CHAPTER 21

INTRODUCTION TO MICROELECTROMECHANICAL SYSTEMS (MEMS): DESIGN AND APPLICATION

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1	INTRODUCTION	863	5	EXAMPLES OF MEMS DEVICES AND THEIR APPLICATIONS	870
2	MICROFABRICATION PROCEDURES	864	6	CONCLUSIONS	872
3	DESIGN AND SIMULATIONS	866		APPENDIX: BOOKS ON MEMS	873
4	FABRICATION FOUNDRIES	868		REFERENCES	874

1 INTRODUCTION

In general, microelectromechanical systems have features in the micrometer- and, increasingly, nanometer-size range. Often, they are miniaturized systems that combine sensors and actuators with high-performance embedded processors on a single integrated chip. The word *electromechanical* implies the transfer of technology from mechanical to electrical and vice versa. Those devices embedded in functional systems are some times referred to as microsystems. This field is increasingly leading to devices and material systems whose size is on the order of a nanometer, that is, the size of molecules. Microsystems and nanotechnology enable the building of very complex systems with high performance at a fraction of the cost and size of ordinary systems. As such, these systems are the enabling technology for today's explosive growth in computer, biomedical, communication, magnetic storage, transportation, and many other technologies and industries. Microsystems and nanotechnology challenges range from the deeply intellectual to the explicitly commercial. This field is by its very nature a link between academic research and commercial applications in the aforementioned and other disciplines. Indeed, these disciplines span a very broad range of industries that are at the forefront of current technological growth.

The integration of microelectronics and micromechanics is a historic advance in the technology of small-scale systems and is very challenging for designers and producers of MEMS. The addition of micromachined parts to microelectronics opens up a large and very important parameter space to technological development and exploitation.

The MEMS structures and devices result from the sequence of design, simulation, fabrication, packaging, and testing. There are varieties of devices that can be classified as MEMS. There are passive devices, that is, nonmoving structures. There are devices that involve sensors and devices that involve actuators, which have micromechanical components. These are conceptually reciprocal in that sensors respond to the world and provide infor-

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mation and actuators use information to influence something in the world. Another class includes systems that integrate both sensors and actuators to provide some useful function. This classification, like most, is imperfect. For example, some devices that are dominantly sensors have actuators built into them for self-testing. Airbag triggers are an example. However, the framework provides a simple but quite comprehensive framework for considering MEMS devices.

In this chapter we will discuss some aspects of the design of these devices and introduce the reader to the technology used. In addition, we will discuss the structure of some of those devices.

2 MICROFABRICATION PROCEDURES

The fact that the field of MEMS largely grew out of the integrated circuit (IC) industry has been noted often. There is no doubt that the use of fabrication processes and associated equipment that were developed initially for semiconductor industry has given the MEMS industry the impetus it needed to overcome the massive infrastructure requirements. However, it is noted that the field of MEMS has gone far beyond the materials and processes used for IC production. The situation is indicated schematically in Fig. 1. About a half dozen materials, notably silicon and its oxide and nitride, and standard microfabrication processes, such as lithography and ion implantation, oxidation, deposition, and etching, have generally been employed to make ICs. The set of materials used in IC devices is expanding to include, for example, low-dielectric-constant materials, polymers, and other nonconventional IC materials.

Many MEMS can be made with the same set of materials and processes as used for microelectronics. However, one of the hallmarks of the emerging MEMS industry is the use of numerous other materials and processes. Most basically, substrates other than silicon are being employed for MEMS. Silicon carbide has been demonstrated to be a good basis for many mechanisms that can stand higher temperature service than silicon. Diverse materials can be used within MEMS devices. While aluminum and, recently, copper are the metals used in IC devices, micromachining of many other metals and alloys has been demonstrated. Magnetic materials have been incorporated into some MEMS devices. Piezoelectric materials are especially attractive for MEMS because of their electrical–mechanical reciprocity. That is, application of a voltage to a piezoelectric material deforms it, and application of a strain produces a voltage. Zinc oxide and lead zirconium titinate (PZT) are important piezoelectric materials for MEMS. Many other examples of materials employed for MEMS could be given. However, the point is clear. Micromechanics are made of many more kinds of materials than microelectronics.

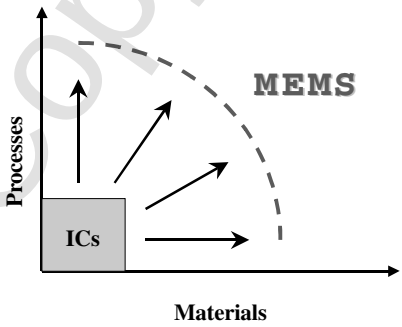


Figure 1 The number of materials and processes employed to make MEMS greatly exceeds those used to manufacture integrated circuits.

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Because of the varieties of materials used in MEMS fabrication, the processes for producing and modifying them widened far beyond those found in the IC industry. However, something more fundamental is at work when it comes to processes for making MEMS. Integrated circuits are monolithic and, despite up to 30 layers in some cases, are made by largely two-dimensional thin-film processes that yield what some call 2.5-dimensional structures. By contrast, micromechanical devices must have space between their parts so they can move, and the dimension perpendicular to the substrate is often very fundamentally necessary for their performance. Development of processes to make micrometer-scale parts that can move relative to each other was the breakthrough that enabled MEMS. Such micromachining processes fall into three major categories, which will now be reviewed briefly.

Surface micromachining involves the buildup of micromechanical structures on the surface of a substrate by deposition, patterning, and etching processes. The key step is the etching away of an earlier deposited and patterned sacrificial layer in order to free the mechanism. Figure 2 shows the steps needed for such processing.[1,2]

This process was first demonstrated about 35 years ago, when a metal–oxide–semiconductor field effect transistor (MOSFET) with a cantilever mechanical gate was produced.[3] The most common sacrificial material now is silicon dioxide, which is conveniently

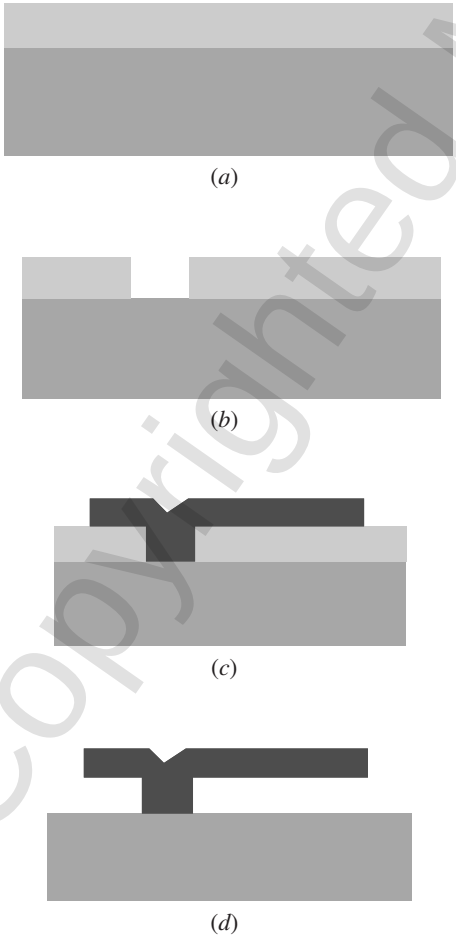


Figure 2 Surface micromachining steps: (*a*) Step 1: Deposit sacrifical layer. (*b*) Step 2: Pattern layers. (*c*) Step 3: Deposit structure layer. (*d*) Step 4: Etch sacrifical layer.

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dissolved from under a movable part using hydrofluoric acid. Surface micromachining has been used to produce an amazing variety of micromechanical devices, some of which are now in large-scale production. Microaccelerometers and MEMS angle rate sensors are examples.

Figure 3 shows examples of mechanical structures built by surface micromachining.

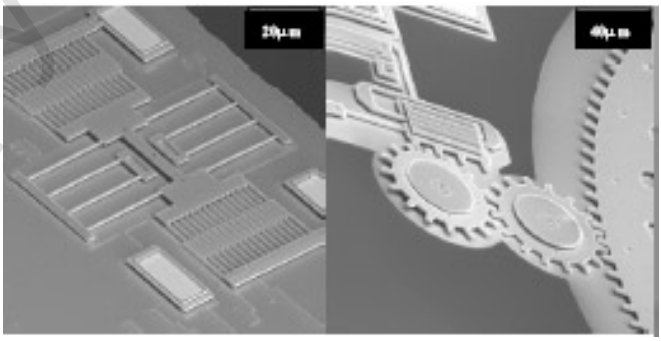
Bulk micromachining, as the name implies, involves etching into the substrate to produce structures of interest. It can be done with either wet or "dry," that is, plasma, processes, either of which can attack the substrate in any direction (isotropically) or in preferred directions (anisotropically). Bulk micromachining has two primary variants. The first depends on the remarkable property of some wet chemical etches to attack single-crystal silicon as much as 600 times faster along some crystallographic directions compared to others. This anisotropic process is called orientation-dependent etching (ODE). It was known long before the emergence of MEMS technologies and has become a mainstay of the industry. ODE is especially useful for producing thin membranes that serve as the sensitive element in micropressure sensors. It is employed for production of these and other commercial MEMS devices. The second approach to bulk micromachining is to use plasma-based etching processes that attack the substrate, usually silicon, in preferential directions. Deep reactive ion etching (DRIE) is a plasma process that is used increasingly to make MEMS. It can produce structures that are over 10 times as deep as they are wide. Bulk micromachining steps are shown in Fig. 4*a*. Examples of devices developed using bulk micromachining are shown in Fig. 4*b*.

The third general class of micromachining processes is a collection of the numerous and varied techniques that can produce structures and mechanisms on the micrometer scale. Laser-induced etching and deposition of materials, electroetching and electroplating, ultrasonic and electron discharge milling, ink jetting, molding, and embossing are all available to the MEMS designer.

Similar to ICs, MEMS devices are made using creative combinations of the materials and processes noted above. Some remarkable micromechanisms have been demonstrated, largely in academic fabrication facilities, and commercialized using diverse foundries.

3 DESIGN AND SIMULATIONS

To verify that the devices function, the designer has to model the MEMS device. The modeling involves writing the equation of motion or physical modeling of the performance of



(*a*) (*b*)

Figure 3 Examples of surface micromachining: (*a*) simple sensors and actuators; (*b*) gear train.

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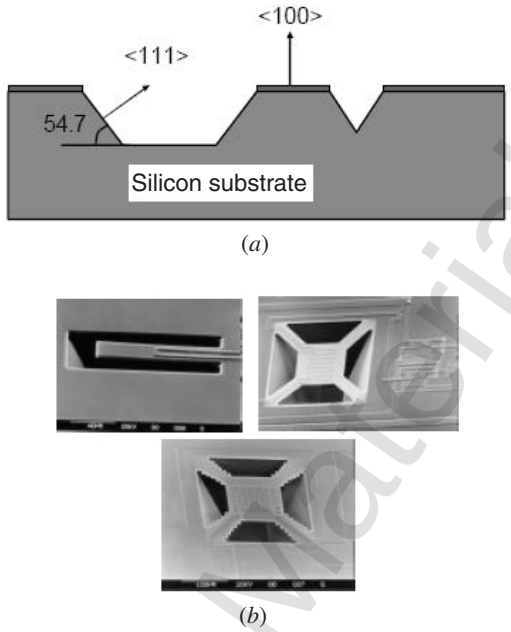


Figure 4 (*a*) Bulk micromachining anisotropic etch. (*b*) Examples of bulk micromachining devices.

the device. Finite-element techniques are used to solve these modeling equations. There are a variety of computer aided design (CAD) tools to aid the designer in the simulation and modeling of the device. In a very fundamental way, these tools are more complicated than the software for design of either solely ICs or solely mechanical devices. This is due to the close coupling of both electrical and mechanical effects within many MEMS. Consider a microcantilever that is pulled down by electrostatic forces. Its simulation has to take into account both the flow of electrical charge and mechanical elasticity in an iterative and self-consistent fashion.

Thermal, optical, magnetic, fluidic, and other mechanisms are also active in some MEMS and have to be handled self-consistently in the simulation phase.

Two basic approaches have been taken in the past decade to the need for specialized software for the design and simulation of MEMS. In the first approach, CAD design, tools and available software from electronic design were modified to accommodate the requirement for MEMS design. In the second approach finite-element modeling was applied to MEMS. Software from the Tanner Tools very large scale integrated (VLSI) design suite were used for MEMS, for example MEMS-PRO,[4] which was recently acquired by MEMSCAP,[5] as was the popular mechanical engineering software from ANSYS.[6] Recently, new suites of software specifically developed for MEMS were marketed. Most of them include electronic, mechanical, and thermal simulation, and some have other physical mechanisms as well as processing simulation tools. Such software is available from CFD Research Corporation, Coventor (formerly called CRONOS Technologies), IntelliSense Corporation, and Integrated Systems Engineering. These tools vary widely in the mechanisms and material parameters that they include, the details of design and simulation of devices, and the fabrication facilities with which they interface. The choice of suitable software to use for MEMS design is still challenging. MEMSCAP is based on CADENCE (which is the most popular IC design tool[7]). It consists of a set of tools which enable the design flow either bottom up or top down. It

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incorporates the MEMS design environment into existing and well-known environments with easy intellectual property (IP) cells or design reuse and the ability to exchange data between multidisplinary teams. The MEMSCAP simulator is based on the CADENCE environment, so the designer can simulate MEMS devices with the IC schematics and simulation. Models can be generated from the ANSYS finite-element model or from written analytical equations. Behavior models/scalable symbolic view can be generated. The Verilog-A model can also be generated. The generated model can be used to perform optimization simulations inside the environment or to realize a system simulation. In addition, emulators are available for etching, cross section projection of the different material layers.

The design of MEMS devices involves knowledge of the sequence of materials to be used to realize the device. The sequence of materials used could be the standard sequence, in which case a standard technology process may be used in conjunction with other processing steps, for example, postprocessing. The sequence of materials to be used could be custom designed by the designer, which requires knowledge of the materials and their thin-film properties. Designers usually design the device and identify the material to be used and then use CAD tools to verify the performance. Iteration procedures are part of the design until the required performance is reached. After satisfactory simulation performance, the device is sent to fabrication foundries.

4 FABRICATION FOUNDRIES

After designing and simulating MEMS and deciding on the materials they will contain and the processes needed to make them, the next concern is which fabrication facility to employ. Sometimes, a standard IC facility can be used with postprocessing steps. Postprocessing involves adding or removing materials from the standard fabricated device. For example, using a standard complementary metal–oxide–semiconductor (CMOS) fabrication facility, we could realize the suspended-plate structure shown in Fig. 5. In this case the CMOS is removed from the bulk substrate to create the suspended structure on top of the etched pit.

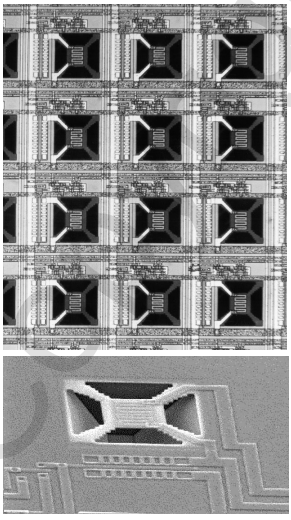


Figure 5 Micro-hot-plate array and scanning electron micrograph of one of the elements.

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For example, the micro-hot-plate shown in Fig. 5 was realized in CMOS technology in a standard foundry with a postprocessing step of bulk micromachining to produce the suspended thin film with a resistive heater. The small mass of the heated element permits temperature changes of 300°C in a few milliseconds.

Many MEMS structures and devices have been produced by such postprocessing of CMOS chips.[8–10] Techniques which are not compatible with CMOS have also been used, in which case surface micromachining techniques produce mechanical structures on top of the substrate. A micromirror fabricated using surface micromachining is an example of such a device.

Figure 6 is a schematic of two pixels of the Digital Mirror Device manufactured by Texas Instruments. The torsion hinges are 5×1 μm in area and about 100 nm thick. The individual mirrors are 16 μm square. Over 500,000 of them are found in a single device, making this the system with the most moving parts produced in the history of mankind. The inventor, Larry Hornbeck, and the company received Emmy Awards in 1998 for outstanding achievement in engineering development.

There are now several foundries specifically for the production of MEMS. The fact that design rules in MEMS are roughly two generations behind those in ICs is significant. This enables MEMS foundries to buy used equipment from the microelectronics industry. Mass production of many MEMS now is done using 100- and 150-mm wafers. Several companies and organizations in the United States and abroad offer fabrication services for MEMS somewhat analogous to those in IC foundries. They include BFGoodrich, Advanced MicroMachines, CMP (France), Institute of Microelectronics (Singapore), IntelliSense, ISSYS, Surface Technology Systems (U.K.), and many more.

Most of these foundries have all the facilities in-house to produce complete MEMS devices. However, the wide variety of materials and processes that can be designed into MEMS means that it is not always possible to find all the needed tools under one roof. Hence, the Defense Advanced Research Projects Agency instituted a new type of foundry service several years ago. It is called the MEMS-Exchange.[11] This organization contracts with diverse industrial and academic fabrication facilities for a wide range of services. The MEMS designer can draw from any of them. A completed design is sent to MEMS-Exchange, which handles scheduling, production, billing, and other factors, such as the protection of proprietary designs.

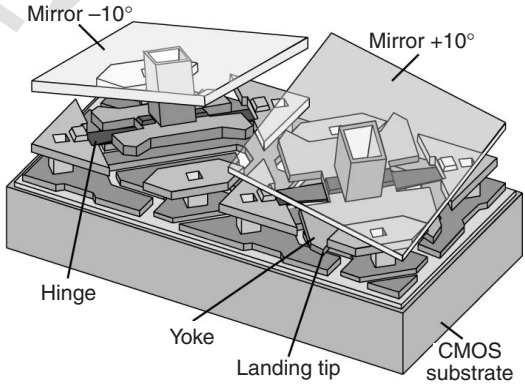


Figure 6 Micromirror.

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5 EXAMPLES OF MEMS DEVICES AND THEIR APPLICATIONS

There are varieties of applications of MEMS. This section gives a brief overview of MEMS applications with reference to commercial devices. There are many fields in which MEMS devices have been introduced. Table 1 shows examples of MEMS applications.

Table 1 summarizes some of the applications of MEMS and shows the air bag accelerometer developed by Analog Devices in which the structure of the sensors is based on a variable-capacitor device. Figure 7 shows the surface micromachining of the Analog Devices accelerometer. Mechanical structures were studied to develop miroresonators, such as the fixed–fixed beam of Fig. 8, and circular resonators.

Researchers are using MEMS techniques to produce an array of nanoresonators that can be integrated with other components. Figure 8 shows a working radial contour-mode disk resonator with 10 μm radius and quality factor $Q = 1595$ at atmospheric pressure.[12] Work is aimed at coupling such resonators together to make large arrays. These devices were used in the design of electric filters for high-frequency communication systems. The benefit of using MEMS device is the high quality factor, which implies a high-efficiency circuit. Figure 9 shows an example of a mechanical switch which is an electrostatic switch. It is used in high-frequency circuits as a small-loss switch. The radio-frequency switch is small, on the order of 50 μm $\times$ 50 μm.

Figure 9 shows a micrograph (top) and schematic of the Raytheon MEMS microwave switch. The electrode under the flexible membrane is the actuator. The capacitance of the switch varies from near zero (open) to 3.4 pF (closed). The signal path is about 50 μm wide.

Figure 10 shows a gas sensor developed using CMOS technology and the associated circuits that make it a smart gas sensor.[13]

The above examples illustrate the variety of applications of MEMS devices as well as the variety of materials used. Other examples can be found in Ref. 14.

The last letter in MEMS stands for systems. This is due partly to the fact that a MEMS device is quite complex. However, MEMS devices are ''only'' components which are used in larger and more complex systems. That is, individual sensors or actuators can be used as components and incorporated into subsystems or systems in order to perform some useful function. The accelerometer in the air bag subsystem of an automobile and the DMD in a projection system in a theater are examples. However, it is also possible to closely couple both MEMS sensors and actuators into miniature systems all on one substrate. These are called ''systems on a chip.'' Microfluidics with all the needed functionality on a substrate, including pumps and valves, as well as channels, mixers, separators, and detectors, are under development for compact analyzers. These will be relatively evolutionary advances over current microfluidic chips. High-density data storage systems with both actuation and sensing functions represent a more revolutionary example of integrated microsystems.

The variety of commercially available MEMS and their applications have both increased dramatically in recent years. The production of MEMS is now more than a $20 billion industry worldwide, with about 100 million devices marketed annually. While this industry grew out of the microelectronics industry, it is more complex in many important ways. Most fundamentally, it requires the integration of both microelectronics and micromechanics. Many MEMS involve several closely coupled mechanisms, some of which behave differently on the micrometer spatial scale than on familiar macroscopic scales. This complicates both the design and simulation of MEMS. So also does the much wider variety of materials and processes used to make MEMS compared to microelectronics. Because many MEMS have to be open to the atmosphere, their packaging, calibration, and testing are complex. Questions about the long-term reliability of MEMS are being answered as MEMS devices spend more years in use by consumers and industries.

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Table 1 Examples of MEMS Applications

Pressure Sensors	Inertia Sensors	Optical Devices	Data Storage	RF-MEMS	Acoustic MEMS	MicroFluidic	Chemical Sensors
Aeronautical	Air bag accelerometer	Optical beam steering	Hard disk component	Miniature antenna	Microphone	Micropumps	Polymer gas sensors
Blood pressure	Motion control sensors	Microlasers	Miniature read/write	RF-switch	Acoustic vibratos	Microvalves, microchannels	Tin oxide gas sensors
Auto tire	Automobile suspension	Optical switch	Magnetic devices	Filters and resonators		Lab on chip	Preconcentarors
Touch pressure	Vibration sensor	Micromirrors	Optical storage	Inductors and capacitors		Ink bubble jet nozzle	Smart gas sensors

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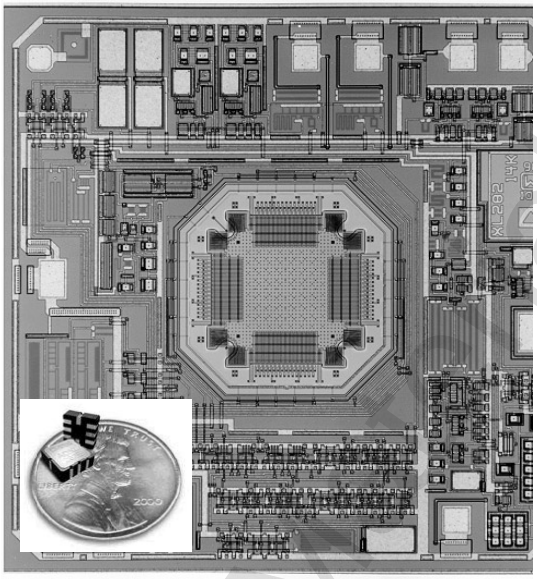


Figure 7 Photographs of exterior of new two-axis microaccelerometers in leadless packages on a penny and micrograph of chip from Analog Devices. In this device, the microelectronic and micromechanical components are tightly integrated on the silicon substrate.

6 CONCLUSIONS

We have discussed the advances in the microfabrication structures that allowed the realization of three-dimensional structures at the micrometer scale. As listed above, the materials and microfabrication processes used are unlimited to realize MEMS devices. Many MEMS involve several mechanical structures which behave differently on the micrometer spatial scale. Several CAD tools were developed to aid in the design of such devices. The design of such miniature devices is challenging and complicated as compared to devices at the macroscale level. Despite such engineering challenges, MEMS offer high performance and are small, have low power, and are relatively inexpensive. They both improve on some existing applications and enable entirely new systems. Some applications are targeted from the outset of

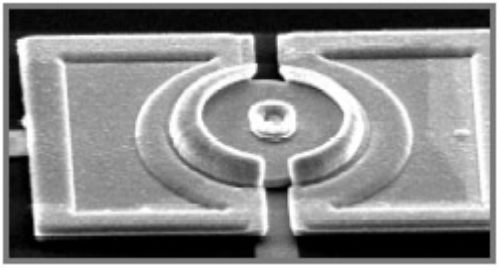


Figure 8 Circular resonators.

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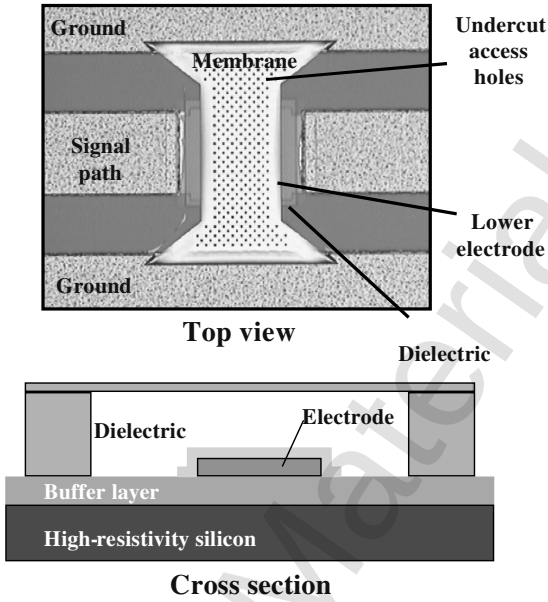


Figure 9 Microwave switch.

design, but others are opportunistic. That is, the large number of MEMS components on the market makes them available to design engineers for a very wide variety of uses.

APPENDIX: BOOKS ON MEMS

A great deal of information on the design, simulation, fabrication, packaging, testing, and application of MEMS is available. This information is presented as journal articles, confer-

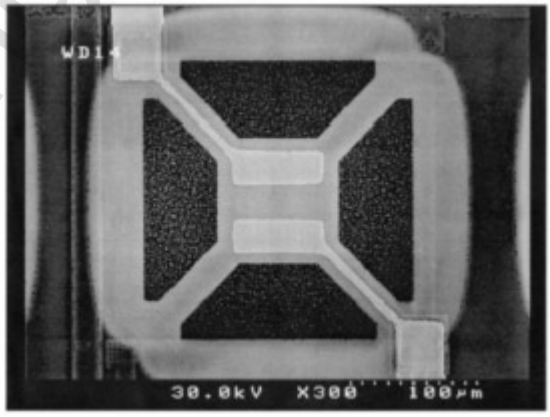


Figure 10 Scanning electron micrograph of CMOS gas sensor.

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ence proceedings, and books as well as being available from the World Wide Web. In the past several years many books on MEMS have been published:

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