MICROTECHNOLOGY AND MEMS

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With 235 Figures

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# MICROTECHNOLOGY AND MEMS

The series Microtechnology and MEMS comprises text books, monographs, and state-of-the-art reports in the very active field of microsystems and microtechnology. Written by leading physicists and engineers, the books describe the basic science, device design, and applications. They will appeal to researchers, engineers, and advanced students.

**Mechanical Microsensors**
By M. Elwenspoek and R. Wiegerink

# Preface

This book on mechanical microsensors is based on a course organized by the Swiss Foundation for Research in Microtechnology (FSRM) in Neuchâtel, Switzerland, and developed and taught by the authors. Support by FSRM is herewith gratefully acknowledged.

This book attempts to serve two purposes. First it gives an overview on mechanical microsensors (sensors for pressure, force, acceleration, angular rate and fluid flow, realized by silicon micromachining). Second, it serves as a textbook for engineers to give them a comprehensive introduction on the basic design issues of these sensors. Engineers active in sensor design are usually educated either in electrical engineering or mechanical engineering. These classical educational programs do not prepare the engineer for the challenging task of sensor design since sensors are instruments typically bridging the disciplines: one needs a rather deep understanding of both mechanics and electronics. Accordingly, the book contains discussion of the basic engineering sciences relevant to mechanical sensors, hopefully in a way that it is accessible for all colours of engineers. Engineering students in their 3$^{rd}$ or 4$^{th}$ year should have enough knowledge to be able to follow the arguments presented in this book. In this sense, this book should be useful as textbook for students in courses on mechanical microsensors (as is currently being done at the University of Twente).

At this place we wish to acknowledge colleagues who contributed in one way or the other to the text. This is in first place the whole micromechanics group at the University of Twente: Han Gardeniers, Theo Lammerink, Gijs Krijnen, Erwin Berenschot, Meint de Boer, Dick Ekkelkamp, Hans Hassink, Cees van Rijn, Wietse Nijdam, Remco Sanders, Henk van Wolferen, Gui Chengun, Peter Leussink, Johannes Burger, Niels Tas, Edwin Oosterbroek, Willem Tjerkstra, Stein Kuijper, Robert Zwijze, Theo Veenstra, Erik van Veenendaal, Jasper Nijdam, Henk Wensink, John van Baar, Joost van Honschoten, Marko Blom, Han van Egmond, Albert van den Berg, Jaap van Suchtelen, Henri Jansen, Hans-Elias de Bree, Cristina Neagu, Frans Blom, Frans van de Pol, Siebe Bouwstra, Wim Hendriks, Harrie Tilmans, Albert Prak, Cees van Mullem, Vincent Spiering, Gert-Jan Burger, Rob Legtenberg, Joost van Kuijk, Jan van Vlerken, Edwin Smulders, Bob Haverkort, Thijs van Thor, Jan-Cees te Riet-Scholten,

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# Contents

# 1. Introduction

The use of silicon microsensors for pressure, acceleration, angular rate and fluid flow is increasing at high rates since micromachining has become a more or less mature technology. These sensors are used in great numbers especially in automobiles, process control, in the medical field and for scientific instrumentation. Market studies in the past years (mid nineties) have predicted an enormous increase in the need of these sensors. Recent predictions on market volumes of microcomponents (besides mechanical sensors ink jet printer heads and hard disk heads) are in the range of US$100 billion annually in Europe alone (Micromachine 1998).

The production price for pressure sensors has dropped well below one dollar per piece. Similar developments are expected from sensors for acceleration and angular rate. This dramatic development is due in first instance to the way microsensors are fabricated. The technology derives from integrated circuit fabrication technology where the production price per piece is roughly reciprocal to the number of fabricated units. This production method is called "batch processing", where a large number of components are made at the same time. Basically, silicon is machined using etching techniques, thin film deposition and waferbonding. This fabrication method is now known as "silicon micromachining". Silicon micromachining has become reliable, which is a second important reason for the commercial success of microsensors.

The working principle of mechanical sensors (except a certain class of flow sensors) relies on the mechanical deformation of a construction (deflection of a membrane or a mass suspended by a beam). This deformation is translated into an electrical signal.

Silicon happens to be an optimal material for mechanical sensors because of quite extraordinary mechanical properties. For sensors one needs a reproducible signal which means for the case of mechanical sensors that the structure must deform under an equal load in the same way.

Thus one needs a material free from mechanical hysteresis and free of creep. Hysteresis is due to yield of the material, or in other words due to plastic deformation. Silicon fails before it is deformed plastically, at least at room temperature. In fact, the stress at which silicon fails is considerably larger than the yield stress of stainless steel: in this sense, silicon is much stronger than all metals. Note however, that this does not mean that silicon is preferable over steel for all types of construction. If steel is stressed at some point of the construction above the yield strength, it deforms until nowhere the yield stress is exceeded. This way the structure as a whole will not fail. This is quite different in silicon constructions: if the yield strength is surpassed somewhere, silicon fails and the structure breaks down. This property of silicon – being brittle – is advantageous for sensors: If the sensor is overloaded, it breaks and will not function at all, in place of giving a false signal.

The other important property for sensing reproducible mechanical deformation is creep. This is a phenomenon, shown by all materials, in which a construction continues to deform at constant external load. For example, if a load from an elastically deformed spring is released the spring does not resemble its initial length immediately, only approximately, and from this length it "creeps" slowly back to its original length. This phenomenon occurs even if the load is small enough so that the yield strength is nowhere exceeded. This is a process, which can take minutes or hours. Single crystalline silicon belongs to the best materials with respect to creep; the effects are of the order of ten parts per million. The amount of creep depends on the geometry of the samples. Bethe's study revealed that creep of silicon and other materials becomes much more serious for thin cantilever beams (Bethe 1989).

The mechanical deformation due to mechanical forces can be measured in a number of ways. Use can be made of piezoelectricity, changes of the electric resistance due to geometric changes of resistors or due to strain in the resistors, changes of electric capacitance, changes of the resonant frequency of vibrating elements in the structure, or changes of optical resonance.

Silicon is not piezoelectric. Therefore, in order to translate a deformation to an electrical signal using piezoelectric effects one needs other materials, usually in the form of thin films. To date there are no reliable thin film materials available for this purpose. On the other hand, quartz is piezoelectric accordingly there are indeed mechanical microsensors machined from quartz. This book concentrates on silicon sensors.

Very common is the use of strain gauges in conventional sensors. The resistance of a conductor depends on its geometry, so conductors assembled on deforming bodies will give information about the deformation. Semiconductors have an additional materials effect: the conductivity depends on the strain in the material. This effect is called piezoresistivity. The relative change of the resistance per strain is called the gauge factor. For conventional metal strain gauges the gauge factor is of the order of one, while the piezoresistive effect in silicon increases the gauge factor of silicon strain gages to one hundred. The disadvantage of the piezoresistive effect is its temperature dependence.

Vibrating elements in the sensor construction also play the role of strain gauges: resonant strain gauges. The interest in resonant sensors has its root in the following attractive features: The output signal is a frequency. A frequency is much easier transferred into a digital signal; no AD-converter is required to feed the signal into a computer. A frequency as a signal is much more robust to disturbances than an amplitude (e.g. a voltage). Vibrating microbridges can replace strain gauges. They have much greater resolution than metal or piezoresistive strain gauges. We know two silicon resonant sensors on the market. One is fabricated by Druck, based on a design by John Greenwood (Greenwood 1984), and the other one is sold by Yokogawa Electric, designed by K. Ikeda (1990). The disadvantages of resonant silicon sensors are that they are not easy to make (which makes them quite expensive) and the technology is yet not well established. The high costs might be compensated by new simpler mechanical constructions for the load supply and by the simpler electronics.

A third important way to measure the mechanical deformation of a body is the capacity of a charged distribution of conductors. The capacitance depends on the geometric distribution, so any measurements of a capacitance of conductors assembled to the deforming body will give information about its form. Capacitive sensors have some advantages over piezoresistive sensors: they are less sensitive to temperature variations, and the sensitivity is larger, which is due to the mechanical construction, as we shall see in Chap. 5. The electronics however is more complex.

A category of microsensors, which do not always rely on a mechanical deformation, belongs to mechanical sensors: flow sensors. Many of these sensors rely on thermal effects, where a heater is used and the temperature is measured, either of the heater itself or of the medium in its surrounding. The flow changes the temperature distribution. There are also types of flow sensors where a deformation is induced by forces exerted on a sensor element by the streaming fluid: the fluid flow causes shear forces, drag forces and pressure gradients.

Designing a microsensor is a formidable task, which involves the whole range from the basic physics of the device and its interaction which the ambient, its fabrication to systems issues like electronic interfacing, electronic circuitry and packaging. This book has a double function: it is written as a review, and as a textbook to teach students the subject of mechanical microsensors. We make the attempt to describe all ingredients necessary to perform this task. We expect that the reader has basic knowledge of mathematics, in particular vectors and calculus. The book is directed to engineers and scientists of any of the fundamental engineering disciplines (mechanical and electrical engineering, physics and chemistry). This means that in deriving the basic models we start from a fairly basic fundament, however we make use of rather advanced mathematics of a level a student in engineering should have mastered after his second year.

We tried to give a comprehensive overview of the mechanical microsensors described so far, with the emphasis on the basic ideas. We describe the functioning of the sensors both, on a qualitative level and on a quantitative level.

We start the discussion with the description of MEMS. MEMS is the modern acronym for microelectromechanical systems, the sensors are a subset of this field. More important, sensors are quite often *part* of MEMS. This chapter also contains a summary on scaling, to give the reader some feeling about changes of our world when dimensions shrink. An overview on silicon micromachining follows. This chapter is a very condensed version of "Silicon Micromachining", by one of the authors and Henri Jansen (Elwenspoek and Jansen 1998). The fabrication technology of course is one of the essentials for the design of microsensors. The next two chapters are devoted to theory of mechanical deformation and on the two most important transduction mechanisms for mechanical microsensors, namely piezoresistive and capacitive. Chapters on the sensors themselves follow: sensors for pressure, force, acceleration, angular rate and fluid flow. The latter contains some basic theory of flow and heat transfer. A most advanced (from a technological point of view) and most complex (regarding systems design) type of sensors, resonant sensors, will be described next. The last two chapters are devoted to sensor interfacing: electronics and packaging.

# 2. MEMS

In many technical systems there is a strong trend for miniaturisation. This trend results on one hand from the fact that small components and systems perform differently: small systems can perform actions large systems cannot (example: minimal invasive surgery). In many cases a miniaturisation makes the systems more convenient (example: GSM telephone). On the other hand technology derived from IC-fabrication processes allows the production of miniature components in large volumes for low prices (examples: pressure sensors for automobile applications, ink jet printers).

The technology for miniaturisation develops from a number of fabrication methods: We mentioned IC-fabrication methods, but there are many groups at universities and companies that aim at the fabrication of small systems using technologies that derive from more conventional machining, such as cutting, drilling, sand blasting, spark erosion, embossing, casting, mould injection etc. In this book we concentrate on silicon micromachining and on the mechanical microsensors that can be fabricated by this method.

## 2.1 Miniaturisation and Systems

There are two basic notions used to indicate the science of miniaturised mechanical components and systems: Micro systems technology (MST, this notion was coined originally in Germany) and Microelectromechanical Systems (MEMS, invented in the USA). While MEMS is more specific to mechanical components, MST includes also microoptical systems, chemical sensors, analysis systems etc. However, in all microsystems mechanical and electromechanical functions must be realised, therefore in practice, both notions have a very large overlap. The important word in both notions is *system*. Here, system is used in contrast to *component*. Microthings are necessarily systems because of the small details in the systems. One cannot assemble a microsystem from components from the shelf. Example: if a factory wants to build a car, which is a pretty complex system, the whole car is designed using (in principle) available components (motor, transmission, doors, windows, wheels, etc.). These are purchased or fabricated following the specification of the designers and assembled. Such a procedure is impossible with microthings. First of all, the components are too small to be assembled at reasonable costs. Further, there are no components that fit together. In designing a microsystem, the components have to be designed during the design of the whole system. There is no design phase of the system separate from the design phases of components: the design of a microsystem is an integral process. Even more: the fabrication of the microsystem is an integral process. This process is being provided by silicon micromachining. We shall illustrate the design- and fabrication process a few times.

Referring to microsensors, we have leaned by a painful process that the sensing element, the electronic interfacing and the package (if you wish, the mechanical interface) must be designed as a whole. Designing one part of the system after the other in most cases will lead to sensors which cannot be packaged, or of which the package is too expensive.

A second systems aspect plays a major role in the fabrication process. Micromachining is very complex and not developed to a standard technology. The process space is still largely unexplored. When designing a microsystem, the fabrication process of the system must be designed, too. Thus system design and process design are integrated in a single design process. Microsystems designers therefore must have a large number of skills and a rather broad experience. This is quite different from IC-design and processing. For IC-processes there are strict and clear design rules which guide the circuit designer, and he does not have to worry how the circuit is actually made. Microsystems designer must be able to design both: the system and the fabrication process.

A third systems aspect is the following: Usually microsystems have complex functions. The functions have roots in different physical domains. For a sensor this is clear: a sensor must transmit a signal from a particular domain (chemical, mechanical, thermal) to the electrical domain. A sensor designer must of course know the domains to which the sensor has ports. As an example, in a pressure sensor a membrane is deformed and the deformation is the measure for the pressure. The sensor designer must know the mechanical properties of membranes. The deflection of the membrane can be measured by optical interferometry. In this case, the designer must know optics as well. The designer must know how to treat his (usually) small electrical signal, how to amplify it, how to realise the interfaces to a computer, so he must have knowledge of electronics, too. Sensor designers therefore are Jacks of all trades. In practice, they have to work in groups of engineers of different colours, and understand enough of other disciplines in order to be able to communicate.

## 2.2 Examples of MEMS

Since this book is devoted to microsensors, there will be no extensive discussion of other microsystems such as actuators, microstructures, microrobots etc. We give a few examples here. We find this important because the technology – silicon micromachining – enables us to fabricate complex systems and simple systems for more or less the same price. So there is the chance (and the challenge) to integrate many functions in a single piece in an integrated production process.

Using silicon it is obvious to think of the combination of mechanical and electronic functions. Much work has been done to develop integrated sensors, or