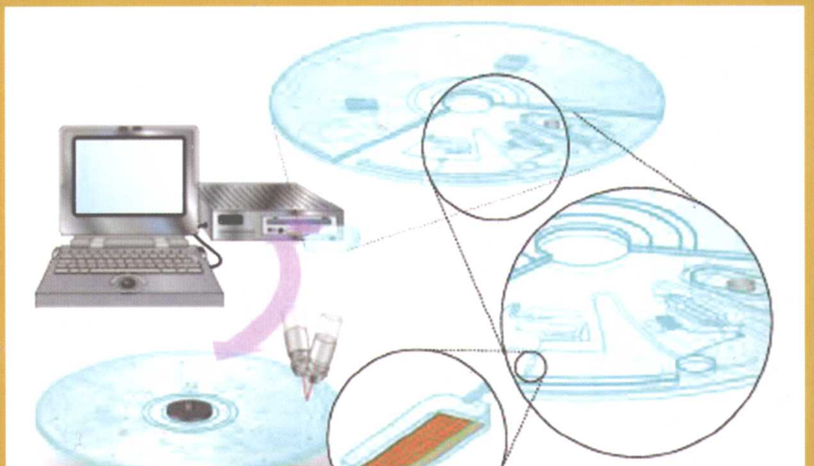
Third Edition

Fundamentals of MICROFABRICATION AND NANOTECHNOLOGY

VOLUME III

From MEMS to Bio-MEMS and Bio-NEMS

Manufacturing Techniques and Applications



Marc J. Madou

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Third Edition

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VOLUME III

From MEMS to Bio-MEMS and Bio-NEMS

Manufacturing Techniques and Applications

I dedicate this third edition of Fundamentals of Microfabrication to my family in the US and in Belgium and to all MEMS and NEMS colleagues in labs in the US, Canada, India, Korea, Mexico, Malaysia, Switzerland, Sweden and Denmark that I have the pleasure to work with. The opportunity to carry out international research in MEMS and NEMS and writing a textbook about it has been rewarding in terms of research productivity but perhaps even more in cultural enrichment. Scientists have always been at the frontier of globalization because science is the biggest gift one country can give to another and perhaps the best road to a more peaceful world.

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Roadmap

From MEMS to Bio-MEMS: Manufacturing Techniques and Applications consists of ten chapters in three parts. In Part I, we compare available manufacturing options for microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS), introduce inspection options for the produced parts (metrology), and summarize available modeling software for MEMS and NEMS. Nonlithography-based (traditional) manufacturing techniques are contrasted with lithography-based (nontraditional) methods in Chapter 1. In Chapter 2, we investigate nature as an engineering guide, and we contrast top-down and bottom-up approaches in Chapter 3. In Chapter 4 we learn about packaging, assembly, and self-assembly from integrated circuits to DNA and biological cells. In these chapters we aim to help the reader decide upon an optimized manufacturing option to tackle specific manufacturing problems. We then introduce some selected new MEMS and NEMS processes and materials in Chapter 5. Finally, we cover metrology techniques for MEMS and NEMS and summarize MEMS and NEMS modeling in Chapter 6.

Of the three chapters in Part II, the first deals with scaling laws, the second with actuators, and the third with issues surrounding power generation and the implementation of brains in miniaturized devices. In Chapter 7, on scaling laws, we look at scaling from both intuitive and mathematical points of view. We are especially interested in deviations from linear scaling, where downscaling reveals new unexpected physical and chemical phenomena. The scaling chapter also constitutes an introduction to the subsequent treatises on actuators in Chapter 8 and on power and brains in Chapter 9. An actuator—like a sensor—is a device that converts energy from one form to another. In the case of an actuator, one is interested in the ensuing action; in the case of a sensor, one is interested in the information garnered. Scaling enables one to compare various actuator mechanisms, such as those proposed to propel a rotor blade, bend a thin silicon membrane, or move fluids in fluidic channels. Power generation poses quite a challenge for miniaturization science; the smaller the power source, the less its total capacity. We will consider the powering of miniaturized equipment, as well as the miniaturization of power sources themselves, in Chapter 9. In the same chapter, we also discuss the different strategies for making micromachines smarter.

In Part III, Chapter 10, we review the MEMS and NEMS markets. Today, the MEMS field has made the transition out of the laboratory and into the marketplace with a plethora of new products, including a strong entry into the consumer electronics field (mobile phones, cameras, laptop computers, games, etc.). If MEMS is entering adolescence, the word *nano* still seems to derive from a verb that means "to seek and get venture capital funding" instead of from the Greek noun for dwarf. Today, the market dynamics for MEMS and NEMS commercial products are very different, and we treat MEMS and NEMS applications separately in this chapter.

As highlighted in Chapter 1, which compares nonlithography-based (traditional) and lithography-based (nontraditional) manufacturing, we hope that a better understanding of how to match different manufacturing options with a given application will guide the identification of additional killer applications for MEMS and NEMS and encourage more companies and research organizations to innovate faster based on their in-house manufacturing tools and know-how.

Note to the Reader: *From MEMS to Bio-NEMS: Manufacturing Techniques and Applications* was originally composed as part of a larger book that has since been broken up into three separate volumes. *From MEMS to*

Bio-NEMS: Manufacturing Techniques and Applications represents the third and final volume in this set. The other two volumes include *Solid-State Physics, Fluidics, and Analytical Techniques in Micro- and Nanotechnology* and *Manufacturing Techniques for Microfabrication and Nanotechnology.* Cross-references to these books appear throughout the text and will be referred to as Volume I and Volume II, respectively. The interested reader is encouraged to consult these volumes as necessary.

Author

Dr. Madou is the Chancellor's Professor in Mechanical and Aerospace Engineering (MEA) at the University of California, Irvine. He is also associated with UC Irvine's Department of Biomedical Engineering and the Department of Chemical Engineering and Materials Science. He is a Distinguished Honorary Professor at the Indian Institute of Technology Kanpur, India, and a World Class University Scholar (WCU) at UNIST in South Korea.

Dr. Madou was Vice President of Advanced Technology at Nanogen in San Diego, California. He specializes in the application of miniaturization technology to chemical and biological problems (bio-MEMS). He is the author of several books in this burgeoning field he helped pioneer both in academia and in industry. He founded several micromachining companies.

Many of his students became well known in their own right in academia and through successful MEMS start-ups. Dr. Madou was the founder of the SRI International's Microsensor Department, founder and president of Teknekron Sensor Development Corporation (TSDC), Visiting Miller Professor at UC Berkeley, and Endowed Chair at the Ohio State University (Professor in Chemistry and Materials Science and Engineering).

Some of Dr. Madou's recent research work involves artificial muscle for responsive drug delivery, carbon-MEMS (C-MEMS), a CD-based fluidic platform, solid-state pH electrodes, and integrating fluidics with DNA arrays, as well as label-free assays for the molecular diagnostics platform of the future.

To find out more about those recent research projects, visit http://www.biomems.net.

Acknowledgments

I thank all of the readers of the first and second editions of Fundamentals of Microfabrication as they made it worthwhile for me to finish this completely revised and very much expanded third edition. As in previous editions I had plenty of eager reviewers in my students and colleagues from all around the world. Students were especially helpful with the question and answer books that come with the three volumes that make up this third edition. I have acknowledged reviewers at the end of each chapter and students that worked on questions and answers are listed in the questions sections. The idea of treating MEMS and NEMS processes as some of a myriad of advanced manufacturing approaches came about while working on a WTEC report on International Assessment Of Research And Development In Micromanufacturing (http://www.wtec.org/micromfg/report/Micro-report.pdf). For that report we travelled around the US and abroad to visit the leading manufacturers of advanced technology products and quickly learned that innovation and advanced manufacturing are very much interlinked because new product demands stimulate the invention of new materials and processes. The loss of manufacturing in a country goes well beyond the loss of only one class of products. If a technical community is dissociated from manufacturing experience, such as making larger flat-panel displays or the latest mobile phones, such communities cannot invent and eventually can no longer teach engineering effectively. An equally sobering realization is that a country might still invent new technologies paid for by government grants, say in nanofabrication, but not be able to manufacture the products that incorporate them. It is naïve to believe that one can still design new products when disconnected from advanced manufacturing: for a good design one needs to know the latest manufacturing processes and newest materials. It is my sincerest hope that this third edition motivates some of the brightest students to start designing and making things again rather than joining financial institutions that produce nothing for society at large but rather break things.

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Scaling Laws, Actuators, and Power and Brains in Miniature Devices

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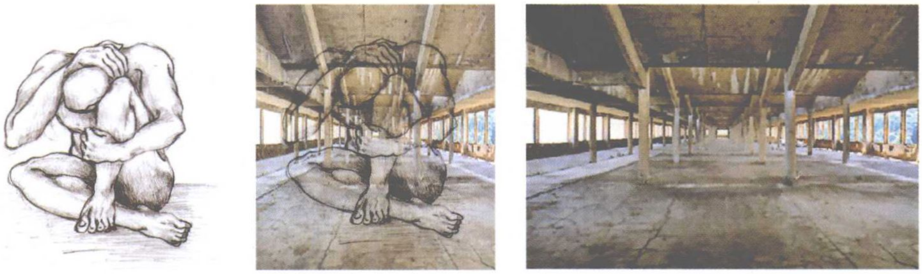
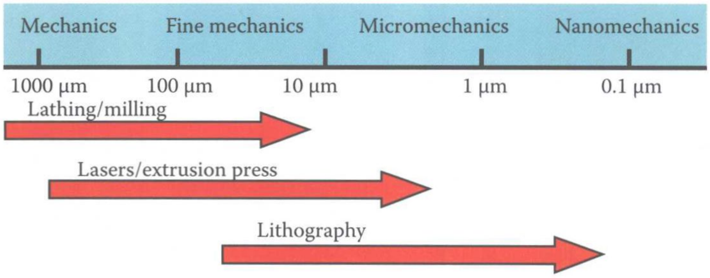
PART I

From Traditional Manufacturing to Nanotechnology



In ten years the only manufacturing left in the United States will be 1) those facilities vital to the defense industry, 2) those industries that are uniquely high-tech, 3) those that cannot absorb long-distance freight charges, and 4) those industries that service "on the spot" instantaneous demand (although even that is questionable).



From macromachining to nanomachining.

Introduction to Part I

Introduction to Part I

In Part I, we compare available manufacturing options for microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS), introduce inspection options for the produced parts (metrology), and summarize available modeling software for MEMS and NEMS. Nonlithography-based (traditional) manufacturing techniques are contrasted with lithography-based (nontraditional) methods in Chapter 1. In Chapter 2, we investigate nature as an engineering guide, and we contrast top-down and bottom-up approaches in Chapter 3. In Chapter 4 we learn about packaging, assembly, and self-assembly from integrated circuits (ICs) to DNA. In these chapters, we aim to help the reader decide upon an optimized manufacturing option to tackle specific manufacturing problems. We then introduce some selected MEMS and NEMS processes and materials in Chapter 5. Finally, we review metrology techniques for MEMS and NEMS and summarize MEMS and NEMS modeling in Chapter 6.

1

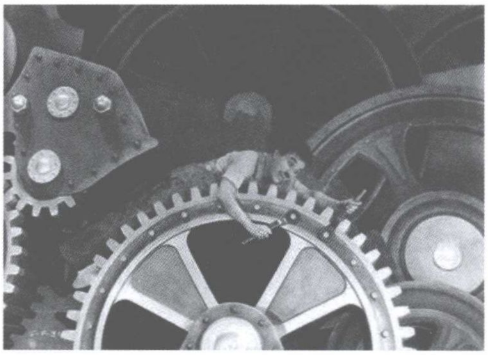
Nonlithography-Based (Traditional) and Lithography-Based (Nontraditional) Manufacturing Compared

1995–02, America lost 2 million industrial jobs, mostly to China. China lost 15 million of such jobs, mostly to machines.

Fortune

Despite the shrinking of America's industrial work force, our country's overall industrial output increased by 50% since 1992.

Economist



Charlie Chaplin's *Modern Times*.

Outline

Introduction

Micromachining, or microelectromechanical system/nanoelectromechanical system (MEMS/NEMS), is emerging as a set of new manufacturing tools to solve specific industrial problems rather than as a monolithic new industry with generic solutions for every manufacturing problem. It is important to evaluate the merit of using one certain MEMS/NEMS technique above all the other available micromanufacturing options [say, lithography-based LIGA* (i.e., nontraditional manufacturing) vs. nonlithography computer numerical control machining (CNC) (i.e., traditional manufacturing)] so as to find the technique that is optimal for the application at hand—in other words, one needs to zero-base the technological approach to the problem.[1] For example, micromachinists are often not aware of the capabilities of traditional machining (nonlithography) and use Si micromachining for parts that could have been made better with a more conventional manufacturing technology. By applying the right tool to the machining job at hand, we hope that micromachining will lead to many more successful commercial applications than there are today.

We start this chapter by listing reasons why one might want to miniaturize a given device at all. We follow this with a short treatise on the maturation of MEMS into a bona fide manufacturing technique that is complimentary today to traditional manufacturing methods. We go on contrasting serial, batch, and continuous manufacturing processes and distinguish between lithography-based (nontraditional) and nonlithography-based (traditional) manufacturing methods, capturing all of this in a large comparison table. In this same context, we explore the difference between truly three-dimensional (3D) manufacturing with equal versatility of machining along all three axes and the more constrained manufacturing methods, such as lithography-based techniques, where the capabilities in one dimension (say the height or *z*-axis) are very different from those in the other two dimensions (say the *x*, *y* plane). We then justify our recommendation to design MEMS from the package inward rather than starting from the MEMS itself. Finally, we introduce a decision tree to help determine the best manufacturing choice for a miniature device when given its detailed specifications. The utility of this decision tree is demonstrated using, as an example, the micromanufacture of a disposable glucose sensor with glucose meter.

Why Use Miniaturization Technology?

Over the last twenty years, many MEMS applications have proven their mettle in the marketplace, and consumer electronic applications that started emerging over the last five years (MEMS are now found in iPods, computers, cameras, GPSs, etc.) have catapulted MEMS once more in the public eye. A long list of reasons confirms why miniaturization presents so many opportunities for product innovation in so many different areas. Some of the most obvious reasons for miniaturization are summarized in Table 1.1. Usually, not all those reasons apply at once. For example, the small dimensions of micromachines might be crucial in medical and space applications but often lack importance in the automotive industry, where cost is the more important driver.

Table 1.1 Why Use Miniaturization Technologies?

- Minimizing of energy and materials consumption during manufacturing
- Redundancy and arrays
- Integration with electronics, simplifying systems (e.g., single-point vs. multipoint measurement)
- Reduction of power budget
- Taking advantage of scaling when scaling is working for us in the microdomain, e.g., faster devices, improved thermal management
- Increased selectivity and sensitivity
- Minimal invasiveness
- Wider dynamic range
- Exploitation of new effects through the breakdown of continuum theory in the microdomain
- Cost/performance advantages
- Improved reproducibility
- Improved accuracy and reliability
- Self-assembly and biomimetics with nanochemistry
- More intelligent materials with structures at the nanoscale

---

* LIGA is a German acronym for "**Li**thographie, **G**alvanoformung, **A**bformung," which in English is (x-ray) lithography, electroplating, and molding. It is a process in MEMS/NEMS that was developed in the early 1980s by a team under the leadership of E. Becker and W. Ehrfeld at the Institute for Nuclear Process Engineering [*Institut für Kernverfahrenstechnik* (IKVT)] at the Karlsruhe Nuclear Research Center. For details, Volume II, Chapter 10.

In Volume I, Chapter 1, when analyzing Moore's law describing the exponential growth in integrated circuit (IC) transistor density, we pointed out that similar exponential improvement in technology sophistication pertains to engineering skills in optics, genetics, and magnetic storage density. Humankind seems "hard-wired" to continue to innovate at an ever-increasing rate (see also Ray Kurzweil's Accelerating Returns, in Volume II, Chapter 2). Miniaturization is just one of the most important means by which humankind is shaping its own destiny rather than being at the mercy of evolution. Adaptation through evolution operates at a pace too slow to produce humans who thrive in the ever faster environmental changes they have created for themselves. In other words, we might have no choice but to adapt through ever-increasing technology sophistication rather than our DNA.

From Perception to Realization

MEMS Finally Succeeds in the Market

In the early 1980s, Si micromachining seemed often applied to show the world that University X also had a clean room or that research group Y could make a yet longer-lasting surface micromachined micromotor. The earlier predicament of Si-based micromachining as the "GaAs of the 1980s and early 1990s" [that is, a very good technology with little acceptance from an entrenched and highly standardized industry (think also Mac vs. PC)] had something to do with the intellectual/philosophical climate of silicon MEMS research and development in the early 1980s. Francis Bacon (1561–1626) explained how, in the advancement of knowledge, one is easily misled by what he calls "idolatry." Two of the "idols" he identifies point in the direction of a universal tendency to oversimplify, often manifested by the assumption of more order in a given body of phenomena than actually exists, and a tendency to be struck by novelty.[2]

Both idols apply to how Si micromachining became misrepresented. Little commonality exists between the many different microdevices made possible by micromachining. Actually, MEMS products represent discontinuous innovations—they are not simply incremental improvements on a previously existing technology. Each new product requires some new thinking on the part of the developers. The striking visual aspects of Si micromachined devices easily give a sense of novelty to any observer. This second idol drove most of the interest in micromachining by the popular press and the efforts of many academics. This climate contributed to overly optimistic expectations for very fast results, with a market size dwarfing the IC industry, and an overemphasis on Si as an answer to all miniaturization problems. In Chapter 10, on MEMS and NEMS applications, we suggest that a realistic number for the market of Si MEMS products today is less than 3% of the IC market (even the $6.3 billion MEMS sales in 2006, i.e., 3% of the $211 billion IC market for 2006, does include non-Si devices). Subsequently, government and industry funding sources experienced a hangover.

Bacon's idols aside, the very large academic involvement in the micromachining field had some other explanations. The IC industry technologically and financially outdistanced universities and forcibly pushed the latter to explore topics requiring lower startup expenses and areas where innovation still seemed likely. It was a perfect fit, as micromachining is an excellent topic for numerous PhD topics. In the 1980s, Si micromachining became a favored filler for clean room overcapacity, especially in Europe, where the IC industry suffered major setbacks against US and Japanese competition. By the end of the century, it was apparent that the Si micromachining industry was still very small compared with the IC industry (less than 3%) but had large numbers of people involved in its research and development. Middlehoek and Dauderstadt estimated, as early as 1994, that about 10,000 researchers worldwide were involved in Si sensor research and that $7.5 billion had been spent over the preceding twenty-five years.[3] Many MEMS researchers have now switched to nanotechnology (NEMS) research instead.

Another major shortcoming in Si MEMS, as practiced in academia, pertains to the lack of interdisciplinary teams. More than any other field, microengineering requires interdisciplinary teamwork rather than specialists. Multidisciplinary work from the design phase on is crucial in the development of a successful sensor product. Many of the participating university groups characterize themselves as multidisciplinary, but the opposite is often true; this lack of multidisciplinary focus continues to obstruct the production of more practical results. It reminds us of a statement by C.P. Snow (1905–1980), who remarked that the separate departments at a university had ceased to communicate with one another. The prefix *uni* in university, he said, lost its meaning as the institution, striving for more and more power as government funds replenished research dollars, had turned into a loose confederation of disconnected mini-states instead of an organization devoted to the joint search for knowledge and truth.

For micromachining to lose the stigma of a technology looking for an application, used in research backrooms and excess industrial clean rooms only, it became important for MEMS to realize some product successes. These industrial successes started appearing principally in the early to mid-1990s and include pressure sensors (on a small scale as early as 1972 at National Semiconductor), accelerometers (1992, from Analog Devices), projection displays (digital mirror devices from TI in 1995), ink-jet nozzles (thermal ink-jet from HP, 1984), electrokinetic platforms (Caliper and Agilent, 1999), fiber optic switches (NTT, 1995), and the first digital mirror device-based products (Texas Instruments, 1996). The first mechanical MEMS applications in industry were modest success stories only, with dollar evaluation in initial public offerings for mechanical MEMS companies typically only in the $5 million to $45 million range. Ever since biotechnology and information/communication industries started taking an interest in MEMS, huge stock market success stories began to appear, and large corporations bought small MEMS companies for billions of dollars. But today, many investors still cringe when they hear the terms *MEMS* or *NEMS*, because of the ill-fated optical MEMS bubble of the late 1990s and a BIOMEMS field that never seems to live up to its promises.

Fortunately, as we will learn in Chapter 10, on MEMS and NEMS applications, mechanical and optical MEMS in consumer electronics, started taking off over the last five years, and even MEMS for large optical switches in telecommunications is now regaining a foothold. The real MEMS breakthroughs continue to originate overwhelmingly from start-up companies (e.g., Illumina and Cepheid) and large corporations (e.g., ADI and Bosch) rather than academia. Micromachining in industry is more correctly seen as a diverse set of tools to solve practical problems in the crafting of subminiaturized 3D structures rather than as a goal by itself. The multidisciplinary approach and matrix organization of MEMS teams in industry further explains their more impressive MEMS accomplishments.

In academia, with its very vertical departmental structure and isolation from practical manufacturing and application understanding, miniaturization science is still often hyped beyond recognition in order to secure grants, tenure, or money from government agencies, large corporations, and venture capitalists. Describing academic MEMS efforts as unbiased fundamental work or fine-tuning of micromachining skills, rather than proclaiming each new result as the latest breakthrough in sensor technology or analytical chemistry, would often serve society better.

The new wave of nanomachining and nanochemistry efforts, mostly grounded in the fundamental research phase at this stage, holds the promise that university scholars might regain the miniaturization playing field in the near future. We can only hope that the hype surrounding nanotechnology settles down and that funding agencies and companies give researchers and scientists enough time to realize the stupendous opportunities that nanotechnology holds. To realize the economic potential of MEMS and NEMS, society will need a new generation of engineers who are comfortable with chemical and biological issues as well as many different types of micro- and nanomanufacturing considerations. Academia will have to become more matrix organized, if only to prepare the proper workforce for the coming age of nanomachining. From the fundamental point of view, micromachining and nanomachining are also of extreme interest, as these fields provide an excellent opportunity for operating experiments in a regime where continuum theory breaks down, holding the potential for discovery of important new chemical and physical phenomena. Unfortunately,

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