HANDBOOK OF

Microlithography, Micromachining, and Microfabrication

Volume 2: MICROMACHINING AND MICROFABRICATION

Editor
P. RAI-CHOUDHURY

IEE MATERIALS AND DEVICES SERIES 12B

HANDBOOK OF

Microlithography, Micromachining, and Microfabrication

Volume 2: MICROMACHINING AND MICROFABRICATION

P. Rai-Choudhury, Editor

SPIE OPTICAL ENGINEERING PRESS
A Publication of SPIE—The International Society for Optical Engineering
Bellingham, Washington USA

THE INSTITUTION OF ELECTRICAL ENGINEERS
London, UK

Library of Congress Cataloging-in-Publication Data

Handbook of microlithography, micromachining, & microfabrication / P. Rai
-Choudhury, editor.
p. cm.
Includes bibliographical references and index.
ISBN 0-8194-2379-3 (v. 2)
1. Microlithography. 2. Micromachining. 3. Microfabrication.
I. Rai-Choudhury, P.
TK7836.H3423 1997
670—dc21 96-40237
CIP

Copublished by

SPIE—The International Society for Optical Engineering
P.O. Box 10
Bellingham, Washington 98227-0010
Phone: 360/676-3290
Fax: 360/647-1445
Email: spie@spie.org
WWW: http://www.spie.org/
SPIE Press Monograph PM40: ISBN 0-8194-2379-3

The Institution of Electrical Engineers
Michael Faraday House
Six Hills Way, Stevenage, Herts.
SG1 2AY United Kingdom
Phone: +44 (0)1438 313311
Fax: +44 (0)1438 360079
Email: books@iee.org.uk
WWW: http://www.iee.org.uk
IEE Materials and Devices Series 12B: ISBN 0-85296-911-2

Printed in the United States of America.

PREFACE

Microlithography, micromachining and microfabrication are rapidly finding applications in many areas, from sensors and actuators to biomedical devices, as well as their uses in microelectronics device manufacturing. Lithography is the key technology that has driven the dynamic growth of the IC industry over the past two decades. To date, optical lithography continues to be the mainstream technology for the IC industry, and is being used in production by leading-edge high-volume manufacturers to support 0.25-μm minimum feature size. Although the exposure system using 193-nm optical lithography is expected to extend to 0.13 μm, the industry remains undecided as to the choice of an exposure system beyond 0.13 μm. The options include extreme ultraviolet (EUV or projection x-ray), e-beam projection, massive parallel direct write, and 1x proximity x-ray. The field of lithography will continue to be very dynamic, and demands an authoritative handbook for process development and production to aid in the training of scientists and engineers.

Microlithography and micromachining are also driving microelectromechanical systems (MEMS). The MEMS technology is rapidly spreading internationally. Within the next decade the cost of micromachined devices will drop to the point where there will be explosive demand for such devices for use in such industries as automotive, aircraft, and disposable medical products. In addition, MEMS will find applications for in-situ process monitoring, environmental health and safety monitoring, and numerous other areas. Use of lithography for fabrication of many microelectromechanical devices frequently requires processing procedures that range from the fabrication of high-aspect-ratio to ultrafine structures.

There are a number of books on lithography, but there still is a need to compile all the diverse information into an easily accessible handbook-type format. SPIE PRESS is publishing the *Handbook of Microlithography, Micromachining, and*

Microfabrication in two volumes. Volume 1 is on Microlithography, and Volume 2 is on Micromachining and Microfabrication.

Volume 2 focuses on the process technology and the numerous device applications using micromachining and microfabrication. This handbook will be useful to researchers and engineers who are not specialists in the field and will serve as a reference book for the experts. It will also attempt to collate pertinent available resource information. The material is presented in such a manner as to allow the book to be utilized as both a textbook and reference book. This handbook is intended for use primarily in industrial laboratories, universities, libraries, and manufacturing facilities.

Acknowledgments

Special thanks must go to my wife, Margaret, for all of her expertise with the English language and for her support thoughout this project. I would like to thank Mary Barnard, Susan Price, and Ruth Haas for their editing and organization of the book, and Eric Pepper for encouragement to undertake this handbook.

P. Rai-Choudhury
August 1997

CONTENTS

HANDBOOK OF

Microlithography, Micromachining, and Microfabrication

Volume 2: MICROMACHINING AND MICROFABRICATION

CHAPTER 1

Micromachining and Trends for the Twenty-First Century

Paul J. McWhorter
Sandia National Laboratories

A. Bruno Frazier
University of Utah

P. Rai-Choudhury
SPIE—The International Society for Optical Engineering

CONTENTS

1.1 INTRODUCTION

Imagine a machine so small that it is imperceptible to the human eye. Imagine working machines with gears no bigger than a grain of pollen, dwarfed in size by a microscopic dust mite (Fig. 1.1). Imagine these machines being batch fabricated tens of thousand at a time, at a cost that begins to approach zero. Imagine a realm where the world of design is turned upside down, and the seemingly impossible suddenly becomes easy—a place where gravity and inertia are no longer important, but the effects of atomic forces and surface science dominate. Welcome to the microdomain, a world now occupied by an explosive new technology known as MEMS (MicroElectroMechanical Systems) or, more simply, micromachines.

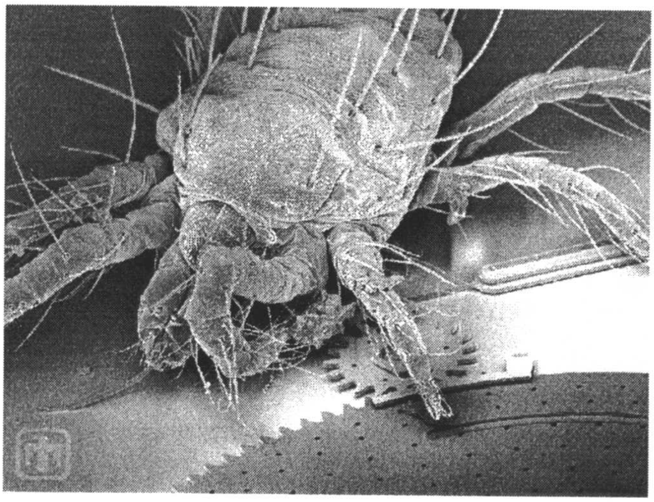

FIG. 1.1 Sandia National Laboratories' MEMS locking mechanism is dwarfed in size by a microscopic dust mite.

MEMS is the next logical step in the silicon revolution. The silicon revolution began over three decades ago, with the introduction of the first integrated circuit.[1] The integrated circuit has changed virtually every aspect of our lives and has been the key defining technology of the twentieth century. The hallmark of the integrated circuit industry over the past three decades has been the exponential increase in the number of transistors incorporated onto a single piece of silicon. This rapid advance in the number of transistors per chip leads to integrated circuits with continuously increasing capability and performance. Continual advances in the manufacturing process control, cleanliness, and critical dimension precision have resulted in the ability to make devices in which the cost of individual transistors or memory cells becomes essentially free. Integrated circuits, which contain tens of millions of transistors, all virtually identical, and all operating as expected, are now routinely made at an affordable cost. As the cost of the basic integrated circuit building block becomes essentially free, the computation, processing, and communication power that can be achieved in an affordable desktop computer staggers the imagination. Processing power that just a few years ago could only be found on the most expensive computers at the world's best research facilities can now be readily acquired in the average household. With this affordable computation power, integrated circuits have become ubiquitous. They are becoming part of virtually all commercial, consumer, and military products. As time has progressed, large, expensive, complex systems have been replaced by small, high-performance, inexpensive integrated circuits.

While the growth in the functionality of microelectronic circuits has been truly phenomenal, for the most part this growth has been limited to data processing, storage, and communication. It is interesting to compare the desktop computer of today with the computer of ten years ago. In many ways, the computer of today is very different than the computer of a decade ago, but in other ways, they are very similar. While the raw processing power, speed, and data storage of today's computers is light years ahead of a decade ago, the two computers look basically the same. In both cases we see people sitting in front of boxes, providing information to the box through the keyboard, and getting information from the box via a CRT. While what the box can do has seen dramatic advances, the way we interact with the box remains basically unchanged. This is because the advancement of the integrated circuit technology has been driven solely by the objective of shrinking the linear dimension of the transistor, the basic building block of the integrated circuit. As the linear dimension of the transistor shrinks, it gets faster, and you can get more of them on a given piece of silicon. This results in chips that can process and store more information faster. To date, this has been the silicon revolution.

The next silicon revolution will be different and more important than simply packing more transistors onto the silicon. The power and capability of the chips of tomorrow will transcend simply storing and processing information. We believe that the hallmark of the next 30 years of the silicon revolution will be the incorporation of new types of functionality onto the chip; structures that will enable the chip to not only reason, but to sense, act, and communicate as well. This will result in chips that will have an ability to affect their surroundings and to communicate what they know to the outside world in new and dramatic ways. Besides processing data, the chips of tomorrow will process such things as chemicals, motion, light, and knowledge. This will be the hallmark of the next silicon revolution, and will have as profound an effect on the next century as the integrated circuit has had on the last.

With the next silicon revolution, the metrics to mark our progress will change. To date, the technology has measured its march by a single metric: the number and size of transistors that can be packed on a single piece of silicon. This metric will be supplanted by metrics that measure how capable a chip is, i.e., to what degree the chip can understand its environment, affect its environment, and enlighten its user.

Dramatic advances in the MEMS field over the last five years begin to show a glimpse into the realization of the new silicon revolution. MEMS enable the fabrication of machines that are vanishingly small. These machines have the ability to perform a variety of functions, including: physical[1-9] and chemical sensing,[10-14] actuation,[15-19] steering light,[20-24] and communication.[25-27] This field has generated intense interest and widespread speculation about the future applications of these minuscule machines. Much of the speculation has centered around the most obvious characteristic of these machines: their size. The fact that these machines are small has captured the imagination of the world. People have been speculating about free-ranging, autonomous robots cruising through the microdomain performing useful work: cleaning our blood veins, repairing broken nerves, repairing tiny defects in integrated circuits, and so forth. For the most part, much of this speculation has missed the mark because it has focused on the most obvious, and not the most important characteristic of MEMS. The most obvious characteristic of MEMS is that they are small. The most important characteristic of MEMS is that they can be made cheaply. To explain this, consider the advanced Pentium processor in a desktop computer. Let's assume for a second that the Pentium chip itself occupied a volume of 100 times its present size, with its other performance and price characteristics the same. The overall size, weight, and form of the desktop computer would not be affected. In fact, this is true of most all applications of integrated circuits. The overall impact of integrated circuits on the world around us would not be dramatically affected if they were much larger. On the other hand, let's assume for a moment that Pentium processors were 100X as expensive. Now, all of the sudden, many applications where they are presently used could no longer afford them. Their overall impact on the world would be significantly less. Hence, the real impact of integrated circuits, and analogously MEMS, does not come from their size, but from their cost.

MEMS can be made cheaply because they are made by exploiting the existing integrated circuit manufacturing infrastructure.[28-30] Integrated circuits are made by the successive deposition, photopatterning, and then etching of thin films on silicon.[31-32] For the case of integrated circuits, these patterns are formed to create small electrical devices. For the case of MEMS, these same fabrication sequences are used to create mechanical structures. Over the past 30 years, there has been tremendous investment in the microelectronics infrastructure worldwide. The ability of the MEMS field to exploit this existing infrastructure will provide huge momentum in the continued development of this field. In addition to propelling the MEMS field forward, this synergy between MEMS and ICs will have ancillary benefits to the integrated circuit industry. Due to the rapid advance of the integrated circuit industry, microelectronic calibration equipment can become obsolete in a very small number of years. As the circuit complexities continue to increase, microelectronic fabrication facilities quickly end up with no commercially viable circuits that can be produced in them. The primary reason for this is associated with the continued advancement in the requirements on the photolithography and associated processes needed to create ever smaller critical dimensions. If we look at the photolithography requirements for MEMS, however, few applications require linewidths of less than one micron, so a fabrication facility that is obsolete from the perspective of integrated circuits could be state of the art from the perspective of MEMS. Thus, MEMS offers the opportunity to extend the useful life of aging microelectronic fabrication facilities.

As with any great endeavor, the future of MEMS will have winners and it will have losers. MEMS has come to mean many different things, and there is no widely accepted definition of what is and is not MEMS. To some, MEMS is only those technologies that are made using completely standard integrated circuit fabrication processes. To others, MEMS has become much broader, encompassing almost any fabrication technique performed on a small scale. In considering the future potential of MEMS, it is very common to compare the technology to the integrated circuit field, and to project growth based on the growth of the integrated circuit industry.[33] In making this comparison, however, it is important to consider some of the fundamentals that have led to the phenomenal growth of the integrated circuit field. We should realize that the ability of MEMS to mimic the performance, growth, and impact of the integrated circuit field will depend on the degree to which we understand and emulate the fundamental issues driving the growth of the integrated circuit field. The characteristics of integrated circuits that have led to their incredible impact are that they are cheap, they are powerful, and they are reliable. There are certain fundamentals in the integrated circuit field that have led to these three fundamental properties. It is well worth considering these fundamentals in considering strategies for the next silicon revolution. One of the first fundamentals of the integrated circuit industry is that there is a common technology base across many manufacturers, products, applications, and industries. The basic building block of virtually all integrated circuits is the MOS transistor. The function of the integrated circuit is determined by the way in which the transistors are connected. Over the course of the silicon revolution, there has been an unimaginable number of transistors made. With such an incredibly large number of transistors made by many different companies for many different products and applications, an enormous knowledge base has developed about how they work, how to make them, and why they fail. Because of the huge volume of this fundamental building block being made across the world, an extremely large science-based understanding of the operation of the transistor has developed from the atomic level on up. In addition to the science-based understanding, enormous empirical understanding exists for process recipes for fabrication as well as an empirical understanding of the do's and don'ts of manufacturing these devices. This synergy between competing manufactures also leads to large support for the advancement of the manufacturing tools. Companies that make integrated circuit manufacturing tools know that if they can create a more competitive tool, a huge worldwide manufacturing base will buy it. This helps to continue to drive the advancement of the quality of the manufacturing tool set. The fact that the basic transistor building block is the same for all competitors in the integrated circuit industry means that the companies that win are those that can: 1) make the transistors at the lowest cost with the greatest reliability, and 2) can connect them together through design to create products that accomplish functions useful to customers.

In addition to the common technology base, the integrated circuit industry relies on a common material set. Virtually all integrated circuits are made from the same very limited material set. Silicon, silicon dioxide, silicon nitride, aluminum, and tungsten are the materials in virtually all integrated circuits. Few successful products draw on any materials outside this limited set. Introduction of new materials such as ferroelectric materials,[34-35] other metals,[36-38] or other dielectric materials[37-39] have been tried on many occasions but with extremely limited success. Introduction of new materials is risky because it introduces new potential failure mechanisms such as material incompatibility problems, cross contamination problems, thermal incompatibility problems, and process integration problems.[40-43]

Another fundamental that has facilitated the success of the microelectronics industry has been the concept of batch fabrication. Integrated circuits are batch fabricated, thousands at a time, with no individual assembly or manipulation required. The cost of building a single high-performance transistor or 100 million transistors on a wafer is the same.[44] This concept of completely batch fabrication processes is one of the most compelling fundamentals that has resulted in the low cost, and hence high impact of microelectronic devices. It is critical to understand that the impact, of microelectronics comes from the fact that they are cheap, and the fact that they are inexpensive comes from the fact that they are batch fabricated. To the degree that any process sequence is introduced into the manufacturing flow that is not a batch process, the devices will no longer be cheap, and hence will have limited impact. These batch fabrication techniques also contribute to the high degree of process control achieved, which leads to high circuit yields, which also contributes to the low cost.

In now considering the future development of MEMS, it is important to contemplate some of the lessons of the integrated circuit field mentioned above. Today, MEMS does not draw on a common technology base. For the most part, MEMS technologies are application specific. For example, to make a display device, a company would be developing new processes, new technology, and possibly even new materials. To make an accelerometer, a company would develop different processes, different technology and different materials. For the future vision of the next silicon revolution to be fully realized, there is a need to develop industry standard MEMS technologies that can be used across different manufacturers and different products. Future product development should be centered around new designs in standard technologies, not new technologies for new applications. The realization of a common MEMS technology base will also enable manufacturing tool developers to begin to focus on MEMS specific manufacturing tools. Without a common and widely used MEMS technology base, few tool vendors will be interested in this field.

The early work in MEMS has also led to a proliferation of new materials, much broader than those commonly used in the integrated circuit world. The incorporation of new materials into MEMS technologies introduces a number of risks. First, one is no longer able to draw on the enormous data base that exists on the performance, process recipes, and failure mechanisms of traditional microelectronic materials. An additional risk is that of the mind set of the existing integrated circuit manufacturing infrastructure. Managers who are in charge of integrated circuit manufacturing facilities do not view non-traditional materials as new materials or new opportunities; they view them as contamination. Most existing MEMS development activities are working on the assumption that when they demonstrate relevant prototypes, full-scale production will be accomplished in some existing microelectronics fabrication facility.If the new MEMS technology or product includes non-standard materials, this greatly increases the risk that the technology will never be allowed inside the production facility.

It can be seen from the above discussion that there is a need for more standardization in MEMS technology. With the broad number and types of MEMS technologies, it is possible to speculate about which of these will become the standard. A taxonomy to consider the existing MEMS technologies can be built around two metrics. The first metric is how closely the technology mimics the fundamental characteristics of the IC industry, and the second metric is how large of a market (if any) is driving a particular technology. For example, a technology that does not posses many of the fundamental characteristics of integrated circuits, and is not driven by a high volume market, will probably not become the standard. On the other hand, a MEMS technology that contains all of the fundamental characteristics of integrated circuits, and is being driven by a large market, has a reasonable chance of becoming a standard. Since standards depend on the market pull, it is important to consider the near-term applications driving MEMS development. A number of market studies have been performed projecting large growth in the market for MEMS-based devices. A study performed by Systems Planning Corporation has projected that the market for MEMS devices will be $14 billion/year by the year 2000. It projects that these components will enable systems worth almost $100 billion/year. For the most part, such studies are done by looking at application areas that use sensors and actuators to calculate which of those application areas could be better served by MEMS-based devices and to then assume that MEMS would capture some share of that market. This is similar to the way projections were done in the early days of integrated circuits. When discrete transistors were first introduced as a replacement for vacuum tubes, people became very excited because they could see that radios that were built with tubes and were big and bulky could now be built much smaller, cheaper, and better using transistors. People projected markets of millions of dollars a year for transistors because of the possibility of small portable radios. These projections were correct in that they did correctly see the market for smaller cheaper radios. What the projections often failed to see, however, were the huge totally new markets enabled by the new technology, such as high-performance, affordable computers on virtually every desktop. In the same way, today's projections for the market for MEMS could very well be overlooking the totally new applications that are enabled by MEMS. Given that we understand the limitations of trying to predict the future, it is still interesting to consider some applications that seem certain for MEMS.

1.2 APPLICATION EXAMPLES

MEMS has progressed to the point that is clear that the technology will be more than simply a laboratory curiosity, and successful, high volume commercial products will be a reality. While MEMS is an emerging technology and has not yet come close to reaching its full commercial potential, there have been a number of high-volume products introduced recently that are MEMS based.

1.2.1 Displays

While a number of successful products and applications have been realized, it seems certain that display systems will be a major driver for the development of MEMS technologies. Today, information is transferred from electronic devices to people through display technology. The dominant display technologies today are CRTs and liquid crystal display systems. Low-cost, high-performance

MEMS-based display systems would have applications in television projection systems, computer displays, virtual reality headsets, pager displays, and practically any other product that could benefit from providing information to the user. This application area is particularly well suited for MEMS because it exploits some of the fundamental characteristics of MEMS. Like integrated circuits, it is possible to build large arrays of MEMS devices side by side, with each unit being identical.[45-48] This characteristic is ideal for displays, since an array of mirrors can be used to project an image, with each mirror representing one pixel of an image. The other factor that makes this application area attractive for MEMS has to do with the issue of contamination. Because MEMS are very small mechanical devices with minuscule features, they are extremely susceptible to particulate contamination. It is critical, therefore, for them to be protected from the small particulates that exist in normal air. For the display application, it is possible to package the MEMS device in something that amounts to a normal IC package with a transparent lid. The transparent lid can allow light in and out, but will protect the MEMS chip from particulate contamination.

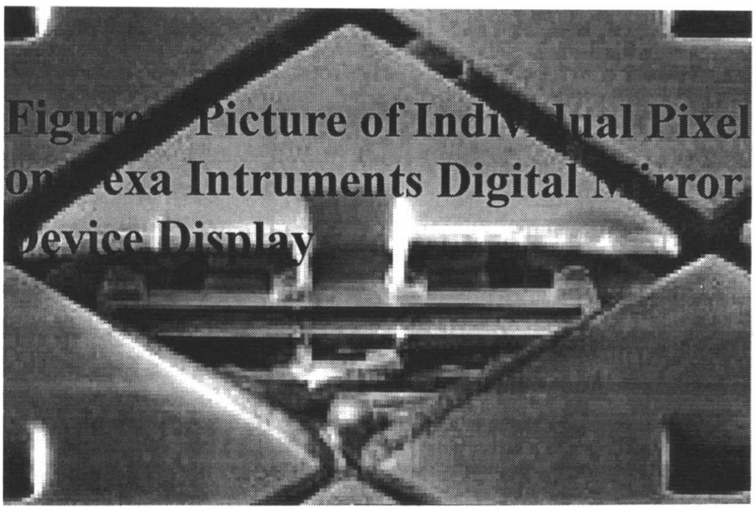

FIG. 1.2 Cross section of one pixel from Texas Instruments Digital Mirror Device.

MEMS are already making inroads into this important application area with Texas Instruments' introduction of its Digital Mirror Device (DMD).[46-47] The DMD (Fig. 1.2) is a projection system based on a very large array of micromachined mirrors. These mirrors are integrated with on-chip CMOS microelectronics which control the position and operation of the mirrors. The