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Introduction

Microelectromechanical systems (MEMS) is a loosely defined term for man-made mechanical components that are characterized by small size. Translated literally, MEMS should have dimensions in the micron-scale and have both electrical and mechanical components that form a system. Many MEMS devices do not meet these requirements. For example, microfluidic channels may not have any electrical components. In Europe, MEMS is often called *microsystems*. This term may be more accurate but MEMS is more catchy and is used in United States, Asia, and increasingly in Europe.

While the exact definition of MEMS is difficult to formalize, most people agree on the idea of MEMS. Typically, the MEMS device introduces a paradigm shift in manufacturing and/or application. For example, miniature silicon accelerometers have largely replaced the costly macroscopic piezoelectric accelerometers. The MEMS accelerometers are smaller, but their real advantage is the manufacturing process that utilizes the batch fabrication processes originally developed for the integrated circuit technology. Batch fabrication enables simultaneous processing of thousands of identical devices on a single wafer. This is in contrast to the traditional series manufacturing one device at the time. Batch fabrication has made the accelerometers economical, and with the lower cost of silicon accelerometers, the use of inertial sensors has widened first in the automotive industry and more recently in the consumer market.

In addition to providing a cheaper and/or better alternative to the existing technology, MEMS has enabled completely new devices: Inkjet print heads have made low-cost color printing a reality. Micromirror arrays containing more than one million individual mirrors were developed for high definition television, and are used in data projectors in offices, classrooms, auditoriums, and in homes for video games and home theaters.

This chapter gives an overview of the MEMS industry, the history, the type of devices on market, and the fabrication methods used to make them. The overview will pave the way for the detailed device studies in the subsequent chapters.

1.1 History of MEMS

The history of micromachining is tied to the development of integrated circuit (IC) technology. Starting in the 1960s, researchers experimented with using IC fabrication technologies (for example lithography, silicon etching, and thin film growth) to make mechanical structures. Some of the early devices such as the resonant gate transistor [1] were not commercially successful but the work lead to a commercial adoption of pressure sensors and accelerometers in the 1970s. Many of the early processes and applications are documented in the classical paper by Petersen [2].

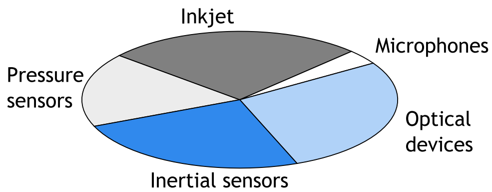
The significant research and development effort in the 1980s and 1990s have lead to new fabrication technologies, devices, and markets for MEMS. Notably, surface micromachining has enabled integration of mechanical components with the integrated circuits leading to low cost accelerometers and micromirror arrays. Commercialization of the MEMS technologies has finally started to impact society on a larger scale. Today, most consumers have, knowingly or unknowingly, encountered MEMS based products.

Building on the technological advancements, MEMS market is currently growing by all measures. The number of MEMS devices sold is increasing and new products are coming out every year. Devices such as microphones that once looked too expensive to implement with microfabrication technologies are sold by millions [3]. While the future for the MEMS is bright, it remains to be seen whether the technology will saturate or if new manufacturing processes and applications will be invented to further drive the development.

1.2 MEMS applications are diverse

The MEMS market size is currently over \$6B per year, but as shown in Figure 1.1, only a few devices are genuinely mass produced. The oldest application, pressure sensors, commands revenue of over \$500M per year. As the price and size of pressure sensors keep decreasing, new applications emerge. For example, integration of pressure sensors inside hypothermic needles [4] or sport watch is possible due to minute size of MEMS pressure sensors.

The other major sensor market, the inertial sensors, has historically been dominated by the automotive industry. Recently, the reduction in price has enabled adoption of MEMS accelerometers in consumer devices such as orientation sensors in digital cameras and game console user interfaces. Gyroscopes have



Emerging applications:

- RF resonators
- RF switches
- Lab-on-a-chip
- Drug delivery systems
- Optical switches
- Microspectrometers

Figure 1.1: The MEMS market is dominated by few applications all generating revenues over \$500M/year. Emerging device fields currently generate revenue less than \$100M/year but show huge growth potentials.

also entered into mass production and show double-digit growth in revenue. The main markets for the gyroscopes are the automotive industry, inertial navigation to aid GPS, and image stabilization for digital cameras. It is expected that the gyroscopes will also be utilized to enhance the human-computer user interface.

For average consumers, the inkjet print heads may be the most familiar microdevice. Each replacement inkjet cartridge has a micromachined inkjet nozzle head. The inkjet print heads are frequently regarded as the largest MEMS market in terms of revenue. However, as the inkjet manufacturers sell the MEMS component as a part of the printer system, it is difficult to attach an accurate dollar value to the MEMS component portion of the inkjet market. Regardless, the inkjet revenue is measured in hundreds of millions.

The lucrative digital microdisplay (DMD) market is dominated by a single manufacturer, Texas Instruments, who holds the key patents in the field. In projection displays, the high contrast ratio of mechanically actuated mirrors enables the micromirrors to compete against the more common LCD technology. The MEMS displays are a unique MEMS product in that they contain millions of moving structures. Fabrication on this scale would not be possible without batch fabrication methods.

Another more recent display product is the reflection based display for portable devices introduced by Qualcomm. The device is based on interferometry, and unlike LCD displays, it does not require any back light. Other optical MEMS devices, such as switches for fiber optical communications, hold promise but may take several years to gain acceptance.

Silicon microphones are the latest entry to the mass market. The growth is driven by cell phone industry that demands solderability – a characteristic not met by otherwise excellent traditional electret microphones. The microphones are an encouraging example of a MEMS product that only a few years ago was deemed too expensive but is now rapidly gaining market share.

Beyond these established markets, a number of MEMS devices hold promise.

The optical switches were regarded the next killer application but the collapse of several network companies in 2001-2002 has dampened the interest in optical networking. Radio frequency (RF) switches is an interesting application as micromechanical switches offer performance advantages over solid-state devices. Currently, the MEMS switches are considered for radars and test equipment where the high performance is needed. Adoption by the cell phone industry appears likely but lifetime and cost issues remain. The low cost and the small size of RF microresonators have also raised interest. This market is attractive as the revenue is high, but in terms of power handling and signal-to-noise ratio, the miniature resonators are not as robust as the established macroscopic resonators. Biomedical devices are appealing, as the small size naturally interfaces well with biological systems. It remains to be seen whether these or some other application will break the $100M barrier.

1.3 MEMS fabrication is based on batch processing

Microfabrication has historically been tied to integrated circuit (IC) fabrication and most of the processing tools and terminology have been adopted directly from IC manufacturing. The parallels are so deep that sometimes a retiring IC manufacturing plant is converted to MEMS fabrication that does not require the latest fabrication technology. But the MEMS fabrication technology is not easy to master. The MEMS specific challenges include packaging of movable mechanical structures, manufacturing of thick structures, and obtaining good absolute dimensional control.

The focus of this book is on device design but some exposure to fabrication technologies is necessary in order to understand the limitations of the technology. In other words, the understanding of the fabrication is not required to explain how a particular MEMS device operates but it explains why the device looks the way it does. The overview given here is enough to explain the general fabrication steps for the devices covered in this book. To supplement the fabrication overview in this book, there are a number of good introductory [5–8] and advanced [9,10] books about microfabrication. In addition, microfabrication has been reviewed in several journal papers that provide concise introduction to the field [2, 3, 11, 12]. These books and review papers combined with the large choice of IC fabrication textbooks [7, 13, 14], provide a solid foundation for micromanufacturing and process integration.

The batch fabrication is a radical departure from the traditional series manufacturing, and is well suited for making relatively simple, mechanical components on a large scale. As illustrated in Figure 1.2, individual devices are photolithographically defined onto a wafer using a photomask and ultraviolet light. The batch fabrication process, specifically the use of photolithography, allows the defining of any shape on the surface of the wafer but it is difficult to fab-

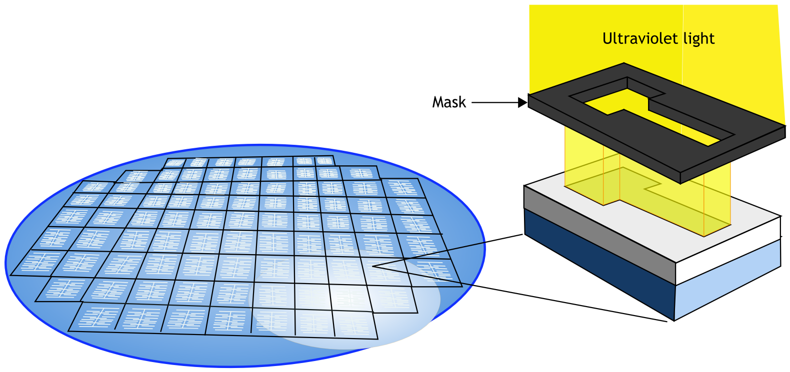


Figure 1.2: An illustration of the batch fabrication. Thousands of components can simultaneously be defined on a single wafer using photolithography.

ricate truly three-dimensional shapes. The process can be compared to carving shapes out of cardboard. Due to fabrication limitations, the MEMS components often look flat or two-dimensional.

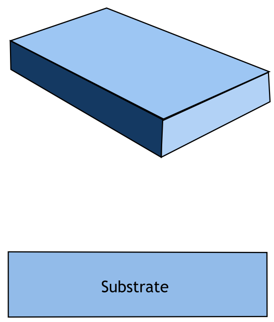
The cost for processing the MEMS wafer does not depend on the number of devices on it and the batch fabrication is an economical way to make a large number of devices. On a typical wafer, there can be thousands of devices and even a small MEMS foundry can fabricate components by millions. Once all the processing steps have been completed, the wafer is diced into individual pieces or dies. Finally, the dies are packaged, often together with an IC.

Numerous MEMS fabrication processes have been developed. Traditionally, the MEMS processes have been divided into surface micromachining and bulk micromachining. We will review these two technologies in the following sections.

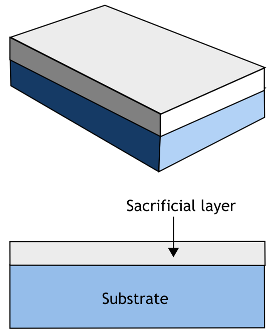
1.3.1 Surface micromachining makes thin structures

Surface micromachining is based on patterning thin-films on top of a substrate wafer [11]. The surface micromachined structures are relatively flat which simplifies the subsequent wafer processing. A typical fabrication process is illustrated in Figure 1.3 where steps of thin-film deposition followed by selective etching are repeated to form semi-3D structures. The thickness of each layer may vary but it is typically less than 5 μm. The simplest structures, such as accelerometers, have two structural layers and one sacrificial layer as shown in Figure 1.3. The record in complexity is the five structural layer process by Sandia National Laboratories that was developed for complex moving devices (microengines and gears) [15].

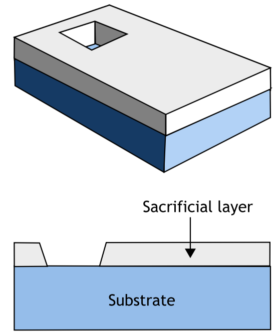
The surface micromachining resembles the traditional IC manufacturing that is also based on processing thin-films on a silicon wafer. The compatibility with the IC processing is one of the main advantages of surface micromachining,



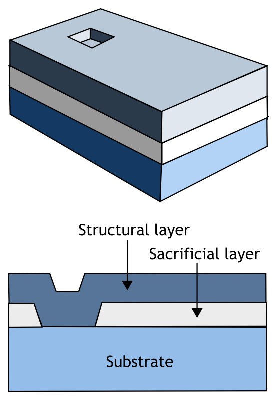
(a) Surface micromachining starts with a substrate wafer, typically silicon with diameter of 100-200 mm and thickness of 500-700 μm.



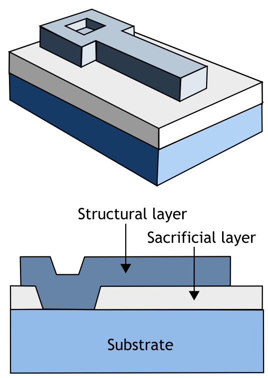
(b) A sacrificial layer is deposited or grown on the wafer. Silicon dioxide with thickness of 1-2 μm is commonly used.



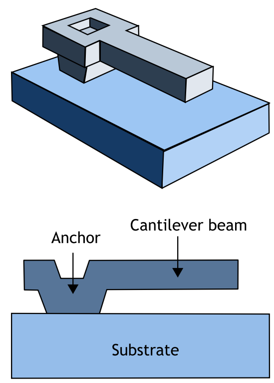
(c) A hole is made by lithography and etching of the sacrificial layer. The smallest dimensions are usually 2-3 μm.



(d) A structural layer, typically 1-5 μm polycrystalline silicon is deposited.



(e) The structural layer is defined using lithography and etching.



(f) The structure is released by removing the sacrificial layer by etching.

Figure 1.3: Typical surface micromachining process involves combinations of layer depositions, optical lithography, and etches to fabricate thin microstructures.

as it is relatively easy to integrate surface micromachining with IC:s to combine mechanical and electrical components on the same chip. The single-chip integration may lead to better performance and reduced packaging cost especially if a large number of connections between the mechanical and electrical parts are needed. For example, the realization of micromirror arrays with more than a million individually controlled mirrors would not be possible without on-chip control for the individual mirrors.

1.3.2 Bulk micromachining makes thick structures

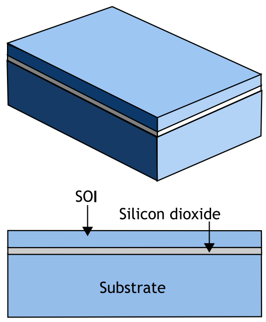
Unlike surface micromachining, which is based on thin-film deposition on top of a substrate wafer, bulk micromachining defines structures by selectively etching the substrate [12]. This can result in relatively thick structures; the typical wafer thickness of 500-700 μm is about 100 times the typical thickness for surface micromachines. The large thickness is useful, for example, in inertial sensors that benefit from a large mass. In addition to the thickness, the bulk micromachined structures can be made of single-crystal silicon as opposed to amorphous or polycrystalline thin-films. The predictable and stable material parameters of crystalline silicon are desirable for mechanical sensors.

Bulk micromachined accelerometers and pressure sensors were the first commercialized MEMS products. These devices have been hugely successful, for example, MEMS pressure sensors represent over 90% of all sold pressure sensor units [3]. Early bulk micromachined devices were made by wet etching [16] and several exotic processes have been developed. For example, thin membranes for pressure sensors have been defined using epitaxial growth of silicon combined with electrochemical etch stop [2]. The wet processes are still used but advances in plasma processing have made dry etching the mainstream. Especially the combination of deep reactive ion etching (DRIE) and silicon on insulator (SOI) technology has simplified the bulk manufacturing and reduced the device size [17–19].

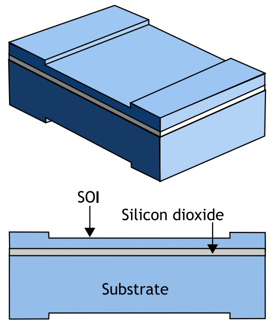
DRIE enables etching narrow channels through the entire wafer and results in almost vertical sidewalls. It is possible to make channels with aspect ratio of 50 to 1 or better, meaning that a 500 μm deep trench can be only 10 μm wide. In contrast to the wet etching where the depth and width of a trench are typically equal, the reduction of device size can be significant and more devices are obtained from a single wafer. As the cost of processing one wafer is approximately constant, the smaller device size directly reduces the device cost.

Figure 1.4 shows a possible process to make accelerometers using SOI wafers, DRIE etching, and wafer bonding. The final structure is hermetically sealed at the wafer level, which greatly reduces the cost of final assembly and packaging. The manufacturing process is quite straightforward and results in a compact structure with well-defined features.

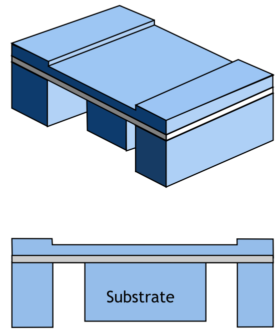
The SOI wafers used in MEMS are manufactured by bonding two silicon wafers together with a 1-2 μm layer of silicon dioxide in between them. The silicon dioxide acts as a natural etch stop and all etched structures have the desired thickness determined by the SOI thickness. The silicon dioxide can also be used as a sacrificial layer for making free structures of single-crystal silicon. As two silicon wafers are used for making one SOI wafer, the SOI wafers are more expensive than bare silicon wafers. However, the material cost increase is compensated by the processing costs savings.



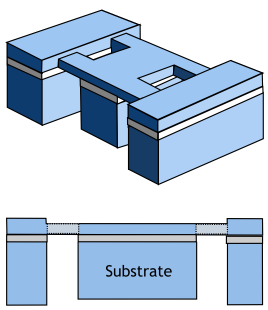
(a) The process is started with a SOI wafer with substrate thickness of 550-650 μm and SOI thickness of 10-20 μm.



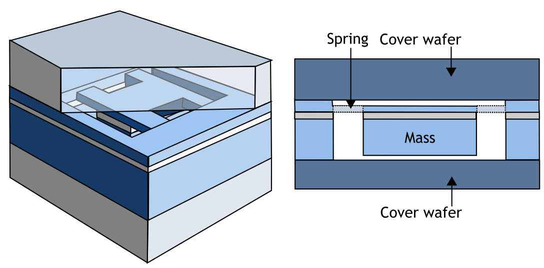
(b) A 2 μm recess is etched on front and back to define where movable structure is.



(c) Trenches are etched using DRIE on the back of the wafer to define the sensing mass. The oxide stops the etch.



(d) Final DRIE on the front of the wafer defines the supporting beams that hold the mass.



(e) The device is completed by bonding wafers on front and back to make a hermetically shielded accelerometer. After dicing, the dies are ready for final assembly.

Figure 1.4: Bulk micromachining process for making a silicon accelerometer.

1.4 Introduction to the *Practical MEMS* book

This book is focused on in-depth analysis of microdevice operation. The emphasis sets the *Practical MEMS* book apart from other MEMS books that cover both the fabrication and device operation. The integrated approach of including both fabrication and analysis has merits and an integrated textbook is a good first introduction to the microsystems. However, the depth of analysis in textbooks that cover both fabrication and applications is limited to describing the device operation.

This book goes further into exploring why certain devices are successful and others have failed. The first part of this book covers the traditional microsensors (accelerometers and pressure sensors) that are a major and growing commercial microsystem application. The emphasis is on measuring small signals that is a fundamental challenge when making small sensor systems. Since ability to do simplified analytical design analysis is invaluable in the early stage of any sensor design, the physical principles behind the sensor operation are illustrated by numerous calculated examples. These examples are carefully chosen to both illuminate the device operation and to quantify the performance trade-offs in the microsensors.

The second half of the book introduces actuators. The merits of different actuation schemes are illustrated by developing scaling laws for different actuation schemes. Capacitive, thermal, piezoelectric actuation theory is developed and illustrated with examples. Applications ranging from optical, RF, and sensing (gyroscopes) are explored with emphasis on critical evaluation of whether MEMS has a competitive advantage to replace the current technologies. Again, the physical challenges of miniaturization are illustrated with several calculated examples. For example, the effect of mirror size is studied in optical MEMS applications such as optical displays and microscanners.

Finally, the book is concluded with an introduction to MEMS fabrication economics. The cost, yield, and profits in batch fabrication are investigated. Several case studies are used to illustrate the challenges of making a profit with microfabrication.

Key concepts

- MEMS stands for microelectromechanical system. Europeans prefer the shorter and often more accurate word *microsystem*.
- Microdevices have been developed since the 1960s. Since the 1990s, the field has been growing rapidly.
- Pressure sensors, accelerometers, optical displays, and inkjet printers are established commercial MEMS applications.
- Optical networking and RF MEMS hold commercial promise but have not yet become significant industry.
- Batch fabrication enables fabrication of thousands or even millions of identical mechanical components on a single wafer
- Optical lithography is used to define the shape of the structures. Large number of devices can be made using the same optical mask.
- Surface micromachining is based on processing and patterning thin-films on a wafer.

- Bulk micromachining is based on etching the wafer to make relatively thick structures.

Exercises

Exercise 1.1
Download or copy from the library the classical review paper from 1982 by Petersen [2] and recent review by Bryzek *et al.* [3] and answer to the following questions: 1. How does the MEMS fabrication processes in the papers differ? 2. List applications that are highlighted in papers. How does applications in the two papers differ and is this difference reflected in manufacturing processes?

Exercise 1.2
Using your favorite search engine, find at least three estimates for the world wide MEMS market size. Comment on how reliable you feel the sources are and whether there is discrepancy between the estimates.

Exercise 1.3
Using your favorite search engine, find an estimate of the world wide market size for integrated circuits (ICs) and compare it to the MEMS market size. Noting that silicon microcircuits and silicon microsensors were invented around the same time in the 1960s, think of reasons that could explain the difference in the market size.

Exercise 1.4
Why surface micromachining is more compatible with integrated circuit fabrication than bulk micromachining?

Exercise 1.5
List MEMS applications that you have personally encountered.

Exercise 1.6
Why optical lithography is important in microfacrication?

Exercise 1.7
The number of citations is a relatively objective way to judge the importance of academic publications. Most publications are cited less than ten times, the papers that resonate well with the academic community will be cited more than 30 times, and seminal papers receive over a hundred citations.

Google Scholar (`scholar.google.com`) is a free tool to search scholarly literature. Google Scholar will also give an estimate of the number of citations for each search result has received. The more cited articles will have a higher ranking and will appear first. For example, search "RF MEMS" will display the article by C. Goldsmith, *et al.* titled "Performance of low-loss RF MEMS capacitive switches," that has been cited more than 200 times.

Try out Google Scholar to find a highly cited journal paper on: i. MEMS accelerometer, ii. MEMS pressure sensor, iii. MEMS gyroscope, iv. RF MEMS switch, v. optical MEMS, vi. MEMS microphone, and vii. MEMS inkjet print head. Note the number of citations manuscripts in different applications have received and compare the search results. How does the importance to the academic community correlate with the commercial interest? Note that in old applications such as accelerometers the word MEMS may not appear in the article. Other relevant keywords include silicon and solid-state.