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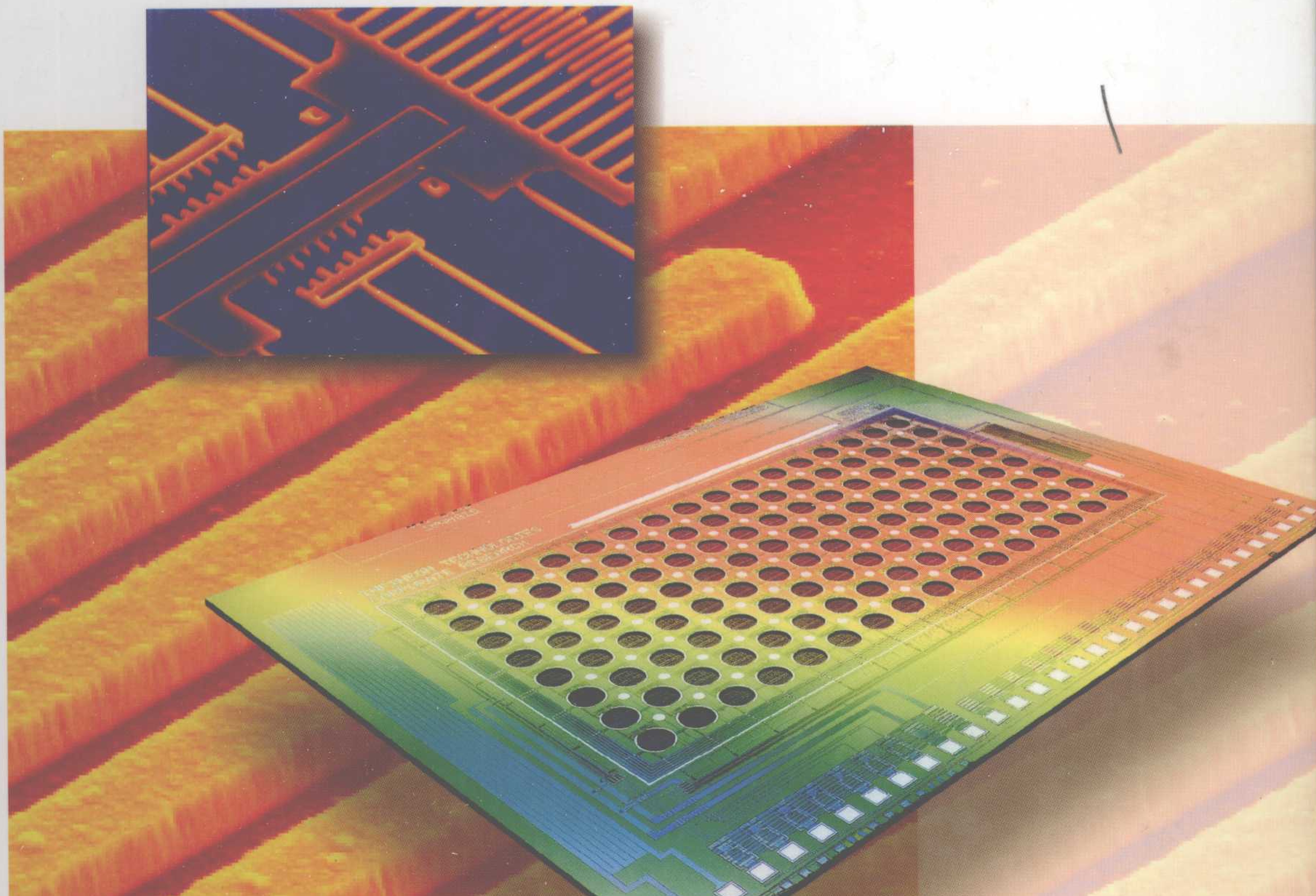
Enabling Technology for MEMS and Nanodevices



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Advanced Micro & Nanosystems
Volume 1

Enabling Technology for MEMS and Nanodevices

Edited by
H. Baltes, O. Brand, G. K. Fedder, C. Hierold, J. G. Korvink, O. Tabata

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Cover picture
Poly-Si lateral resonator coated with thin SiC film by C. R. Stoldt et al. (top left); IFX DNA sensor array biochip by Infineon Technologies (bottom right).

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Preface

We are proud to present you with this first volume of *Advanced Micro & Nanosystems*, which we call *AMN* for short. *AMN* addresses the needs of engineers and technologists who turn scientific ideas and dreams into product reality, and of entrepeneurs who keep these companies running. It also addresses graduate students who will evolve to either of these roles. There is much hype about Nano these days, just as there once was for Micro. Ultimately, however, the hard work of very creative individuals turns hype into realistic visions and finally into manufacturable devices. We have taken the word 'system' into the title for this reason. We emphasise the next step, the step beyond getting it right the first time, the deciding step that enables science to evolve to a viable technology. So much for our goal with *AMN*, and back to the present volume. We have grouped the eleven contributions into two sections.

The first section of seven articles is entitled *MEMS Technologies and Applications*, and starts off with Pasqualina Sarro's article on the third dimension of silicon, which addresses the fact that much of silicon processing is still planar, and of course MEMS technology offers ways around this limitation. This is followed by an article by Jim Knutti on MEMS commercialization. Jim has done it many times over, and his article is rare as it is difficult to teach this subject in a university atmosphere, and most companies see the process as a trade secret. Vladimir Petkov and Bernard Boser review capacitive interfaces for MEMS in the third chapter. Packaging is discussed by Victor Bright, Conrad Stoldt, David Monk, Mike Chapman and Arvind Salian, a very important task, especially if we remind ourselves of the role that packaging plays in the success and manufacturing cost of any integrated device, and the complexity of challenge that MEMS and NEMS present.

Mobile communication is steadily moving up the frequency scale, as well as the commercial importance scale, and in the next article Farrokh Ayazi discusses MEMS contributions to the area of high frequency filters and resonators, with their promise of reducing the chip count of a typical application whilst improving the component quality. MEMS is also making inroads into the mass storage area, with the promise of zero energy non-volatile devices, very high density data storage, and robustness with regard to external influences, so critical for security applications, as discussed in the article by Thomas Albrecht, Jong Uk Bu, Michel

Despont, Evangelos Eleftheriou, and Toshiki Hirano. The section closes with an article on scanning electrochemical probes by Christine Kranz, Angelika Kueng, and Boris Mizaikoff. These devices open our eyes not to photons or other particles, but to electrochemical gradients, opening up a new world of nanoscale information and imaging.

The second section of four articles is entitled *Nanodevice Technologies and Applications*. Two articles discuss the emerging topic of nanofluidics. The first, by Martin Geier, Andreas Greiner, David Kauzlaric and Jan G. Korvink, discusses the needs, and some solutions, for simulation tools with nanoscale resolution but multiscale in their approach. The second article, by Jan Lichtenberg and Henry Baltes, looks at nanofluidic devices and their uses. Next, Joseph Stetter and G. Jordan Maclay examine carbon nanotube (CNT) sensors. We can expect CNTs to make many inroads into the sensor field with its promise as a small electrical conductor and a chemical catalyst. The section ends with an article by Roland Thewes, Franz Hofmann, Alexander Frey, Meinrad Schienle, Christian Paulus, Petra Schindler-Bauer, Birgit Holzapfl, and Ralf Brederlow on CMOS-based DNA sensor arrays.

First and foremost we thank our authors for their hard work and timely contributions. The editors are grateful to the publishers, Wiley-VCH, for their support of the book series. In particular, the editors thank the publishing editor, Dr. Martin Ottmar, for his management of this enterprise and to Hans-Jochen Schmitt and Dr. Jörn Ritterbusch for their support.

We also look forward to welcoming you back, dear reader, to the next volume of *AMN*, which will take a timely look at recent advances in using CMOS technologies for MEMS. The articles are provided by an impressive team of experts in the field from around the world, so that we can expect this volume to condense a vast range of expertise in a handy reference format.

Henry Baltes, Oliver Brand, Gary K. Fedder, Christofer Hierold, Jan G. Korvink, Osamu Tabata

May 2004
Zurich, Atlanta, Pittsburgh, Freiburg and Kyoto

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Contents

Preface *V*

List of Contributors *IX*

1 **M^3: the Third Dimension of Silicon** *1*
P. M. Sarro

2 **Trends in MEMS Commercialization** *21*
J. W. Knutti and H. V. Allen

3 **Capacitive Interfaces for MEMS** *49*
V. P. Petkov and B. E. Boser

4 **Packaging of Advanced Micro- and Nanosystems** *93*
V. M. Bright, C. R. Stoldt, D. J. Monk, M. Chapman, and A. Salian

5 **High-frequency Integrated Microelectromechanical Resonators and Filters** *165*
F. Ayazi

6 **MEMS in Mass Storage Systems** *193*
T. R. Albrecht, J. U. Bu, M. Despont, E. Eleftheriou and T. Hirano

7 **Scanning Micro- and Nanoprobes for Electrochemical Imaging** *237*
C. Kranz, A. Kueng and B. Mizaikoff

8 **Nanofluidic Modeling and Simulation** *289*
M. Geier, A. Greiner, D. Kauzlaric and J. G. Korvink

9 **Nanofluidics – Structures and Devices** *319*
J. Lichtenberg and H. Baltes

10 Carbon Nanotubes and Sensors: a Review *357*
J. R. Stetter and G. J. Maclay

11 CMOS-based DNA Sensor Arrays *383*
R. Thewes, F. Hofmann, A. Frey, M. Schienle, C. Paulus, P. Schindler-Bauer, B. Holzapfl, and R. Brederlow

Subject Index *415*

1
M^3: the Third Dimension of Silicon

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Abstract

Microsystems technology is a fascinating and exciting field that has played and will continue to play a very important role in building a bridge between science and society. Physical properties and material characteristics are translated into structures and devices that can have a large positive impact on people's lives. Silicon micromachining has been largely responsible for the expansion of sensors and actuators into more complex systems and into areas not traditionally related to microelectronics, such as medicine, biology and transportation. The shift to 3D microstructures has not only added a physical *third dimension* to silicon planar technology, it has also added a *third dimension* in terms of functionality and applications. In this chapter, the basic issues and fundamental aspects of this field are briefly introduced. A few examples that illustrate *the power of the small world* are given and possible ways to pursue further miniaturization and/or increase in functionality are discussed.

Keywords

microsystems technology; MEMS; silicon micromachining; 3D microstructuring.

1.1 **Introduction** *2*
1.2 **M^3: Microsystems Technology, MEMS and Micromachines** *2*
1.2.1 Microsystem Technology *3*
1.2.2 MST versus IC *4*
1.3 **M^3: Multidisciplinary, Miniaturization, Mankind Needs** *5*
1.3.1 Miniaturization *6*
1.3.1.1 Bulk micromachining *6*

Advanced Micro and Nanosystems. Vol. 1
Edited by H. Baltes, O. Brand, G.K. Fedder, C. Hierold, J. Korvink, O. Tabata

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1.3.1.2 Surface Micromachining *7*
1.4 The Power of a Small World *8*
1.4.1 MST in Transportation *9*
1.4.2 MST in Medicine *10*
1.4.3 MST in Biology *11*
1.4.4 MST in Telecommunication *12*
1.5 Future Perspectives *13*
1.5.1 Autonomous Microsystems: More Intelligence in a Small Space *13*
1.5.2 Top Down or Bottom Up: the Next Phase in Miniaturization *15*
1.5.2.1 Top down *16*
1.5.2.2 Bottom Up *16*
1.5.3 The Link Between Nanoscience and the Macro World *16*
1.6 Conclusions *18*
1.7 Acknowledgments *19*
1.8 References *19*

1.1 Introduction

The fascination for the small world has been a constant in the research in physics, biology and engineering. Many scientists share a great interest in miniaturization technologies and in studying the behavior of materials and structures in the micro- and nanometer range. The investigation of the small world of matter is crucial to understanding how things work and this knowledge can be used to create novel microstructures and devices, thus offering the necessary tools and components to realize applications of great societal importance.

Microsystems technology is a fascinating and exciting field that has played and will continue to play a very important role in building a bridge between science and society to translate physical properties and material characteristics into structures and devices that can have a large positive impact on people's lives. In this chapter, the basic issues and fundamental aspects of this field are briefly introduced and an attempt is made to indicate where we are now and where we are going and how the small world makes a big difference.

1.2 M^3: Microsystems Technology, MEMS and Micromachines

Microsystems technology (MST) generally refers to design, technology and fabrication efforts aimed at combining electronic functions with mechanical, optical, thermal and others and that employ miniaturization in order to achieve high complexity in a small space. Microsystems are thus intelligent microscale machines that combine sensors and actuators, mechanical structures and electronics to sense information from the environment and react to it. These tiny systems are or soon will be present in many industrial and consumer products and will have a huge impact on the way we live, play and work.

In addition to MST, there are a number of other terms and acronyms that are used to describe this field, referring either to technologies, design concepts or integration issues. The most frequently used or encountered terms come from the three major geographical areas involved in this field:

- Europe → Microsystems technology (MST);
- USA → Microelectromechanical systems (MEMS);
- Japan → Micromachines (MM).

Apparently in Europe the accent is placed on the miniaturization of the entire systems, in the USA on the mechanical components being brought into the microelectronic world and in Japan on the miniaturization of a machine. Maybe this reflects in some way the cultural backgrounds of the three regions.

Although the names are somewhat different, basically they all accentuate both the miniaturization and the multi-functionality and system character. Some groups consider the presence of a movable part in the system necessary to be able to talk about MEMS, but in most cases the multi-functional character and miniaturization are the essential ingredients or prerequisites.

In view of the truly global character of research and the many transnational cooperations in this area, a new way to address this field collectively is M^3:

$$\mathrm{MST} \cdot \mathrm{MEMS} \cdot \mathrm{MM} = M^3$$

The exponential factor 3 can also be seen in relation to the *third dimension*. In fact, it not only combines all definitions identifying this field, it also stresses and symbolizes the importance of the introduction of an active 'third dimension' to silicon, literally and figuratively, and the impact these truly three-dimensional (3D) microsystems have in applications ranging from health care to consumer products.

We could also see the M^3 as summarizing three key characteristics of this field: *M*ultidisciplinary, *M*iniaturization, *M*ankind needs:

$$M^3 = M \cdot M \cdot M$$

Each of these aspects will be addressed in the following sections. Let us now take a closer look at the general concept of microsystems (or MEMS or MM) technology.

1.2.1
Microsystem Technology

Microsystem technology (MST) has experienced about two decades of evolution, mainly driven by a few key applications. It is likely to drive the next phase of the information revolution, as microelectronics has driven the first phase. A multi-bil-

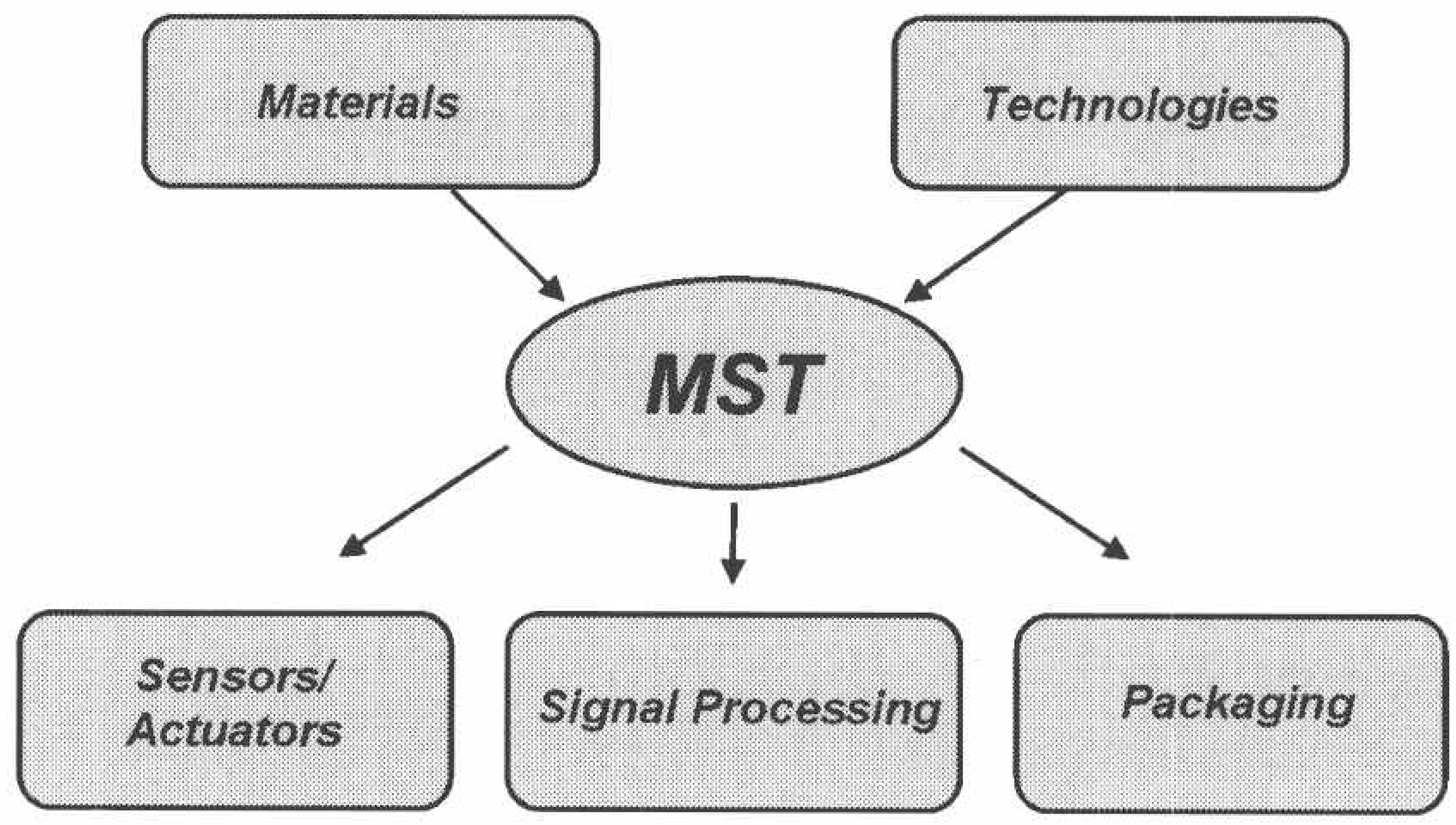

Fig. 1.1 Microsystems technology: the next phase in information evolution

lion dollar market by the middle of the next decade has been forecast and although there is some discrepancy in the figures presented by different bureaus and agencies, a common belief in a consistent growth is shared by all.

The general concept of MST, schematically depicted in Fig. 1.1, is to combine new materials with microprocessing technology (mostly well suited for low-cost mass production purposes) and micromachining technologies to form the three basic building blocks of every microsystem: sensing/actuation element, signal processing, package.

Advances in material science and processing are at the base of each MST product. Three main groups of materials are to be distinguished: materials for the package, materials for the actual device and the electronics and materials for the mechanical/electrical connection between these. Progress in semiconductor processing has evolved in a number of substrate materials predestined for use in microstructured devices, such as silicon, silicon-on-insulator, silicon carbide and gallium arsenide. Pricing and reliability considerations have led to the almost exclusive use of silicon-based micromachined devices. Packaging and assembly have focused on ceramics, printed circuit board (PCB) technology and multi-chip modules (MCMs) [1].

1.2.2
MST versus IC

The continuous advances in silicon-based integrated circuit (IC) technology, in terms of both processing and equipment, have definitely contributed to microsystems developments. At the same time the enormous growth in microsystems applications has stimulated the development of dedicated equipment and generated a larger knowledge of material and structure characteristics, especially in the mechanical area, which have been of great help to the IC world.

MST is often envisioned as being similar to semiconductor microelectronics and, although they possess many similarities, there are also some strong differences, as indicated in Tab. 1.1. Some of the most important ones are the lack of a 'unit cell' (no transistor-equivalent) and of a stable front-end technology (no CMOS equivalent). Moreover a multidimensional interaction space (not only elec-

Tab. 1.1 Important differences between MST and IC

	MST	*IC*
Unit cell	No unit cell	Transistor
Front-end technology	No single stable technology	CMOS
Interaction space	Multidimensional	Electrical
Basic disciplines	Multidisciplinary	Physics and engineering

trical connections) is present and it is a very multidisciplinary field as next to physics and engineering other disciplines such as chemistry, material science and mechanics play an important role.

Therefore, research is evolving toward a MST unit that is not a single unit cell, like the transistor, but small, specifically designed, components libraries that could be refined over time to become standard building blocks for each MST device domain.

1.3
M^3: Multidisciplinary, Miniaturization, Mankind Needs

Microsystems technology has a strong *multidisciplinary* character. Integration across several disciplines takes place. Next to physics and engineering, the basic disciplines of microelectronics, we find that chemistry and biology are becoming more and more a part of MST as new materials and phenomena play a major role in the development of new microsystems. Also, of course, as movable or flexible parts are often essential components of the system, the role of mechanics or rather micromechanics is much larger than it ever was in conventional microelectronics. Although the broad range of expertise and know-how that this field requires might make the path to problem solving and product development more difficult, it can also be seen as enrichment in the engineering world.

In fact, microelectronics is entering many industrial sectors that are becoming increasingly multidisciplinary environments, such as biotechnology, health care and telecommunication. Consequently, growing interest in an interdisciplinary educational program is observed as it will become extremely important to prepare a new generation of engineers capable of operating in such multi-disciplinary environments. Another positive aspect of the way in which research and development in this field is carried out is the development of important social skills such as dealing with people from different fields and speaking different languages (literally and figuratively), something that is more the norm than the exception. This learning process could be very useful in the global world in which we operate nowadays.

1.3.1
Miniaturization

Another key aspect of MST is *miniaturization*. Miniaturization is necessary

- to achieve increased functionality on a small scale;
- to utilize particular effects and phenomena that are of no specific relevance at the macroscale level;
- to increase performance in order to make new areas of application possible;
- to interface the nanoworld.

It is generally pursued by using silicon IC-based technologies, with proper modification or the addition of specifically developed modules. A key process is the 3D machining of semiconductor materials, leading to miniaturized structures constituting the sensing, actuating or other functional parts. The main processes are bulk micromachining (BMM) and surface micromachining (SMM).

1.3.1.1 **Bulk micromachining**

Bulk micromachining covers all techniques that remove significant amounts of the substrate (or bulk) material and the bulk is part of the micromachined structure [2]. Typical BMM structures are shown in Fig. 1.2. This microstructuring of the substrate is often done to form structures that can physically move, such as floating membranes or cantilever beams. Other types of structures that can be realized by bulk micromachining are wafer-through holes, often used for through wafers interconnects in chip stacks and very deep cavities or channels to form microwells or reservoirs for biochemical applications. The substrate (generally silicon) can be removed using a variety of methods and techniques. In addition to a number of processes using wet (or liquid) etchants, techniques using etchants in the vapor and plasma state (generally referred to as dry) are available.

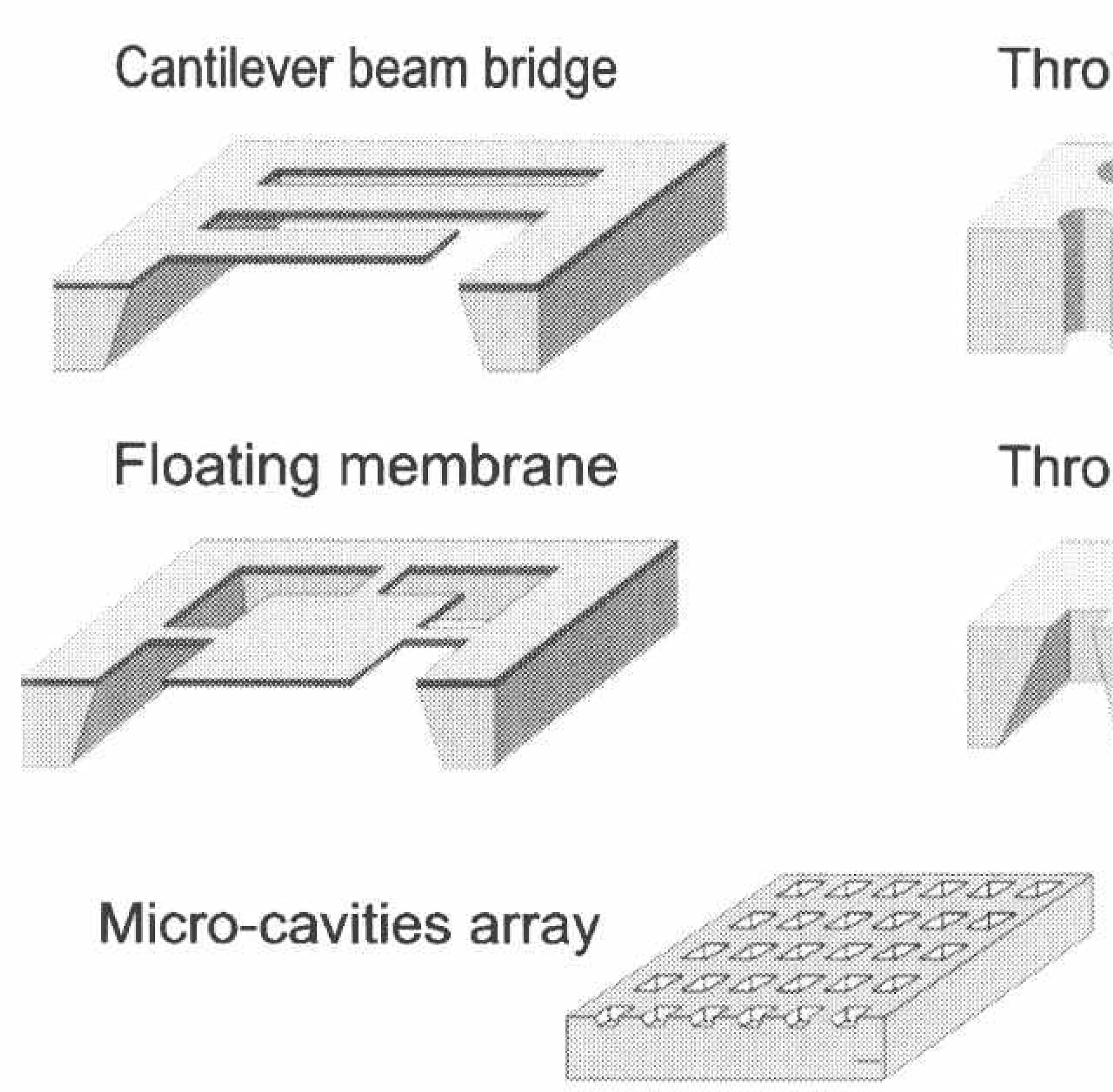

Fig. 1.2 Typical bulk micromachined structures