An Introduction to
Piezoelectric Materials
and Applications

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The cover picture on the front shows a schematic representation of the perovskite structure.

The cover picture on the back shows various typical piezoelectric components and products as well as a 'piezoelectric active lens mount' used for active vibration control in microlithography.

This book was written as part of the dissemination activities of the SmartPie research program (www.smartpie.nl). The first chapters of this book have been published in June 2012 in a separate book, *An Introduction to Piezoelectric Materials and Components*.

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Preface

From the early history of mankind ceramics have played an important role. Historians can determine the different time periods in the worlds history by recognising the ceramic products that were used. Ceramics were used for artificial expression, for household purposes and as a structural material. Today ceramics also play an important role in technological applications, such as biomedical implants or heat resistant tiles and of course piezoelectric ceramics. Although already studied during the mid-18th century, the Curie brothers demonstrated the piezoelectric effect in crystals of quarz, tourmaline, topaz, cane sugar and Rochelle salt in 1880. The first application was an ultrasonic submarine detector by Pierre Langevin in 1917. During the next decades intense research driven by the demand of new applications led to the development of barium titanate and later lead zirconate titanate. Piezoelectric materials nowadays play a major role in the so called smart materials.

Although not usually recognised, piezoelectric materials play an important role in numerous applications in our everyday life. In the morning at home the piezo buzzer from our alarm clock wakes us. In our car, fuel efficiency is enhanced by piezoelectric fuel injection, our airbag is controlled by a piezoelectric acceleration sensor and when we park an ultrasonic parking sensor keeps us from collisions. At work microscopes or precision machines use very accurate piezoelectric motors and sensors or at the factory an ultrasonic cleaning bath with a piezo transducer cleans our work pieces or tools. And what about piezo inkjet printers or hard disk drive positioning? Our mobile phones use piezoelectric haptic feedback and photo cameras adjust the camera focus for us with a piezo motor. At the hospital piezoelectric echoscopy devices look inside our body or piezo motors are used for MRI monitored microsurgery. Back at home again we cook our meal on a gas stove or barbecue with a piezo igniter. The applications of piezoelectric materials are ubiquitous. At least ten times a day we make use of the piezoelectric effect.

When I was first introduced to this fantastic piezoelectric material I was delighted by a material with such interesting, mechatronic properties. It is fascinating that this material has the inherent capability to convert mechanical action into electric energy, and vice versa. Not much later in 2005 we founded the Applied Piezo foundation in order to bring together researchers, users, developers and suppliers of piezoelectric materials and applications. At the start of the SmartPie research program a piezo course was developed in order to provide a common ground for our researchers. The authors of the current book Pim Groen and Jan Holterman played an important role in this piezo course. With these insights in mind we wanted to write a book in order to aid students and developers in the understanding of the theoretical background and practical application of piezoelectric materials.

With such a great but hidden impact on human life we want to provide a clear overview of this technology and its applications. This book *An Introduction to Piezoelectric Materials and Applications* is written to provide that overview for the student and engineer of mechatronic applications with piezoelectric materials.

Acknowledgements

I would like to thank the following people for their support in this project:

- The authors Jan Holterman and Pim Groen. Jan Holterman whose PhD research found a practical application in lithographic machines, and with whom I since then worked on many other applications. I appreciate Jan's never ending desire to explain things better and more accurate. Pim Groen who has spent a career in both academical and industrial environment gaining the knowledge he put in this book. Besides being an excellent scientist Pim also has a very pleasant, practical view on piezoelectric applications.
- Guus Rijnders, Ruud Steenwelle, and Vincent Spiering for their contributions on thin film piezo.
- Martin Verweij for his contribution to the chapter on acoustic transducers.
- Hao Sun for his contribution to the chapter on energy harvesting.
- Rien Koster for his contribution to the section on piezoelectric motors.
- Frans Blom, Stephan Tiedke, and Erik Veninga for their contributions to the chapter on practical considerations.
- Eddy Brinkman who wrote our book *The hidden use of piezo technology in applications all around us* helped us also to organise this book.
- Theo de Vries, Miranda Wessels and Mark Horsthuis made the colourful figures and tables. They left no stone unturned to get every pixel on its proper place and every colour just right.
- Sandra Bohnstedt who had a clear vision about the cover; the first impression of the book.
- The members of the SmartPie consortium who provided the opportunity to write this book.

I am honoured to work with these people. I hope this book will encourage and support you in the development of new applications and the needed technology for these applications.

Jan Peters

Chairman, Stichting Applied Piezo
and
Director, Imotec b.v.

About the authors

Jan Holterman got acquainted with piezoelectric materials and components during his PhD research at the University of Twente, into active vibration control using smart materials. He successfully applied integrated piezoelectric actuators and sensors for active damping within microlithography machines and he has been involved in various piezoelectric application projects and patents. Currently he is with Imotec b.v., a mechatronic engineering company with a specialization in piezoelectric applications.

Pim Groen got involved in perovskites and ceramics during his study in Solid State Chemistry at Leiden University. He joined Philips Research in Eindhoven in 1987 and did his PhD in the field of cuprate superconductors, again perovskite related structures, in 1990. At Philips Research he worked on a variety of inorganic materials and ceramics for electronic and lighting applications and later in Aachen (Germany) on electronic ceramics, including piezoelectric ceramics. In 2002 he changed position to Morgan Electroceramics to continue his work on piezoelectric ceramics. Currently he is working at Holst Centre as program manager and is also working as part-time professor at the University of Delft in the group Novel Aerospace Materials (NOVAM) on Smart Materials & Sensors.

About Applied Piezo

The Stichting (foundation) Applied Piezo is a group of cooperating industrial companies with supplemental expertise in the field of piezo technology. There is a close relation with universities and several organisations that are active in the field of piezo technology. The aim of Applied Piezo is to define and execute new projects together, to promote piezo technology, to stimulate knowledge development and innovation and to provide a network where knowledge, expertise and products can be exchanged. Besides traditional bulk applications Applied Piezo is working on piezo systems based on thin film processes for MEMS devices and piezo composites for making integrated products.

About SmartPie

SmartPie is a Dutch scientific research program on piezo technology. SmartPie is an acronym for “SMART systems based on integrated PIEzo”. The aim of the SmartPie research is to strengthen the innovative position and perception of the Dutch high tech industry by providing it with new piezo-based technology. The research will provide new piezo materials and applications, through which a total paradigm shift will occur in the type of base technologies being used. This consortium is built upon an initiative of Dutch SME’s and the following partners are involved: Aito, C2V, Imotec, Solmates, Océ Technologies, TNO, Delft University of Technology, Eindhoven University of Technology, University of Twente. The SmartPie consortium gratefully acknowledges the support of the Smart Mix Programme of the Dutch Ministry of Economic Affairs and the Ministry of Education, Culture and Science.

Contents

Part I

Introduction and materials

1

Introduction

In this chapter, we
- *briefly sketch the history of piezoelectricity;*
- *give a glance of everyday life applications of piezoelectricity;*
- *present the scope of this book.*

Piezo technology is everywhere…

1.1 Piezoelectricity in everyday life

Materials always have had a large influence on society. This was obvious in the Stone Age, Bronze Age, and Iron Age. We have named these eras by the most advanced material in that period, since these materials determine and limit the state of technology at the time. Also in modern society, the influence of materials is still present. However, nowadays the materials as such are not as visible anymore as they used to be. They are more and more embedded in complex devices and high tech systems that make whole economies exist and function in an efficient way.

Piezoelectric materials are among these ‘invisible’ materials that are widespread around us, although they are unknown to the public at large. Mobile phones, automotive electronics, medical technology, and industrial systems are only a few areas where piezoelectric components are indispensable. Echoes to capture the image of an unborn baby in a womb make use of piezoelectricity. Even in a parking sensor at the back of our car, piezoelectric material is present.

FIGURE 1.1 Echoscopy image of an unborn baby in a womb

1.2 Piezoelectric effect

What's the reason for piezoelectric materials to be applicable so abundantly? Well, its the nature of the material itself: it has the ability to convert mechanical energy into electric energy and vice versa.

direct effect

inverse effect

The *direct* piezoelectric effect is that these materials, when subjected to mechanical stress, generate an electric charge proportional to that stress. The *inverse* piezoelectric effect is that these materials become strained when an electric field is applied, the strain again being proportional to the applied field. Clever use of piezoelectric materials enables the realization of a wide variety of technical functions.

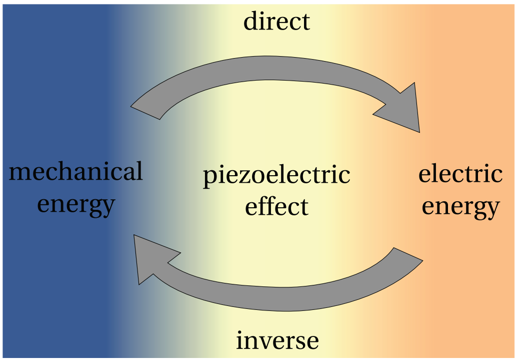

FIGURE 1.2 Piezoelectricity enables conversion from mechanical energy into electric energy and vice versa

1.3 History of piezoelectrics

tourmaline

pyroelectricity

The history of piezoelectricity – as a physical phenomenon to be used intentionally – goes back to the beginning of the 18th century. At that time the Dutch brought a precious stone called *tourmaline* from the East Indies to Europe. Tourmaline had a peculiar feature: while being heated, the material attracted other materials such as ashes. Almost half a century later the Swedish botanist and physician Carl Linneaus – also famous as developer of biological nomenclature – had a hunch that this phenomenon might have something to do with electricity. And indeed, within a decade, the German physicist Franz Aepinus confirmed that this 'peculiar feature' was electric. This phenomenon was later known as *pyroelectricity*: the ability of a material to generate a temporary voltage when it is being cooled or heated.

Pyroelectricity lead to the discovery of piezoelectricity, which was to a large extent a French affair. When Charles-Augustin de Coulomb assumed that electric charge might be produced by pressure, René-Just Haüy and later also Antoine César Becquerel tried to apply their knowledge of pyroelectricity to perform experiments to investigate Coulomb's assumption. However, they were not very successful.

discovery of piezoelectricity

In 1880 the brothers Pierre and Jacques Curie finally discovered the direct piezoelectric effect, also with pyroelectricity as a basis. They observed that by pressing in a certain direction on crystals of tourmaline, quartz, cane sugar and Rochelle salt (also known as Seignette's salt), these crystals were able to generate charge on certain positions of their surfaces. The German physicist Wilhelm G. Hankel gave this phenomenon the name 'piezoelectricity' – named after the ancient Greek *piezein* that means to press or to squeeze, and *elektron* meaning amber, describing substances that (like amber) attract other substances when rubbed. One year later, the French-Luxembourgian physicist Gabriel Lippmann predicted the inverse piezoelectric effect, which was experimentally verified by the Curie brothers in that same year.

etymology of 'piezoelectricity'

Practical applications

So far the 'founding fathers' and the scientific history. This interesting phenomenon of materials that can convert mechanical energy into electric energy – and vice versa – cried out for practical applications. And they came. During World War I, in 1917 Paul Langevin developed the predecessor of *sonar*, a device to detect other objects under water. He managed to make a *quartz*-based transducer to send ultrasonic waves, and a receiver to detect the returning echo. By measuring the time span between the emitted wave and the wave that returned after bouncing off an object, a submarine should be able to determine the distance to that object. To date, sonar is still a major application of piezoelectric technology, where modern (ceramic) materials are being used.

sonar
quartz

Sonar as a successful application of a piezoelectric material stimulated others to discover new piezoelectric materials and to develop new devices. An eye-catching example is the use of Rochelle salt as a single crystal needle in the pick-up part of early electronic phonographs, starting in 1935. Around 1950 Rochelle salt was replaced by *piezoelectric ceramics*, and in turn they were replaced by magnetic cartridges in the 1970's. From then, it took about ten years before compact disc players massively replaced phonographs.

piezoelectric ceramics

The second World War had a large influence on the development of new piezoelectric materials. Independent from each other – due to World War II – Japanese, Russian and American research groups discovered the so-called *ferroelectrics*, a new kind of man-made materials with much better piezoelectric properties than their natural counterparts. *Barium titanate* ceramics were the first materials in this

ferroelectrics
barium titanate

FIGURE 1.3 Quartz crystal