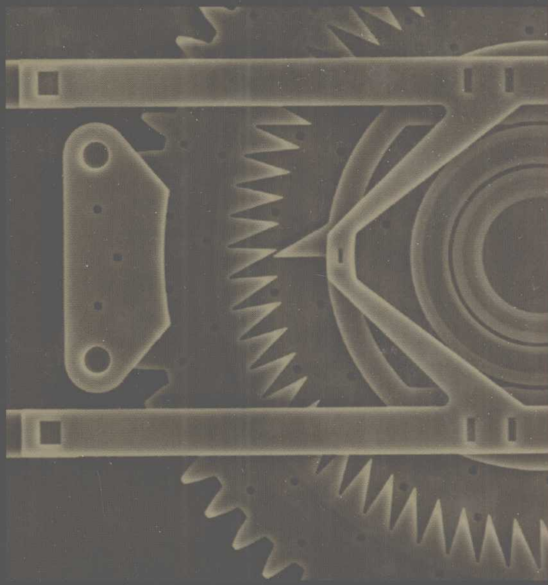
Micro Electro Mechanical System Design



James J. Allen

CRC Taylor & Francis
Taylor & Francis Group

Micro Electro Mechanical System Design

James J. Allen

Taylor & Francis
Taylor & Francis Group

Boca Raton London New York Singapore

A CRC title, part of the Taylor & Francis imprint, a member of the Taylor & Francis Group, the academic division of T&F Informa plc.

Published in 2005 by
CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8247-5824-2 (Hardcover)
International Standard Book Number-13: 978-0-8247-5824-0 (Hardcover)
Library of Congress Card Number 2005041771

Library of Congress Cataloging-in-Publication Data

Allen, James J.
Micro electro mechanical system design / James J. Allen.
p. cm. -- (Mechanical engineering ; 192)
Includes bibliographical references and index.
ISBN 0-8247-5824-2 (alk. paper)
1. Microelectromechanical systems--Design and construction. 2. Engineering design. I. Title. II. Mechanical engineering (Taylor & Francis) ; 192.

TK153.A47 2005
621--dc22 2005041771

T&F informa

Taylor & Francis Group
is the Academic Division of T&F Informa plc.

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Contents

1 Introduction

1.1 HISTORICAL PERSPECTIVE

Making devices small has long had engineering, scientific, and aesthetic motivations. For example, John Harrison's quest [1] to make a small (e.g., hand-sized) *chronometer* in the 1700s for nautical navigation was motivated by the desire to have an accurate time-keeping instrument that was insensitive to temperature, humidity, and motion. A small chronometer could meet these objectives and allow for multiple instruments on a ship for redundancy and error averaging. A number of technological firsts came from this work, such as the development of the roller bearing. Driven by the need for portability, the miniaturization of many mechanical devices has advanced over the years.

The 20th century saw the rise of electrical and electronic devices that had an impact on daily life. Until the advent of the *point contact transistor* in 1947 by Bardeen and Brattain [2] and, later, the *junction transistor* by Shockley [3], electronic devices were based upon the *vacuum tube* invented in 1906 by Lee de Forest. The transistor was a great leap forward in reducing size, power requirements, and portability of electronic devices.

By the mid 20th century, electronic devices were produced by connecting individual components (i.e., vacuum tubes, switches, resistors and capacitors). This resulted in large devices that consumed significant power and were costly to produce. The reliability of these devices was also poor due to the need to assemble the multitude of components. The state of the art was epitomized by the world's first digital computer [4], ENIAC (electronic numerical integrator and computer), which was developed at the University of Pennsylvania [5] for the Army Ordnance Department to carry out ballistics calculations. The need for ENIAC illustrates the need for computers to assist in the development of engineering devices that was emerging at the time. However, ENIAC consisted of thousands of electronic components, which needed to be replaced at frequent intervals, consumed significant power, and wasted heat.

Several key events occurred in the late 1950s that would motivate development of electronics at an increased pace beyond the discrete transistor. The development of the planar silicon transistor [6,7] and the planar fabrication process [8,9] set the stage for development of fabrication processes and equipment to achieve electronic devices monolithically integrated on a single substrate with small feature sizes. The development of this technology for integrated circuits started the *microelectronics revolution*, which led to the production of microelectronic devices with smaller and smaller features and continues to the present day.

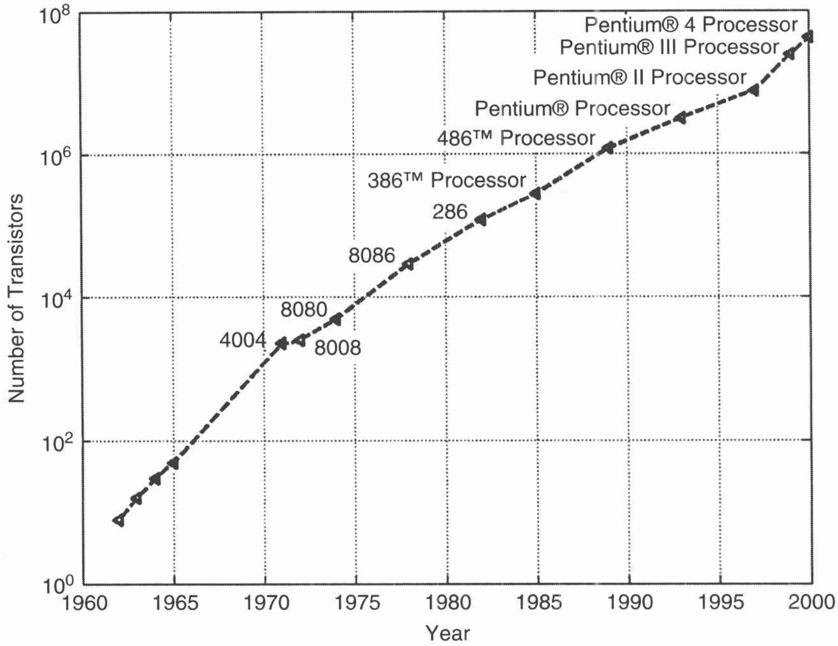


FIGURE 1.1 Moore's law as expressed by the number of transistors in integrated circuits vs. time. (These data are a compilation of data taken from several sources.)

Microelectronic technology developed rapidly, as can be seen by the paper presented by Gordon Moore [10] in 1965 in which he predicted the rapid growth of microelectronics. At this point, microelectronics was producing integrated circuits with 50 transistors on 1-in. wafers, which could be spaced 50 μm apart. Silicon had emerged as the microelectronic material of choice due to the ability to produce a high-quality, stable silicon dioxide layer, which is essential to the fabrication of transistors. In his paper, Moore stated,

> The complexity of minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short term this rate can be expected to continue, if not increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years.

The pace of microelectronic development has been maintained over the years, as can be seen in Figure 1.1.

Dr. Richard Feynman presented a seminal talk, "There's Plenty of Room at the Bottom" on December 29, 1959, at the annual meeting of the American Physical Society at the California Institute of Technology (Caltech); the text was first published in the 1960 issue of Caltech's engineering and science magazine [11] and has since been reprinted several times [12,13]. In the talk, Dr. Feynman conceptually presented, motivated, and challenged people with the desire and advantages of exploring engineered devices at the small scale. This talk is frequently sited as the conceptual beginnings of the fields of *microelectromechanical systems* (MEMS) and *nanotechnology*. Dr. Feynman provided some very insightful comments on the scaling of physical phenomena as size is reduced as well as some prophetic uses of the small-scale devices upon which he was speculating.

- Scaling of physical phenomena
  - "The effective viscosity of oil would be higher and higher in proportion as we went down" in size.
  - "Let the bearings run dry; they won't run hot because the heat escapes away from such a small device very, very rapidly."
- Miniaturizing the computer
  - "...the possibilities of computers are very interesting — if they could be made to be more complicated by several orders of magnitude. If they had millions of times as many elements, they could make judgments."
  - "For instance, the wires should be made 10 or 100 atoms in diameter, and the circuits should be a few thousand angstroms across."
- Use of small machines
  - "...it would be interesting in surgery if you could swallow the surgeon. You put the mechanical surgeon inside the blood vessel and it goes into the heart and looks around."

During this presentation, Dr. Feynman offered two $1000 prizes for the following achievements:

- Build a working electric motor no larger than a 1/64-in. (400-μm) cube
- Print text at a scale (1/25,000) that the Encyclopedia Britannica could fit on the head of a pin

In less than a year, a Caltech engineer, William McLellan, constructed a 250-μg, 2000-rpm electric motor using 13 separate parts to collect his prize [14]. This illustrated that technology was constantly moving toward miniaturization and that aspects of the technology already existed. However, the second prize was not rewarded until 1985, when T. Newman and R.F.W. Pease used e-beam lithography to print the first page of *A Tale of Two Cities* within a 5.9-μm square [14]. The achievement of the second prize was enabled by the developments of the microelectronics industry in the ensuing 25 years. Images of these achievements are available in references 16 and 17.

1.2 THE DEVELOPMENT OF MEMS TECHNOLOGY

Microelectromechanical system (MEMS) technology (also known as microsystems technology [MST] in Europe) has been inspired by the development of the microelectronic revolution and the vision of Dr. Feynman. MEMS and MST were built upon the technological and commercial needs of the latter part of the 20th century, as well as the drive toward miniaturization that had been a driving force for a number of reasons over a much longer period of time. The development of MEMS technology synergistically used to a large extent the materials and fabrication methods developed for microelectronics. Table 1.1 is a historical time line of some of the key events in the development of MEMS technology.

MEMS technology is a result of a long history of technology development starting with machine and machining development through the advent of microelectronics. In fact, in a continuum of devices and fabrication process MEMS occupies the size range from 1 mm to 1 μm. In this book, size scales are referred to as *macro*, *meso*, *micro*, and *nano* scale. Table 1.2 attempts to provide a more definitive definition of these terms.

The development of the discrete transistor and its use began to replace the vacuum tube in electronic applications in the 1950s. In the early days of the development of the transistor, the piezoresistive properties of the semiconductor materials used to develop the transistor, silicon and germanium, were researched [18]. This advance provided a link between the electronic materials and mechanical sensing. This link was exploited early in the time line of MEMS development to produce strain gages and pressure sensors.

The key technical advances that precipitated the microelectronic revolution were the development of the planar silicon transistor [6,7] and fabrication process [8,9]. The planar silicon fabrication process provided a path that enabled the integration of large numbers of transistors to create many different electronic devices and, through continuous technical advancement of the fabrication tools (lithography, etching, diffusion, and implantation), a continual reduction in size of the transistor. This ability to increasingly miniaturize the electronic circuitry over a long period of time was predicted by Moore in 1965 in what was to become known as *Moore's law.* The effects of this law continue today and at least for the next 20 years [19]. This development of fabrication tools for increasingly smaller dimensions is a key enabler for MEMS technology.

In 1967, Nathanson et al. developed the resonant gate transistor [20], which showed the possibilities of an integrated mechanical–electrical device and silicon micromachining. In the early days of microelectronics and through the 1970s, *bulk micromachining*, which utilizes deep etching techniques, was developed and used to produce pressure sensors and accelerometers. In 1982, Petersen [21] wrote a seminal paper, "Silicon as a Mechanical Material." Thus, silicon was considered and utilized to an even greater extent to produce sensors that needed a mechanical element (inertial mass, pressure diaphragm) and a transduction mechanism (mechanical–electrical) to produce a sensor. Bulk micromachining was also utilized to make ink nozzles, which were becoming a large commercial market due to the computer revolution's need for low-cost printers.

In 1983, Howe and Muller [22] developed the basic scheme for surface micromachining; this utilizes two types of material (structural, sacrificial) and the tools developed for microelectronics to create a fabrication technology capable

TABLE 1.1
A Time Line of Key MEMS Developments and Other Contemporary Technological Developments

Time	Event	Company	Ref.
1947	ENIAC (electronic numerical integrator and computer)	University of Pennsylvania	
1947	Invention of the bipolar transistor		2
1954	Piezoresistive effect in germanium and silicon		18
1958	First commercial bare silicon strain gages	Kulite Semiconductor	
1959	"There's plenty of room at the bottom"		11,12
1959	Planar Silicon Transistor		6,7
1959	Planar fabrication process for microelectronics		8,9
1960	Feynman prize awarded for electric motor no larger than a 1/64-in. cube		14,16
1961	Silicon pressure sensor demonstrated	Kulite Semiconductor	
1965	Moore's law		10
1967	Resonant gate transistor		19
1974	First high-volume pressure sensor	National Semiconductor	
1977–1979	Micromachined ink-jet nozzle	International Business Machines, Hewlett-Packard	
1982	Silicon as a mechanical material		20
1982	Disposable blood pressure transducer	Foxboro/ICT, Honeywell	
1985	Feynman prize awarded for producing text at a 1/25,000 scale		15,17
1983	Surface micromachining process		21
1987	Digital micromirror device (DMD) invented	Hornbeck	
1988	Micromechanical elements		22
1986	LIGA process		25
1989	Lateral comb drive		23
1991	Polysilicon hinge		24
1993	ADXL50 accelerometer commercially sold	Analog Devices Inc.	
1996	Digital light processor (DLP™) containing DMD commercially sold	Texas Instruments	
2002	Analog Devices ADXRS gyroscope introduced	Analog Devices Inc.	

of producing complex mechanical elements without the need for postfabrication assembly. Many of the essential actuation and mechanical elements were demonstrated in the ensuing years [23–25].

Also in the 1980s, the LIGA (Lithographie Galvanoformung Abformung) process [26] was developed in Germany. The material set that LIGA uses is significantly different from bulk and surface micromachining, which tend to use

TABLE 1.2
A Definition of Size Scale Terminology

Size scale	Fabrication technology	Devices	Measurement methods
Macroscale (>10 mm)	Conventional machining	Conventional devices and machines	Attachable sensors (strain gauges, accelerometers); visual and optical measurements
Mesoscale (10 mm ↔ 1 mm)	Precision machining	Miniature parts, devices, and motors	Combination of macroscale, and microscale measurement methods
Microscale (1 mm ↔ 1 μm)	LIGA; bulk micromachining; sacrificial surface micromachining	MEMS devices	Optical microscopy; SEM
Nanoscale (1 μm ↔ 1 nm)	Biochemical engineering	Molecular scale devices	AFM, SEM; Scanning probe microscopy

the microelectronic fabrication tools and materials. LIGA can be used to make parts or molds from electroplateable materials or use the molds to make injection molded plastics.

The 1990s saw the development of commercial products that require the integration of MEMS mechanical and electrical fabrication (IMEMS) technologies due to the need for high-resolution sensing of mechanical elements or the addressing and actuation of large arrays of mechanical elements. Analog Devices, Inc. developed an IMEMS technology [27] to facilitate the development of inertial sensors (accelerometer, gyroscope) for automotive applications. Texas Instruments developed an IMEMS technology [28] to produce a large array ($\sim 10^6$) of mirrors used in projectors, cinema, and televisions. The development of IMEMS technologies is discussed in detail in Chapter 3.

1.3 MEMS: PRESENT AND FUTURE

The 1980s to the mid 1990s saw the development of three categories of fabrication technologies for MEMS. *Bulk micromachining*, *sacrificial surface micromachining*, and *LIGA* have unique capabilities based on the fabrication materials utilized, ability to integrate with electronics, assembly, and thickness of materials. These technologies enable many different types of applications and will be discussed in detail in Chapter 3. The information available on MEMS technology has grown as it has matured. Sample lists of journals, periodicals, and Web sites is provided in Table 1.3 through Table 1.5; these offer a wealth of information and a starting point for further research into the world of MEMS.

TABLE 1.3
MEMS Journals

Journal	Publisher
Journal of Microelectromechanical Systems	IEEE/ASME
Journal of Micromechanics and Microengineering	Institute of Physics
Sensors and Actuators	Elsevier Science Ltd
Microsystem Technologies	Springer-Verlag

TABLE 1.4
MEMS Magazines and Newsletters

Magazine/newsletter	Frequency	Publisher
smalltimes	bimonthly	Small Time Media LLC http://www.smalltimes.com/
Micro/Nano	monthly	Reed Business Information
mstnews: International Newsletter on Microsystems and MEMS	bimonthly	VDI/VDE-IT GmbH

The mid 1990s to the present day has seen a shift in the emphasis of MEMS technology research from fabrication process development and the demonstration of prototype sensors and actuators to the commercialization of MEMS products. The impact of MEMS technology is very broad as can be seen by the brief list of MEMS applications in Table 1.6. These MEMS products range from physical sensors (e.g., pressure, inertial), biological, optical, and robotics to radio frequency (RF) devices. MEMS applications span the range of physics. As a result, the MEMS field affects a wide swath of engineers, physicists, chemists, and biologists.

Today's automobile is one area in which the world of MEMS [29] has a direct impact on daily life. A number of locations within the automobile contain MEMS technology, for example:

- *Accelerometers* are used for multiple functions, such as air bag deployment, vehicle security, and seat belt tension triggers.
- *Gyroscopes* are used — possibly in conjunction with accelerometers — in car stability control systems to correct the yaw of a car before this becomes a problem for the driver.
- *Pressure sensors*: the manifold absolute pressure sensor is used to control the fuel–air mixture in the engine. Tire pressure monitoring has also been recently mandated for use in automobiles.
- The *wheel speed sensor* is a component of the ABS braking system that can also be used as an indirect measure of tire pressure.
- The *oil condition sensor* detects oil temperature, contamination, and level.