear response to the applied el. field. For some applications, the 1.5 kV/cm is a large input value, for example, in mobile devices where a voltage of only 10 V is normally used [34]. In any case, the PMN-PT material can be appropriate for bending actuators in applications operating at higher voltages, where the linearity of the response to the applied el. field is not required.

The PMN-PT material can be processed as a single crystal, a polycrystalline ceramic, and in thick- or thin-film forms, each of them having different functional properties and, therefore, appropriate for different applications. The best functional properties for actuator applications are obtained for PMN-PT single crystals. So, the possibility of processing such single crystals is an important advantage of the PMN-PT material, in contrast to PZT-based materials that were processed as polycrystalline ceramics or thick and thin films. Just recently, the first example of PZT single crystals was reported by Bokov et al. [35]. The elastic (s^E) and piezoelectric (d) coefficients of single crystals, ceramics, and thick films of the PMN-PT composition near the MPB and of the PZT ceramics are collected in Table 1.

The functional properties of the PMN-PT materials depend not only on the material composition [13, 40–43] but also on the processing procedure [18, 19], the crystal orientation [16, 44], the compatibility of the functional material with the electrodes, the poling procedure [20, 45], the grain size [17, 46, 47], and the boundary effects imposed by the material system. In the case of thick films, the clamping of the film to the substrate also influences the effective functional properties of the film [48]. In addition, the properties of the PMN-PT material can be modified by the application of mechanical stresses [49]. In thick PMN-PT films, the properties are influenced by thermal stresses generated in films due to a mismatch of the thermal expansion coefficient of the film and the substrate [50, 51]. On the other hand, a chemical interaction between the film and the substrate may result in a deterioration of the material's functional properties [52]. In order to prevent such interactions, the use of a $Pb(Zr,Ti)O_3$ barrier layer was proposed [31, 50].

3. PMN-PT Actuators

PMN-PT actuators are manufactured by using single crystals or bulk ceramics; however, PMN-PT thick-film actuators were also investigated. Depending on the application, different constructions and realisations of the actuator structures are possible. The simplest actuator design is a free-standing cantilever beam that can be realized as a unimorph, bimorph, or multimorph structure. In addition to cantilever-type actuators, there are also the bridge- and the membrane-type actuators. In combination with the materials and technologies enabling 3D structuring, even arbitrarily shaped actuator structures can be feasible. Furthermore, actuators made from a composite material, where one of materials is PMN-PT, can also be designed.

3.1. Actuator Structures Processed from PMN-PT Single Crystals. The most common type of PMN-PT actuators reported in the literature is the bending type [34, 37, 53]. Kim et al. [37] showed that the tip displacement of the bending-type PMN-PT single-crystal actuators can be several times larger than ones made from PZT ceramic actuators of the same design. The reported normalized displacement (displacement per unit length of the actuator) for a PMN-PT single-crystal actuator and PZT ceramic actuators were 38 μm/cm and 2.5 μm/cm at 10 V (0.67 kV/cm), respectively. Another benefit of the PMN-PT single-crystal bending actuators is that they operate at relatively low voltages and, therefore, with a low power consumption. Ko et al. [34] reported the use of an actuator structure composed of two parallel multilayer PMN-PT actuators for optical-disk-drive applications [34, 54].

Stacked structures with active PMN-PT single-crystal layers were also considered as a solution for an improvement of the bending capabilities of actuators. Woody et al. [55] discussed the results of an investigation of the PMN-PT actuators for adaptive structures in space applications. The actuators were realised as stacked structures with several (up to 40) 0.5-mm-thick active 0.68PMN-0.32PT single-crystal layers with a diameter of 5 mm. It was demonstrated that the actuators had at least two-times-lower power requirements, more than three-times-higher strains generated, higher displacements at cryogenic temperatures, and high bandwidth in comparison to the PZT actuators.

Park and Horsley [58] reported on the fabrication and characterisation of an MEMS-based deformable mirror for ophthalmologic adaptive optics constructed by using single-crystal PMN-PT. Basically, the structure is composed of a 30 μm active PMN-PT membrane layer bonded onto a 5 μm passive single-crystal silicon layer with a 1-μm-thick conductive epoxy. The maximum displacement of such a membrane structure (with 100-nm Cr/Au electrodes on the top and bottom) was over 20 μm for the applied voltage 20 Vpp, which was found to be appropriate for the application.

Wilkie et al. [59] reported on the results of their investigation of a composite actuator structure manufactured by using a layer of 0.68PMN-0.32PT single-crystal fibres in an epoxy matrix, packaged between interdigitated electrode polyimide films.

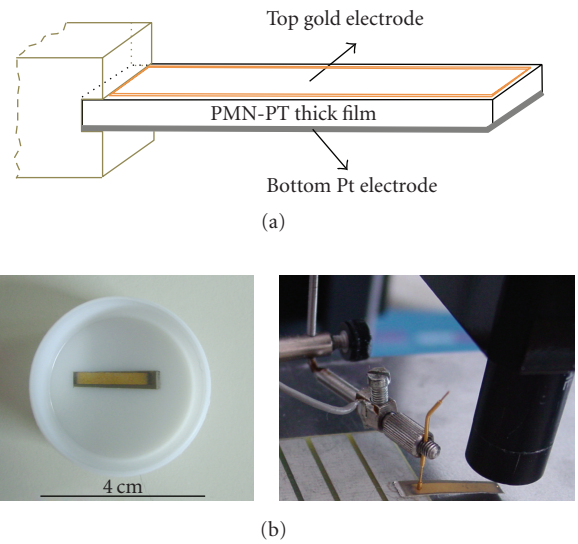

Figure 1: (a) The scheme of the cross-section of the PMN-PT/Pt actuator. (b) The actuator with dimensions 1.8 cm × 2.5 mm × 60 μm (50-μm-thick PMN-PT film and 10-μm-thick Pt electrode) after processing (left) and during the measurement of the displacement (right).

3.2. Actuator Structures Processed from the PMN-PT Bulk Ceramics and Films. Ngernchuklin et al. [60] processed piezoelectric/electrostrictive PMN-PT ceramic actuators by dry pressing the powder and sintering at 1150°C. The actuators were prepared as a bilayer composite of 0.65PMN-0.35PT and 0.90PMN-0.10PT layers. In an earlier report [56] from the same research group, there are the results of an investigation of piezoelectric/electrostrictive PMN-PT actuators with dimensions of 2.6 cm × 11 mm × 2.3 mm prepared by tape casting. The maximum tip displacement of those actuators was 11 μm at 3 kV/cm (a normalized tip displacement per length of 4 μm/cm). Recently, the same authors [4] reported on improved actuator characteristics; that is, the tip displacement of a piezoelectric/electrostrictive PMN-PT actuator with dimensions of 3 cm × 8 mm × 1.2 mm was up to 40 μm at 5 kV/cm (the calculated normalized displacement is 13 μm/cm).

There are only few reports on thick-films actuators. Generally, thick-film piezoelectric actuators have smaller displacements and exert weaker forces in comparison to their bulk relatives. This is because a stiff and relatively thick substrate in comparison to the active piezoceramic film always reduces the bending ability of the thick-film actuator structure. However, a novel approach to manufacturing large-displacement 0.65PMN-0.35PT/Pt (PMN-PT/Pt) actuators by using thick-film technology based on screen printing of the functional layers was recently presented by Uršič et al. in [32]. The actuators were prepared by screen printing the PMN-PT film over the Pt electrode directly onto an Al_2O_3 substrate, which results in a poor adhesion between the electrode and the substrate, enabling the PMN-PT/Pt thick-film composite structure to be simply separated from the substrate. In this way, a "substrate-free" actuator structure was manufactured. The normalized displacement of these

Table 2: The normalized displacement of PMN-PT and PZT bending-types actuators.

Form of bending-type actuator	Normalized displacement of the actuator	Electric field
PMN-PT single-crystal actuators [37]	38 μm/cm	0.7 kV/cm
0.65PMN-0.35PT/0.9PMN-0.1PT bulk actuators [4]	13 μm/cm	5 kV/cm
0.65PMN-0.35PT/0.9PMN-0.1PT bulk actuators [56]	a few μm/cm	10 kV/cm
PZT bulk actuators [37]	2.5 μm/cm	0.7 kV/cm
0.65PMN-0.35PT/Pt thick-film actuators [32]	55 μm/cm	3.6 kV/cm
PZT thick-film actuators on alumina substrates [57]	5 μm/cm	50 kV/cm

actuators is very high, that is, 55 μm/cm at 3.6 kV/cm [32]. In Figure 1, the scheme of the cross-section of the PMN-PT/Pt actuators and photographs of the actuators are shown.

4. Discussion and Summary

The PMN-PT ceramics and the single crystal with a composition on the MPB have the piezoelectric coefficients d_{33} as high as 700 pC/N and 1500–2800 pC/N, respectively. On the other hand, the PMN-PT materials with the compositions $x = 0-0.1$ show relaxor behaviour and are the electrostrictive materials. Due to the large responses of the PMN-PT material to the applied electric field, this material is suitable for actuators, especially for the bending-type actuators.

One important advantage of the PMN-PT material is that it can be processed as a single crystal, a polycrystalline ceramic, and thick- or thin-film forms, each of them having different functional properties and therefore appropriate for different applications. However, the best functional properties were obtained for actuator structures made by using PMN-PT single crystals. On the other hand, the disadvantage of PMN-PT material is that it can be depoled by the application of negative electric field due to switch of the domain walls.

In order to compare the performances of the PMN-PT bending-type actuators prepared from single crystals, ceramics, and thick films, the normalized tip displacements versus the applied electric fields are summarized in Table 2. For comparison, PZT actuators are also added. The largest bending of the actuators was obtained for PMN-PT actuators processed from a single crystal. However, the actuators prepared from PMN-PT thick films also show an extremely large displacement. In comparison to the PMN-PT and PZT actuators prepared from bulk ceramics or thick films, these actuators show a 5-times larger displacement.

PMN-PT actuators have many potential applications. Depending on the application, different constructions and realisations of the actuator structures are possible. Structures including piezo-active PMN-PT single-crystal layers were reported, for example, an MEMS-based deformable mirror for ophthalmologic adaptive optics and much larger stacked actuators for adaptive structures in space applications. The state of the art in the processing of PMN-PT actuators is the development of new, effective functional structures with the desired output for specific applications. There are still a number of challenges to be faced in the production of PMN-PT actuators and wide possibilities for further improvements in their performance to meet the industrial demands for production.

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