MEMS: A Practical Guide to Design, Analysis, and Applications

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NOTICE

Dedication

To the memory of our fathers,
Gerrit Jörgen Korvink and Marius Paul.

Contents

16 LIGA Technology for R&D and Industrial Applications 853

Ulrike Wallrabe and Volker Saile

17 Interface Circuitry and Microsystems 901

Piero Malcovati and Franco Maloberti

Foreword

MEMS are rapidly moving from the research laboratory to the marketplace. Many market studies indicate not only a tremendous market potential of MEMS devices; year by year we see the actual market grow as the technology matures. In fact, these days, many large silicon foundries have a MEMS group exploring this promising technology, including such giants as INTEL and Motorola.

Yet MEMS are fundamentally different from microelectronics. This means that companies with an established track record in these branches need to adapt their skills, whereas companies that want to enter the "miniaturization" market need to establish an entirely new set of capabilities. The same can be said of engineers with classical training, who will also need to be educated toward their future professional activity in the MEMS field.

Here are some questions that a company or technologist may ask:

> I have an existing product with miniaturization market potential. Which technology should I adopt?
>
> What are the manufacturing options available for miniaturization? What are the qualitative differences?
>
> How do we maintain a market lead for products based on MEMS? Is there CAD support? Can we outsource manufacturing?
>
> Which skills in our current capability need only adaptation? What skills need to be added?

Professors Jan Korvink and Oliver Paul have set out to answer these questions in a form that addresses the needs of companies, commercial practitioners, and technologists. They have collected together a set of world leaders in each of the areas that they have identified as significant for MEMS-based production. The experts have written chapters that lead the reader through the specialized knowledge of their field and guide them through the literature they may want to consult for further reading.

Microtechnology and, close on its heels, nanotechnology, are set to change many manufacturing and product paradigms. To stay ahead in this competitive world, we need to assess and reassess our options and establish products that have unique value that helps them stand apart from the rest. Microtechnology is one way to go about this, for it brings along small size, low power consumption, low per-unit manufacturing costs in a mass market, low environmental impact for discardable units, and high sophistication when combined with embedded systems. Professors Korvink and Paul have done an excellent job in providing a handbook that will help you to maintain your competitive advantage now and into the future.

Wolfgang Menz
Professor Emeritus
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Preface

MEMS, or microelectromechanical systems, claim to be the smallest functional machines that are currently engineered by humans. MEMS is an exciting field with rapidly growing commercial importance. When the field started, it was considered highly speculative, but early successes made researchers bold. Their enthusiasm spread to venture capitalists and eventually resulted in a range of commercially available and viable products. Certainly, MEMS technology is not as established as, for example, microelectronics, but every year shows growth in the commercial application of the technology. Consequently, many companies are under competitive pressure to evaluate whether or not MEMS technology has advantages for their own products. And as soon as this question is posed to the engineers of a company, it is our hope that this book will help them to formulate an informed opinion by filling the growing need for a practical collection of information that supports the product development engineer.

This book aims to provide workers in industry with access to comprehensive resources on MEMS devices, systems, manufacturing technologies, and design methodologies. It addresses the rapid evaluation of questions such as: *What is out there? What works? What is still speculative?* We believe that the decision to *design* implies having an application and a market potential, which is followed by selecting solutions (devices, systems, electronics, packaging), then selecting technologies, then selecting design support tools, and finally making business decisions. This book aims to help newcomers to the field ramp up their technology in the shortest time possible by making accessible the views of experts in the respective fields of application.

A central dilemma and at the same time one of the best features of MEMS is its incredibly wide range of applications. As this book has progressed through the stages of production, many MEMS paradigm shifts have occurred *out there*. These have had the effect of both proving the previous point of diversity of applications and of increasing the necessity of having a good starting resource. We think here of the importance of RF-MEMS for mobile telecommunications, micro-optics for internet hardware, and the rapidly growing importance of MEMS in the life sciences as miniaturized laboratories, catheter-based minimally invasive operating theater tools, and in applications for the *in vivo* monitoring of chemical levels paired by exact dosage of medication in ailing patients.

Whereas we cannot hope to foresee how MEMS applications will develop and diversify, we do believe that by looking at existing technologies and applications the experienced engineer can quickly extrapolate toward their own application area and speed up the evolutionary path to expertise. This book provides data for selecting solutions (devices, systems, electronics, packaging), selecting technologies, and selecting design support tools. It also provides rapid access to literature for additional details, as your design evaluation focuses and your information needs change. For this purpose, we aim to answer some central questions that a starting project may have:

Q. *What can I do with MEMS?*
A. MEMS allow you to build sensors and actuators, together with measurement, control, and signal conditioning circuitry, and equipped with power and communications, all in the tiniest space. This enables you to be more accurate, to manufacture more cost-effectively, to achieve autonomy of a larger system, and so on.

Chapter 1, Microtransducer Operation, by Oliver Paul, guides you through the various possibilities and helps to structure systems thinking about MEMS. Here you will find the big picture, with information on which effects are available, by which equations they are described, and how the individual chapters specialize the ideas.

Q. *How do I design for better MEMS products?*
A. As we progress through the evolution of a product, it becomes clear that the optimal operation of a device, or a system, will depend on too many parameters and that a more organized approach to design becomes necessary. Naturally we first think of CAD systems, and the questions to answer here are: *What is available? What are the capabilities? What is the best organization for tools and teams?* Three chapters deal with this very important area.

In Chapter 3, MEMS and NEMS Simulation, Jan G. Korvink, Evgenii B. Rudnyi, Andreas Greiner, and Zhenyu Liu, provide a comprehensive overview of simulation tools, techniques, and approaches, covering both microdevices and nanodevices. Many of the modeling tools are highly specific to MEMS because of the relative scaling of physical effects at decreasing dimensions, but also because of the special manufacturing processes. Here you will learn which tools are available for which effect and how to approach modeling, from the theory all the way to how a simulation team should be organized.

In Chapter 4, System-Level Simulation of Microsystems, Gary K. Fedder shows how the overall behavior of a microsystem can be predicted by relaxing the level of detail of a device simulation, in the guise of a compact model, without necessarily losing any predictive accuracy, thus gaining a kind of SPICE for MEMS.

These techniques are certainly important components of a design suite, but without accurate material property data, it is impossible to plan a design. For MEMS this often means creating special measurement devices or devising special measurement techniques, as can be found in Chapter 2, Material Properties: Measurement and Data, by Osamu Tabata and Toshiyuki Tsuchiya.

Q. *What devices and application areas are enabled by basing a design on MEMS?*

A. A vast variety of devices and applications are covered; the list is continuously growing. The currently most important areas are covered by individual chapters. Working through the chapters, you will see how experts have explored the possibilities offered by the technology and brought out the best of each new idea to achieve devices that not only emulate their macroscopic counterparts but greatly improve on performance and, in many cases, enable technical concepts that are otherwise unthinkable.

Take a look at Chapter 5, Thermal-Based Microsensors, by Friedemann Völklein for a comprehensive discussion on how thermal phenomena (such as temperature and radiation) are measured using MEMS technology. But more than this, thermal effects are also useful to use as intermediaries in a whole range of detector applications, for example in the measurement of electrical power or for gas flow velocity. Consequently, the chapter teaches us to reconsider frequently our notions of a measurement because, once a technology is established (say, making and measuring a very small thermopile), it may be used advantageously in a variety of *new* applications.

In Chapter 6, Arokia Nathan and Karim S. Karim discuss Large Area Digital Photon Imaging, an important technology for the detection of low-energy x-rays (replacing traditional film processing) and other electromagnetic sources. They clearly show that each new application area is a challenge that must be confronted afresh, with expertise built up as you expose the challenges set by a vision. The authors discuss new manufacturing materials, detector devices, electronics in a new technology, the challenge of large area integration, and the exiting area of working on flexible substrates.

For optical benches in miniature, Chapter 7, Free-Space Optical MEMS, by Ming C. Wu and Pamela R. Patterson, shows how MEMS technology not only captures this exciting application area but also how microdevices can leave the plane of the manufacturing substrate. Making truly 3-D structures has proven to be one of the toughest challenges of

MEMS, and I have personally extended the idea to an incredibly rich family of devices in an application area where precise 3-D positioning is one the most demanding requirements.

For many key applications, notably data communications, Integrated Micro-Optics (Chapter 8) is the preferred technology. Hans Zappe shows how this technology has been driven by himself and other workers to enable the design of entire optical microsystems, with exciting applications in accurate sensing, with enormous potential in miniaturization and speed, and ranging over communications, data storage, and sensors applications.

Chapter 9, Microsensors for Magnetic Fields, by Chavdar Roumenin, discusses the classical area of magnetic field measurement. Here we find no moving parts whatsoever; ingenious schemes are necessary to get a useful result from these complex silicon devices. The devices have captured numerous markets, including rotation sensors, proximity switches, compasses, and, lately, catheter devices for nuclear magnetoresonance sensing.

In Chapter 10, Mechanical Microsensors, by Franz Laermer, we encounter the exciting area of automotive sensing, which includes accelerometers for airbag applications and microgyroscopes. In sensing mechanical quantities, we usually need moving parts or are required to channel some of the application's mechanical deformation through our system; this remains a big challenge for any product.

Finally, Andreas Hierlemann and Henry Baltes discuss the very important area of Semiconductor-Based Chemical Microsensors in Chapter 11. Chemistry is rich in effects, in products, and in the vast range of measurement scales that are required for any device or system to become useful, so that this area offers both fantastic opportunities for products as well as huge challenges to implementation engineers. In trying to emulate some of the body's functions (smell or taste), we quickly discover the limits of engineering, and the authors guide us to techniques that try to overcome this limitation.

Q. *Where does the system aspect become important?*

A. Only the smallest numbers of microdevices are used as separate entities in engineering systems. For the vast majority, it is either necessary (due to the low level of signals) or advantageous to engineer entire systems at the microlevel. Because we are creating products for use in areas outside of microengineering, we have to address not only the needs but also the conventions of the application areas. The best new products feel familiar, cost less, and do a whole lot more. Systematic engineering of an application provides tremendous market advantages because products can evolve more rapidly once a technology is established.

In Microfluidics, Chapter 12, Jens Ducrée, Peter Koltay, and Roland Zengerle show us how systems microengineering of entire fluidic systems including pipes, pumps, and a vast range of sensors and manipulation tools results in exciting new applications such as a fountain pen that doesn't leak or a highly precise pipette.

Chapter 13, Biomedical Systems, by Whye-Kei Lye and Michael Reed, addresses the important area of new tools for the treatment of human ailments. With a small number of applications, this chapter only touches on the tip of an iceberg, for this topic could fill an entire book. We believe that this area may eventually dominate MEMS applications as medical techniques, biotechnology tools, and MEMS technology merge.

Q. *Sensors are fine, but can MEMS achieve significant actuation?*

A. MEMS became famous because of the first micromotor, which was certainly spectacular but without significant applications. In the ensuing years, MEMS actuators have grown to capture markets and application areas, with the best-known actuator probably being the digital micromirror device (DMD) array produced by Texas Instruments for video beamer applications.

This exciting area is discussed in Chapter 14, Microactuators, by Jack W. Judy. Here we discover how to get the most mechanical power out of a chip, whether we need force, large movement, linear behavior, or special kinematics. Many cases are worked through, including the Texas Instruments DMD.

Q. *How are MEMS made?*

A. More often than not, they are made in a cleanroom. But the cleanroom must be filled with life, and the naive days of just varying electronic manufacturing processes are certainly over. Choosing a technology will probably be the most critical cost factor for a company embarking on a MEMS adventure, so that the flexibility of the technology for use in other products, its availability as a service, and so forth, will be very important factors. From a design point of view, the most important concept in MEMS is to be able to mix physical effects (such as electrothermal or piezo-optical). This implies forming layers of different (perhaps incompatible) materials and structuring the materials, possibly even in 3-D.

In Chapter 15, Micromachining Technology, Paddy J. French and Pasqualina M. Sarro show how traditional silicon cleanroom equipment can be used and extended to enable a wide range of MEMS manufacturing capabilities. Many of the applications discussed in previous chapters are ideally suited to be manufactured using the techniques shown here.

The chapter also discusses the important issues related to compatibility of MEMS processed with traditional IC manufacturing.

In Chapter 16, LIGA Technology for R&D and Industrial Applications, Ulrike Wallrabe and Volker Saile present one of the first dedicated MEMS technologies capable of producing very high aspect ratio microcomponents, primarily out of metals and plastics. The many successful industrialization projects discussed also demonstrate how research facilities and industry can collaborate fruitfully.

Q. What role do electrical circuits play in MEMS?

A. Electronics represents the key means with which to get signals into and out of MEMS, as well as to provide signal conditioning, control, and a range of other functions that directly derive from traditional analog and digital circuit design.

How these techniques change when we are addressing MEMS applications is thoroughly discussed in Chapter 17, Interface Circuitry and Microsystems, by Piero Malcovati and Franco Maloberti. Future integrated microsystems will benefit significantly from progress in the VLSI field thanks to two key elements: the progress in batch-manufactured silicon sensors, and the introduction of new circuit techniques for designing interface circuits. These two factors will be essential in favoring the transition from *research-driven speculations* to *customer-driven activities*. Malcovati and Maloberti discuss the key issues in realizing integrated microsystems, describing the most suitable circuit techniques for interfacing and processing microsensor output signals. A number of examples of integrated devices illustrate the problems and suggest possible solutions, showing how essential interface circuits are in compensating for sensor shortages and increasing the functionality of microsensor systems.

Q. What is a good strategy to get started in the MEMS field?

A. Follow the steps outlined in this book:

Start reading the chapters on manufacturing techniques to see how typical MEMS manufacturing processes work.

Next, find an application that seems close to your own, and see how the authors solved design challenges and how they exploited the advantages of miniaturization.

Try to conceive of a complete system consisting of sensors, actuators, circuits, and packaging.

Next, detail the choice of effects used in the devices, the circuit techniques needed to extract and condition the signals, and the manufacturing processes needed at each stage.

Based on economics, partition the system into separate manufacturing entities and estimate the cost per unit. Remember that packaging will dominate cost and component complexity will work against yield.

Now that the first iteration is over, re-evaluate each decision you made and extend your data with the options that are available.

Now take the next steps, assuming that the answers to your questions were promising, yielding new possibilities for your application and your company:

Secure your IP by patenting and trademarking. Build up a literature base of what the competition is doing.

Build up a team that will take your concept further. If possible, take on new people who already know the basics of MEMS technology. This will save you lots of money.

Educate your team. Many courses are offered where workers can quickly gain hands-on experience. Make the designers join the lab people in practical courses, and send the entire team to design courses. This will ensure that the team bonds and that and team members talk the same technical language.

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August 2005

1 Microtransducer Operation

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1.1 Introduction

Rooted in mechanical, electrical, and chemical engineering and relying on physical insight, biological techniques, and materials science know-how, microelectromechanical systems (MEMS) engineering is a fundamentally interdisciplinary field. Its fascinating diversity often forces the research and development engineer to take into account a broader range of issues than in many classical, well-established technical disciplines. Simultaneously, the diversity creates the impression of a lack of unity, contrasting strongly with the classical disciplines of science and engineering. These are usually able to offer a core of thoughts stripped of unnecessary details, with well-established foundations and lines of thought, and representations accepted by the majority of researchers active in the field. More peripheral aspects of the disciplines can be built up from a solid basis of knowledge.

The situation is different in MEMS, and in particular in such a general domain as MEMS transducer operation. The bewildering diversity of materials, structures, and effects in MEMS translates into a wide range of operational concepts from which it appears at first sight difficult to extract unifying principles. Nevertheless, when considering the issue of transducer operation from a more generous distance, some unifying aspects may be peeled out of layers of technical details and individual preferences. It is the goal of this chapter to start from basic considerations and gradually build up the surrounding aspects useful for transducer operation.[1,2]

The purpose of microsystems is to collect physical and chemical information of various kinds about their environment and to make this information available in a form more suitable for the human senses and technical systems. It is clear that the task of gathering and transforming information is performed by many technical systems. However, the distinctive feature of microsystems is their ability to perform this task despite or even because of their small size. The definition of *microsystem* varies from researcher to researcher. Nevertheless, it will in general be accepted that a system has to be at most a few cubic centimeters in volume to qualify as a microsystem.

Transduction is performed by miniaturized elements with dimensions scaling from a few millimeters down to submicrometer lengths. Larger structures are usually considered as macroscopic. The description and analysis of such larger components and systems have been the subject of classical textbooks on transducers, sensors, and actuators.[3-5]

In the field of microsystems, the action of transforming information or signals is usually designated by the term *transductions* and *conversion*. Transduction is derived from the Latin verb "transducere," which means "to lead across."[6] In microsystems, information is indeed "led across" the boundaries between different signal domains, that is, it is transformed from one domain into another. In this sense, microsystems contain one or several microtransducers taking advantage of physical and chemical effects on the scale from centimeters down to atomic dimensions, and exploiting appropriate material properties to achieve the transduction goal.

To fill these rather general statements with a clearer meaning, the next section presents the signal domains in more detail and summarizes transduction principles implemented in microsystems to date. Section 1.3 describes important figures of merit of microtransducers, including their limits due to noise. Common techniques to improve transducer performance are then described in Section 1.4, while various methods to power microsystems are the object of Section 1.5.

1.2 Transduction

1.2.1 Signal Domains

In the context of microsystems, the term *information* has to be understood in a broad sense. Any signal with which the microsystem is able to interact is likely to carry a certain amount of information. As an example, the spectral energy density and propagation direction of electromagnetic radiation enable us to extract information from and draw conclusions about the thermodynamic state of the distant source of radiation. Analogously, the direction and amplitude of a magnetic field measured by a microsystem reveal some information about the orientation of the magnet in which the field originates. Similarly, the inertial forces experienced by a microsystem make it possible to determine the dynamics of the substrate carrying the microsystem.

What these three examples have in common is that the information extracted is associated with an energy field: the radiation field in the first example, the magnetic interaction energy in the second, and the mechanical potential in the third. This connection between information, signals, and energy is not surprising in view of thermodynamics, which teaches the intricate relationship between energy, states, entropy, and information.

Current microsystems operate mainly within six signal/energy domains:[6]

1. Mechanical signal/energy domain
2. Electrical signal/energy domain
3. Thermal signal/energy domain
4. Magnetic signal/energy domain
5. Radiant signal/energy domain
6. Chemical signal/energy domain

In addition to these, elementary particle interactions and gravitation in principle provide further signal/energy domains. However, the first is usually included in the radiant signal domain, since the dominant role of microsystems in elementary particle physical or nuclear research is to detect elementary processes via their decay products, which usually lead to particle fluxes "radiated" away from the location of the original process. The gravitational field of the earth provides a handy definition of the vertical direction and is used for example in tilt sensors. Since its main technically relevant effect is to exert a force on masses, it is natural to include it in the mechanical signal/energy domain. More subtle effects expected from the theory of gravitation, such as gravitational waves or black-hole evaporation, have not being relevant in MEMS devices, nor have microsystems been instrumental in elucidating such fundamental phenomena.

Finally, quantum mechanics provides a further, more abstract signal domain going beyond the rather intuitive domains mentioned so far. Quantum mechanics teaches that a considerable amount of information can be encoded in collections of bosonic or fermionic states by the technique of quantum mechanical superposition.[7,8] The resulting states have to comply with the symmetries requested by quantum mechanics from bosonic and fermionic states. States may show so-called entanglement. Preparing entangled states, performing operations on these, and reading out the result holds the promise of highly parallel, efficient computation and secure data transmission.[8,9] Microsystem technology has only started to play a role in providing microstructures useful for this purpose, i.e., the technical infrastructures necessary to hold the tiny quantum mechanical bits of information (qubits). Once breakthroughs have been made and techniques are established, it may well be that the quantum mechanical domain will have to be included with the others as a domain *inter pares* in future introductions to transducer operation.

The ensembles of signals constituting the individual signal/energy domains are listed here in more detail.[10]

The Mechanical Signal/Energy Domain

The mechanical signal/energy domain includes descriptors of the mechanical state of a system, such as:

- Position, orientation, tilt, velocity, angular velocity, acceleration, angular acceleration, relative position, displacement, level, proximity, topography, deformation, strain, stress, density, mass, and resonance frequency

Changes in the mechanical state descriptors often result from externally applied force configurations, such as:

- Localized forces, including amplitude and direction or equivalently perpendicular (normal) and in-plane (shear) components, and torques
- Inertial forces
- Distributed forces such as pressure, from shock waves to vacuum pressures
- Acoustic pressure, impedance, frequency, wavelength, and velocity
- Shear stress and mass flow

The measurement of several mechanical signals by mechanical microtransducers is described in Chapter 10. For the measurement of pressure, shear stress, and mass flow, the thermal techniques described in Chapter 5 are also used.

The Electrical Signal/Energy Domain

Electrical signals include:

- Voltage, electric field intensity and direction, current, power
- Charge, capacitance, dielectric constant, polarization, inductance, resistance, impedance
- Frequency, phase shift, dielectric loss tangent, decay time, duty cycle length
- Spectral distribution, e.g., noise spectral density and amplitude of a side band and its distance to the carrier band

This electrical signal domain benefits from the broad base in instrumentation and signal conditioning techniques contributed by the field of electrical engineering and in particular by microelectronics. Not surprisingly, transforming an initial signal into the electrical domain, conditioning it there, and transforming it into the digital domain, where it is immune to many external disturbances, has been found to be a sound way of proceeding in many microsystems. This approach also has the advantage of being compatible with modern information technology, where signals are usually stored, handled, combined, and distributed in the electrical domain.

For this reason, the electrical signal domain plays a central role in the thermal, magnetic, mechanical, and chemical microsystems described in Chapters 5, 9, 10, and 11, respectively, and most prominently in Chapter 17, which deals with microtransducer interface circuitry.

The Thermal Signal/Energy Domain

Thermal signals include:

- Temperature, entropy, free energy and free enthalpy, and changes thereof
- Heat capacity, thermal conductivity
- Heat quantity, thermal power, heat flux or flow
- Thermal resistance, conductance, impedance
- Thermal time constant and phase shift

The Magnetic Signal/Energy Domain

Magnetic signals include:

- Magnetic field and magnetic induction, both with amplitude and direction
- Magnetic moment, magnetization
- Magnetic permeability and susceptibility

The Radiant Signal/Energy Domain

Radiant signals include:

- Electromagnetic radiation energy density and flux density
- Polarization, coherence, phase shift
- Spectral density

- Reflectance, transmittance, absorptance
- Charged-particle passage, velocity, energy, and mass

As mentioned, signals due to charged particles pertain to nuclear or elementary particle physics. In view of the ionizing properties of corpuscular radiation, similar to energetic electromagnetic radiation, and its detection via radiative effects, such as scintillation, particle signals are generally merged with the radiant signal domain.

Chapters 7 and 8 show how radiant signals can be put to advantage to perform such interesting task as chemical sensing, communication network reconfiguring, and image projection.

The Chemical Signal/Energy Domain

Chemical signals include:

- Concentration, composition, pH
- Chemical potential, electrochemical potential, redox potential
- Reaction rate, equilibrium constants

The detection and measurement of chemical signals is described in Chapter 11.

1.2.2 Block Schematics of Transducers

Now that the questions of the relevant energy domains and the most important signals have been clarified to a first extent, common configurations of microtransducers and their arrangements into microsystems are described. At the same time we continue building up the general terminology used in the MEMS field.

As mentioned, the operation of signal transduction consists of transforming signals from one energy domain into another. For a miniaturized information processing system to be classifiable as a microsystem, a sufficient condition is that along its path from input to output, the signals be outside the electrical domain at some point. However, this definition does not draw a complete picture, since systems definitely classifiable as microsystems have been developed for the purpose of measuring electrical signals and translating them into a convenient electrical output, without the signal ever leaving the electrical domain. Miniaturized voltage probes, including miniaturized probe heads and neural probe arrays inte-