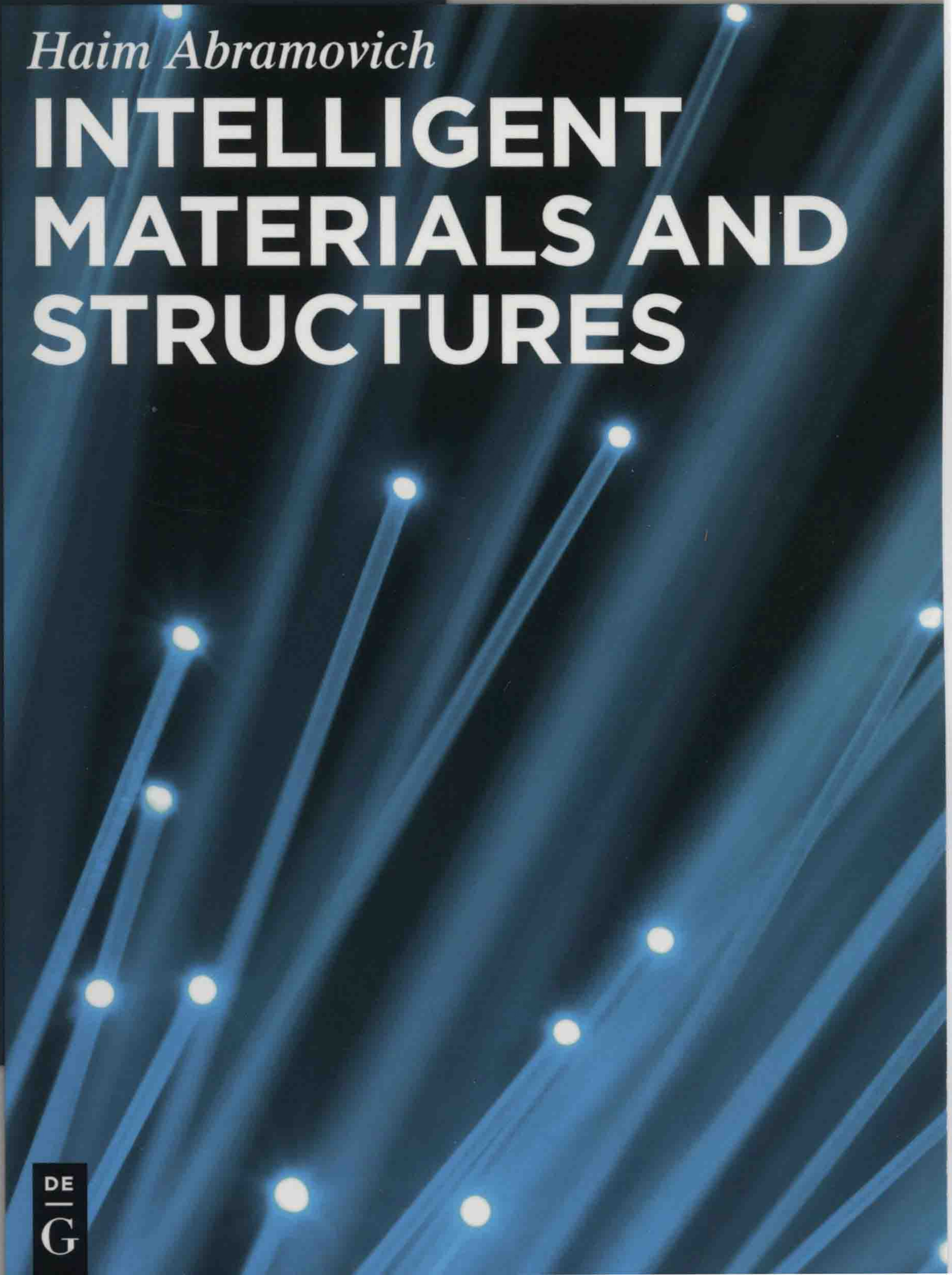
DE GRUYTER

GRADUATE

Haim Abramovich

INTELLIGENT MATERIALS AND STRUCTURES



DE G

Haim Abramovich

Intelligent Materials and Structures

DE GRUYTER

Author
Prof. Dr. Haim Abramovich
Technion Israel Institute of Technology
Krombein Aerospace Structural Laboratory
Technion City
Haifa 32000
Israel
haim@technion.ac.il
abramovich.haim@gmail.com

ISBN 978-3-11-033801-0
e-ISBN (PDF) 978-3-11-033802-7
e-ISBN (EPUB) 978-3-11-038943-2

Library of Congress Cataloging-in-Publication Data
A CIP catalog record for this book has been applied for at the Library of Congress.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.dnb.de.

Cover image: Thinkstock
Typesetting: le-tex publishing services GmbH, Leipzig
Printing and binding: CPI books GmbH, Leck
♾ Printed on acid-free paper
Printed in Germany

MIX
Papier aus verantwortungsvollen Quellen
FSC www.fsc.org FSC® C083411

www.degruyter.com

Preface

Intelligent Materials and Structures aims at dissemination of advanced engineering ideas using relatively new multifunctional materials. The present book was written to provide students and scholars a good understanding of the new emerging interdisciplinary topic of smart/intelligent structures. It should serve as an introductory book for graduate students wishing to study about intelligent materials and structures, enabling them to acquire the necessary physical and mathematical tools to understand the various perplexing aspects of this new engineering field.

The book is based on the research performed during the years by the author on piezoelectric structures including energy harvesting and his teaching of a course at undergraduate–graduate students' level, carrying the name of "Introduction to Smart Structures".

The present book is aimed at providing a textbook to a graduate or graduate–undergraduate course on smart/intelligent structures. It also can serve as a reference for engineers and scientists working in industry or academia.

The book starts with an extended introductory chapter on the main intelligent materials and structures like piezoelectric materials, shape memory alloys, electrorheological & magnetorheological fluids and electrostrictive & magnetostrictive materials. For each of those materials, a long list of relevant references is presented to enable the reader to understand the complexity of each topic and provide him with the necessary basic and advanced literature. Chapter 2 is devoted to laminated composite materials, and presents the classical lamination theory and the first order shear deformation theory. This chapter aims at providing mathematical and physical insight of composite materials with eventual smart/intelligent layers. The first two chapters are therefore suitable for the introduction of intelligent materials and structure to the students. The third chapter is focused on piezoelectricity, its constitutive equations and various beam and plates models. Shape memory alloys and pseudoelasticity are presented in chapter four of the book. Physical explanations of the term memory and pseudoelasticity are described including various models existing in the literature. Electrorheology and magnetorheology are described and reviewed in the fifth chapter of the book, while electrostriction and magnetostriction are part of the sixth chapter. Applications of intelligent materials in structures and devices of aerospace and medicine sectors are part of the seventh chapter together with a new look on piezoelectric based motor. The last chapter of the book presents basic equations for energy harvesting using piezoelectric and electromagnetic based devices together with their relevant literature.

It is hoped that this book, together with other books and the huge numbers of references existing in the literature, will enable readers to become familiar with the new engineering topic of intelligent materials and structures.

The author wishes to thank all his former graduate students for their dedicated research in the field of piezoelectric based structures, Mrs. Tamar Müller for her help

in gathering the numerous manuscripts for the literature review and mainly to his wife Dorit and his children, Chen, Oz, Shir and Or for their support, understanding, love and devotion. Their continuous support throughout the writing period enabled the publishing of the present book.

Haifa, July 2016
Haim Abramovich

Contents

1 Introduction to Intelligent Materials and Structures

1.1 Types of Intelligent Materials

The aim of this chapter is to present the reader with the general topic of smart intelligent structures. The general area of intelligent materials incorporated into smart structures had been investigated for some decades; however since 2000, the number of published manuscripts in various journals had tremendously increased with applications in almost all areas of engineering.

Smart structures (also carrying the name intelligent structures, mainly in the aerospace field) are normally represented as a minor subset of a much larger field of research, as schematically shown in Figure 1.1 (see Refs. [1, 2]).

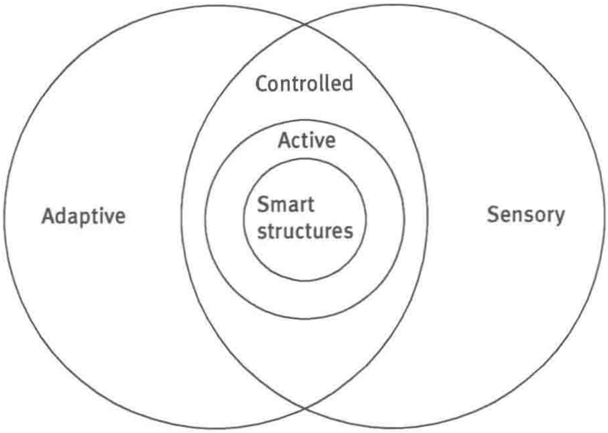


Fig. 1.1: Smart structures as a subset of active and controlled structures [1].

According to Wada et al. [1], structures with actuators distributed throughout them are defined as *adaptive structures*. Typical examples of such adaptive structures are wings of conventional aircraft which possess articulated leading and trailing edge control surfaces. Accordingly, those structures that contain sensors distributed throughout them are called *sensory structures*. These sensory structures have transducers that might detect displacement strains, thus leading to the monitoring of mechanical properties, electromagnetic properties, temperature, or the presence or accumulation of damage. The overlap structures that contain both actuators and sensors, and those that implicitly contain a closed-loop control system aimed at connecting the actuators and the sensors, are defined as *controlled structures*. A subset of the controlled structures are *active structures*. Active structures are distinguished from controlled structures by highly distributed actuators which have structural functionality and are part of the load-bearing system [2]. Within this hierarchy, *smart structures*

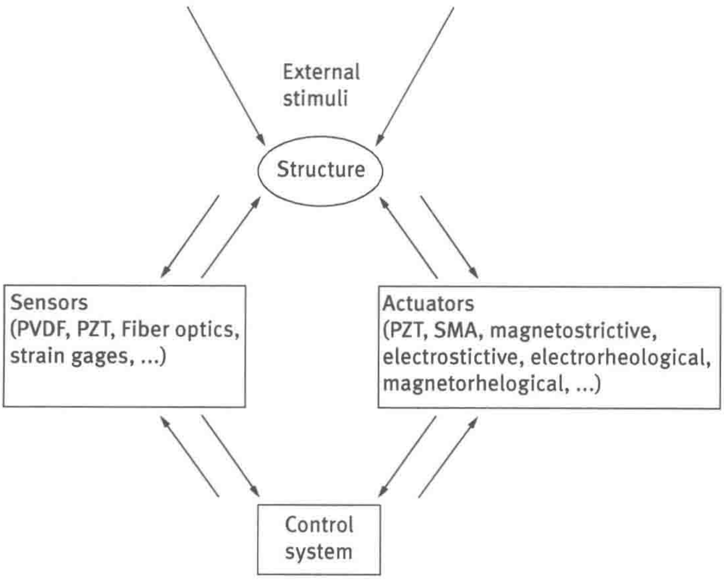


Fig. 1.2: A schematic drawing of a smart structure.

are only a subset of active structures that have highly distributed actuator and sensor systems with structural functionality, and in addition, distributed control functions and computing capabilities. Therefore, the term *smart structures* stands for structures that are capable of sensing and reacting to their environment in a predictable and desired manner, through the integration of various elements, such as sensors, actuators, power sources, signal processors, and communication network. In addition to carrying mechanical loads, smart structures may alleviate vibration, reduce acoustic noise, monitor their own condition and environment, automatically perform precision alignments, or change their shape or mechanical properties on command (Figure 1.2). Another definition frequently appearing in the literature states that a smart structure is a system containing multifunctional parts that can perform sensing, control, and actuation; it is a primitive analog of a biological body. As stated in [3], from this analogy of the bionic system of humans and animals, it can be seen that the following mechanisms may be essential for any material to be made intelligent:

1. A sensing tool to perceive the external stimuli (like a skin which senses thermal gradients or an eye that senses optical signals), to be termed as a *sensor*.
2. A communication network by which the sensed signal would be transmitted to a decision-making mechanism (like the nervous system in humans and animals) and a decision-making device (like the human brain), to be called *control*.
3. An actuating device that could be inherent in the material or externally coupled with it (like stiffening of muscles in humans or animals to resist deformation due to external loading), having the function of *actuator*.

All of these devices would need to be active in real-time applications for the material to respond intelligently and in an optimum time interval.

Smart materials are used to construct these smart structures, which can perform both sensing and actuation functions. Therefore, smart or intelligent materials are designed materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, and electric, or magnetic fields.

Another interesting side of smart or intelligent structures is their interdisciplinary characteristics that require the involvement of a few engineering fields, such as aerospace or mechanical engineering (or any other applicative engineering field), electrical engineering, computer engineering, material science, applied physics, and system engineering. This is why this field is so attractive to many people coming from different fields of engineering and science, leading to many research studies being published in the literature. Although the scientists would publish their work in journals connected to their fields, three dedicated journals appeared to cover the newly emerged field of smart structures.

- *Smart Materials and Structures*,[1] a multidisciplinary journal dedicated to technical advances in (and applications of) smart materials, systems, and structures, including intelligent systems, sensing and actuation, adaptive structures, and active control.
- *Journal of Intelligent Material Systems and Structures*[2] (JIMSS) is an international peer-reviewed journal that publishes the original research of the highest quality. JIMSS reports on the results of experimental or theoretical work on any aspect of intelligent material systems and/or structure research are also called smart structure, smart materials, active materials, adaptive structures, and adaptive materials.
- *Smart Structures and Systems*[3] aims at providing a major publication channel for researchers in the general area of smart structures and systems. Typical subjects considered by the journal include: sensors/actuators (materials/devices/informatics/networking), structural health monitoring and control and diagnosis/prognosis.

Books dedicated to smart structures and their applications were written [4–21] based on the experienced gained during the years. These include the early book of Ghandi and Thompson [4], through books dealing with various aspects of smart structures, like vibrations, dynamics, and health monitoring [6, 9, 14] and ending with books carrying the general title of *Smart Structures*, covering all aspects of the topic [15, 18, 20].

1 Published by IOP Publishing (UK). http://iopscience.iop.org/0964-1726
2 Published by Sage Journals. http://jim.sagepub.com/
3 Published by Techno-Press. techno-press.org/?journal=sss&subpage=5#

Accompanying books deal with mechatronics[4] [13] and adaptronics[5] [21], the German paradigm for adaptive structures. It is worth noting that although the number and variety of books are relative high, only two can be used as undergraduate–graduate text books: the book authored by Leo [12] and the book co-authored by Chopra and Sirohi [20], which is more comprehensive, well posed, and with a long list of references.

Piezoelectric materials can be considered the prime candidate to be included in a smart structure. The term, piezoelectricity, is also called the piezoelectric effect, and it is defined as the ability of certain materials, like quartz, certain ceramics, and Rochelle salts to generate voltage when subjected to mechanical stresses or vibrations, or elongate or vibrate when subjected to a voltage. As stated in [22], the piezoelectric property that carries its name following a direct translation from Greek of the word *piezein* ("pressure electricity") was discovered by Pierre Curie and Jacques Curie in 1880 [23].

By analogy with temperature-induced charges in pyroelectric crystals, the Curie brothers observed electrification under mechanical pressure of certain crystals, including tourmaline, quartz, topaz, cane sugar, and Rochelle salt. In a follow-up manuscript [24], the Curie brothers confirmed the second property of the piezoelectricity, what is called *the converse effect*. Since then, the term piezoelectricity is commonly used for more than a century to describe the ability of materials to develop electric displacement, denoted by the letter D, which is directly proportional to an applied mechanical stress, denoted by the Greek letter σ (Figure 1.3a). Following this definition, the electric charge appeared on the electrodes reverses its sign if the stress is changed from tensile to compressive. As follows from thermodynamics, all piezoelectric materials are also subject to a converse piezoelectric effect (Figure 1.3b), i.e., they deform under an applied electric field. Again, the sign of the strain S (elongation or contraction) changes to the opposite one if the direction of electric field E is reversed. The shear piezoelectric effect (Figure 1.3c) is also possible, as it linearly couples shear mechanical stress or strain with the electric charge.

One has to remember that to understand the physics of piezoelectricity, one has to deepen the crystallographic principles of the effect (see the pioneering work of Voigt [25] in 1910 and the more recently work of Jaffe et al. [26] from 1971). Table 1.1 presents typical values for main piezoelectric materials together with their symmetries as shown in [22]. The present book does not contain this part of the piezoelectricity and the reader interested is referred to Ref. [26] and to many other manuscripts dealing with the crystallography of piezoelectric. One should note that the invention of piezoelectric ceramics (see [26]) led to an astonishing performance of piezoelectric

4 Mechatronics is a multidisciplinary field of engineering that includes a combination of mechanical engineering, electrical engineering, telecommunication engineering, control engineering and computer engineering.

5 Adaptive structure technology, briefly called Adaptronics, is an innovative, new cross sectional technology for the optimization of structure systems.

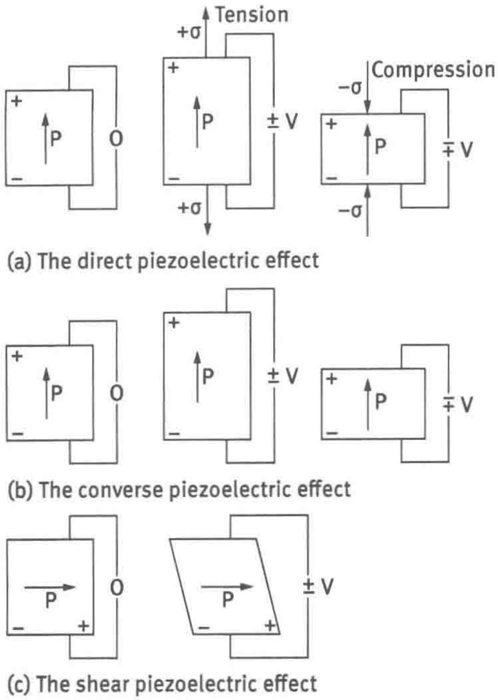


Fig. 1.3: A schematic drawing of the direct (a), converse (b), and shear (c) piezoelectric effects.

Table 1.1: Physical properties of major piezoelectric materials together with their symmetries

Parameter	**MATERIALS**						
	Quartz	**$BaTiO_3$**	**$PbTiO_3$:Sm**	**PZT 5H**	**LF4T**	**PZN-8%PT[001]**	**PZN-8%PT[111]**
Symmetry	32	4mm	4mm	3m/4mm	mm2/4mm	3m/4mm	3m/4mm
d_{33} (pC/N)	2.3	190	65	593	410	2500	84
d_{31} (pC/N)	0.09	0.38	0	−274	−154	−1400	−20
$\varepsilon_{33}^T/\varepsilon_0$	5	1700	175	3400	2300	7000	1000
T_c (°C)		120	355	193	253	160	160

materials with industrial applications in many areas yielding a multibillion dollar industry with a wide range of applications and uses.

The most widely used piezoelectric material is probably the PZT (lead zirconate titanate) [27]. The PZT ceramics shows both the direct piezoelectric effect (generating a voltage when it is strained) and the converse piezoelectric effect (it becomes strained when placed in an electric field). Therefore, the PZT ceramics can be used both as sensor and actuator. Piezoelectric ceramics are polycrystalline in nature and do not present any piezoelectric characteristics in their original state. To induce piezoelectric effects in PZT type ceramics, these materials undergo poling under their Curie temperature at high dc electrical fields of 2 kV/mm (notice that this value is only an averaged one), resulting in an alignment of the polar axis of unit cells parallel to the applied field and thus yielding a permanent polarization of the material. Another important fact associated with the polarization process of the ceramics is its permanently mechanical deformation due to the reorientation of its domains. One has to differentiate between the longitudinal, transversal, and shear effects. The longitudinal effect deals with the active strain in the polarization direction and parallel to the electric field while the transversal effect is due to the resulting Poisson in plane strain. The direction of a shear strain is parallel to the polarization direction and vertical to the electric field. From the application point of view, it is customary that only the longitudinal and transversal effects are being used, while the shear effect is being neglected. One should note the following facts: the maximum strain of PZT is relatively small (0.12%–0.18%) and it is limited by saturation effects and depolarization [28] and that the PZT ceramics exhibits hysteresis of 2% for very small signals and reaches 10%–15% at nominal voltage [28]. The density of PZT is typically $7.6\,\text{g/cm}^3$ [29].

From structural point of view, due to polarization process the PZT is not only electrical but also mechanical anisotropic. The longitudinal Young's modulus for PZT is typically is 50–70 GPa while in the transversal direction the values is only 35–49 GPa (for further information, see also [30]).

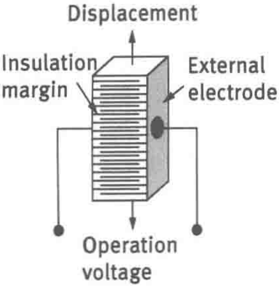
Another constraint is the fact that the piezoelectric effect depends also on the ambient temperature. Below 260 K, it decreases with reducing temperature by a factor of approximately 0.4%/K [31]. The upper temperature is limited by its Curie temperature. PZT actuators can reliably be driven up to 70% of their Curie temperature (between 150 and 350 °C) [30].

Temperatures above the Curie temperature would cause depolarization. High mechanical stress can also depolarize a PZT ceramics. Normally, it is accustomed to limit the applied stress to about 20%–30% of its mechanical compression load limit (200–300 MPa) [28]. Another important issue characterizing the PZT ceramics is the fact that depolarization might occur when applying an electrical voltage in the opposite direction to the polarization one which is larger than its coercivity voltage.[6]

Piezoelectric ceramics can be found in the form of thin sheets (patches), tubes, short rods, disks, fibers/stripes or stacked to form discrete piezostack actuators (see Figure 1.4).

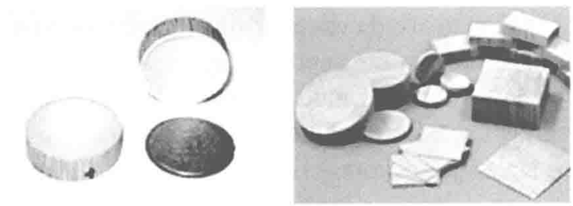
Polyvinylidene fluoride (PVDF) and its copolymers with trifluoroethylene (TrFE) and tetraflouoroethylene (TFE) which are semicrystalline fluoropolymers [31] represent another way of producing piezoelectric materials based on polymers (see Figure 1.5). Like PZT, the PVDF can be used as sensor and actuator. Their electromechanical material behavior shows, like in the case of PZT, the three effects, namely longitudinal, transversal, and shear strains, whereas technically only the transversal effect is normally being used. The significant difference between PVDF and PZT is con-

6 Electric coercivity is the ability of a ferroelectric material to withstand an external electric field without becoming depolarized.



(a) Piezo stacks

(b) Tubes, rods, disks, plates and stacks

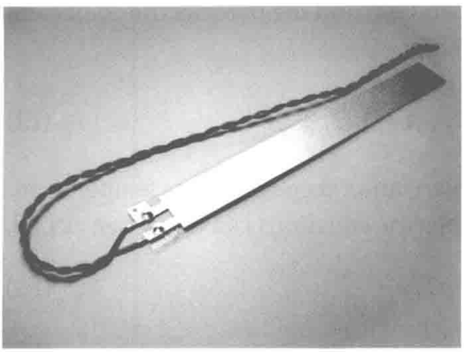


(c) 1-3 Fiber composites

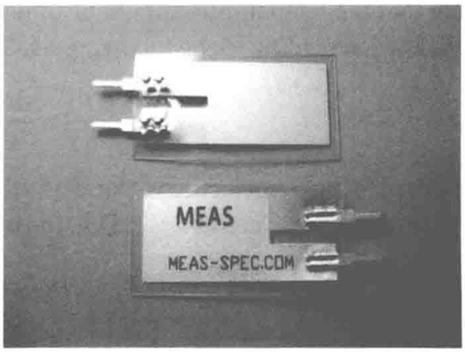
(d) Macro fiber composite (MFC)

(e) PZT fibers

Fig. 1.4: Typical forms of PZT ceramics (a) stacks, (b) tubes, rods, disks, plates and stacks, (c) 1–3 Fiber composite, (d) MFC patches, (e) PZT fibers. Sources: NASA Smart Materials Corp. (a, c–e); PI ceramic (b).



(a) Large PVDF film tab



(b) PVDF patch with connectors

Fig. 1.5: Typical PVDF forms: (a) large film tab, (b) small film tabs.

nected with their electromechanical material behavior namely in the direction of the electric field PVDF would contract instead of elongating like PZT. In plane, PVDF elongates whereas PZT contracts. Comparing the values of the piezoelectric constants (d_{31}, d_{32}, d_{33}) the PZT ceramics has 10–20 times larger piezoelectric strain constants than PVDF [31]. The active strain with 0.1% at up to 100 kHz is of the order of magnitude of PZT but requires significant larger electrical fields of 10–20 kV/mm. The amorphous region has a glass transition temperature (~ −40 °C) that dictates the mechanical properties of the polymer, while the crystallites have a melting temperature (~ 180 °C) that dictates the upper limit of its temperature. However, the piezoelectric effect is limited by the relatively low Curie temperature (~ 100 °C) and it can be reliably used at a maximum temperature of about 60–80 °C. Electrical poling is done using an electric field of the order of 50–80 kV/mm. Depending on whether stretching is uniaxial or biaxial, the electrical and mechanical properties are either highly anisotropic or isotropic in the plane of the polymer sheet. The in-plane Young's modulus varies between 2–3 GPa. In the direction of the electric field, Young's modulus would be about 1 GPa. The piezoelectric strain constants on the other hand are larger in its stretching direction. Similar to PZT, care must be taken to avoid the application of too large voltage, mechanical stress, or temperature to prevent the depoling process of the PVDF. The advantage of PVDF over PZT is its low density of about 1.47 g/cm^3 and the processing flexibility because tough, readily manufactured into large areas, and can be cut and formed into complex shapes. Major disadvantage is their low stiffness significantly reducing authority over the structure limiting PVDF to applications with low requirements concerning the forces.

Another important property of ferroelectric and ceramic (including piezoelectricity) materials, like PZT and PVDF is its pyroelectric effect[7], which is the ability to generate voltage across its electrodes due to changes in the ambient temperature (boot heating and cooling). The changes in the temperature lead to slight movement of the atoms within the crystal structure, leading to spontaneous polarization. One should note that the temperature should be time dependent, and the pyroelectric coefficient is defined according to the following relationship:

$$p_i\left(\frac{C}{m^2\,\mathrm{K}}\right) = \frac{\partial P_{S,i}}{\partial T}, \quad i = 1, 2, 3 \tag{1.1}$$

where p_i is the pyroelectric vector, P is the polarization vector, and T is temperature.

Neglecting dielectric losses [36], the pyroelectric equations can be written as [36],

$$\dot{D} = \varepsilon \dot{E} + p\dot{T} \tag{1.2}$$

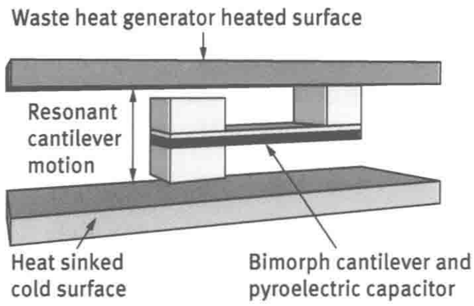
$$\dot{S} = p\dot{E} + \frac{c\dot{T}}{T} \tag{1.3}$$

where D, E, T, and S, are the electric induction, electric field, temperature, and entropy, respectively. ε, p, and c are the dielectric permittivity, the pyroelectric coefficient, and the heat capacity, respectively. Note that ($\dot{}$) represents derivation with respect to time.

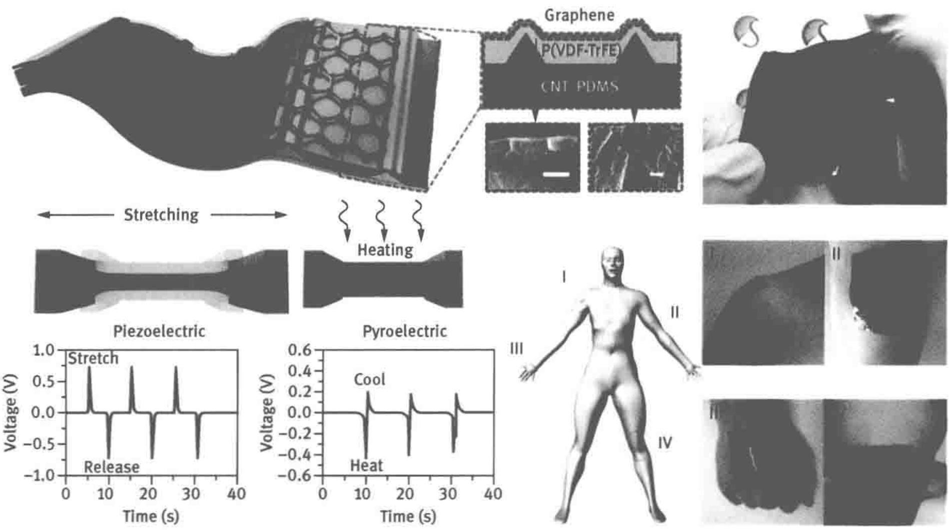
Based on the pyroelectric effect, infrared sensors and harvesting devices are designed to capture the heat time dependent energy and transform it into electrical en-

7 Pyroelectricity – from the Greek word *pyr* which means fire, and the word *electricity*.

(a) Thermal IR detector



(b) Pyroelectric waste heat generator concept



(c) Hybrid piezoelectric-pyroelectric nano-generator concept – from [40]

Fig. 1.6: Pyroelectric applications: (a) IR detector, (b) waste heat generator concept [40], (c) hybrid nano generator [40]. Sources: Warsash Scientific (a).

ergy as was suggested in [33–41]. Typical applications using the pyroelectric effect are shown in Figure 1.6.

An additional class of smart materials is the electrostrictive[8] one [42–51]. The electrostrictive material would have an induced strain proportionally to the square of the applied voltage (or of the applied electric field) and produce electricity when stretched. These materials are primarily used as precision control systems such as vibration control and acoustic regulation systems in engineering, vibration damping in floor systems, and dynamic loading in building construction.

---

8 The electrostrictive effect causes dimensional change of the material under the influence of applied an electric field.

Electrostriction is a basic electromechanical phenomenon in all insulators or dielectrics [42]. It describes the electric field/polarization-induced strain (S_{ij}) to be proportional to the square of the electric field (E_i) or polarization (P_i), and is expressed by the following two equations:

$$S_{ij} = Q_{ijkl} P_k P_l \tag{1.4}$$

$$S_{ij} = M_{ijkl} E_k E_l \tag{1.5}$$

where Q_{ijkl} and M_{ijkl} are the electrostrictive coefficients. As the electrostriction is a fourth-rank tensor property it can be observed in all crystal symmetries [44]. The electrostrictive materials are not poled as the piezoelectric materials, and present a lower hysteresis than the piezoelectric ones; however, as they are more capacitive in nature, a larger driving current is required. They are also highly nonlinear since they respond to the square of the applied voltage/electric field. Electrostrictive ceramics, based on a class of materials are known as relaxor ferroelectrics, which show strains comparable to piezoelectric materials and have already found applications in many commercial systems [51]. The most prominent electrostrictive materials are lead magnesium niobate-lead titanate (PMN-PT)[9] and lead lanthanum zirconate titanate (PLZT). Those materials have a Young's modulus of about 700 GPa, are very brittle, possess a fast response time and low hysteresis loop, are suitable for frequencies up to 50 kHz and can be used only as actuators. Typical illustrations about electrostrictive materials can be found in Figure 1.7.

A property similar to electrostriction described above is the magnetostriction, which is the material property that causes a material to change its length when subjected to an electromagnetic field [52], also known as the Joule effect [53]. Another magnetostriction property, also known as the Villari effect would cause materials to generate electromagnetic fields (will induce a change in the magnetic flux density) when they are deformed by an external force. The third magnetostrictive effect, also called the Barrett effect [54], states that the volume of a material will change in response to the application of a magnetic field. Magnetostrictive materials can thus be used for both sensing and actuation. Terfenol-D[10] (an alloy of terbium and iron (Fe)) is a commercially available magnetostrictive material that has "giant" magnetostriction at room temperature and can be used both as sensor and actuator. It is one of the rarest of the rare earth materials, and hence very expensive. It can be strained at large strains (2%) and has a Young's modulus of 200 GPa. It can generate large actuating

9 They are known as relaxor ferroelectrics possessing high relative permittivities (20,000–35,000) and high electrostrictive coefficients.

10 Terfenol-D, an alloy of the formula $Tb_xDy_{1-x}Fe_2$ ($x \sim 0.3$), is a magnetostrictive material. It was initially developed in the 1970s by the Naval Ordnance Laboratory in USA. The technology for manufacturing the material efficiently was developed in the 1980s at Ames Laboratory under a U.S. Navy funded program. It is named after terbium, iron (Fe),Naval Ordnance Laboratory (NOL), and the D comes from dysprosium.