MEMS (Micro-electromechanical Systems)

MEMS has been identified as one of the most promising technologies for the 21st Century and has the potential to revolutionize both industrial and consumer products by combining silicon-based microelectronics with micromachining technology. Its techniques and microsystem-based devices have the potential to dramatically affect of all of our lives and the way we live.

This report presents a general introduction to the field of MEMS, with emphasis on its commercial applications and device fabrication methods. It also describes the range of MEMS sensors and actuators, the phenomena that can be sensed or acted upon with MEMS devices, and outlines the major challenges facing the industry.

1. Introduction

This report deals with the emerging field of micro-electromechanical systems, or MEMS. MEMS is a process technology used to create tiny integrated devices or systems that combine mechanical and electrical components. They are fabricated using integrated circuit (IC) batch processing techniques and can range in size from a few micrometers to millimetres. These devices (or systems) have the ability to sense, control and actuate on the micro scale, and generate effects on the macro scale.

The interdisciplinary nature of MEMS utilizes design, engineering and manufacturing expertise from a wide and diverse range of technical areas including integrated circuit fabrication technology, mechanical engineering, materials science, electrical engineering, chemistry and chemical engineering, as well as fluid engineering, optics, instrumentation and packaging. The complexity of MEMS is also shown in the extensive range of markets and applications that incorporate MEMS devices. MEMS can be found in systems ranging across automotive, medical, electronic, communication and defence applications. Current MEMS devices include accelerometers for airbag sensors, inkjet printer heads, computer disk drive read/write heads, projection display chips, blood pressure sensors, optical switches, micro valves, biosensors and many other products that are all manufactured and shipped in high commercial volumes.

MEMS has been identified as one of the most promising technologies for the 21st Century and has the potential to revolutionize both industrial and consumer products by combining silicon-based microelectronics with micromachining technology. Its techniques and micro system-based devices have the potential to dramatically affect of all of our lives and the way we live. If semiconductor micro fabrication was seen to be the first micro manufacturing revolution, MEMS is the second revolution.

This report introduces the field of MEMS and is divided into four main sections. In the first section, the reader is introduced to MEMS, its definitions, history, current and potential applications, as well as the state of the MEMS market and issues concerning miniaturization. The second section deals with the fundamental fabrication methods of MEMS including photolithography, bulk micromachining, surface micromachining and high-aspect-ratio micromachining; assembly, system integration and packaging of MEMS devices is also described here. The third section reviews the range of MEMS sensors and actuators, the phenomena that can be sensed or acted upon with MEMS devices, and a brief description of the basic sensing and actuation mechanisms. The final section illustrates the challenges facing the MEMS industry for the commercialization and success of MEMS.

2. Micro-electromechanical Systems (MEMS)

What is MEMS?

Micro-electromechanical systems (MEMS) is a process technology used to create tiny integrated devices or systems that combine mechanical and electrical components. They are fabricated using integrated circuit (IC) batch processing techniques and can range in size from a few micrometers to millimeters. These devices (or systems) have the ability to sense, control and actuate on the micro scale, and generate effects on the macro scale.

MEMS, an acronym that originated in the United States, is also referred to as Microsystems Technology (MST) in Europe and Micro machines in Japan. Regardless of terminology, the uniting factor of a MEMS device is in the way it is made. While the device electronics are fabricated using 'computer chip' IC technology, the micromechanical components are fabricated by sophisticated manipulations of silicon and other substrates using micromachining processes. Processes such as bulk and surface micromachining, as well as high-aspect-ratio micromachining (HARM) selectively remove parts of the silicon or add additional structural layers to form the mechanical and electromechanical components. While integrated circuits are designed to exploit the electrical properties of silicon, MEMS takes advantage of either silicon's mechanical properties or both its electrical and mechanical properties.

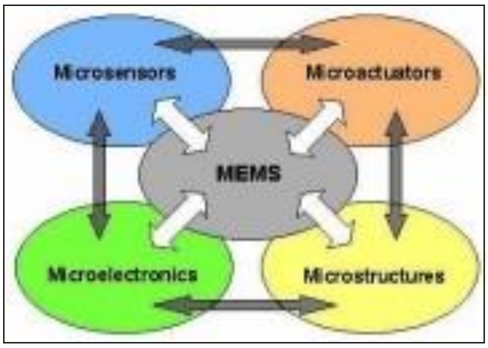


Figure 1. Schematic illustration of MEMS components.

In the most general form, MEMS consist of mechanical microstructures, microsensors, microactuators and microelectronics, all integrated onto the same silicon chip. This is shown schematically in Figure 1.

Microsensors detect changes in the system's environment by measuring mechanical, thermal, magnetic, chemical or electromagnetic information or phenomena. Microelectronics process this information and signal the microactuators to react and create some form of changes to the environment.

MEMS devices are very small; their components are usually microscopic. Levers, gears, pistons, as well as motors and even steam engines have all been fabricated by MEMS (Figure 2). However, MEMS is not just about the miniaturization of mechanical components or making things out of silicon (in fact, the term MEMS is actually misleading as many micromachined devices are not mechanical in any sense). MEMS is a manufacturing technology; a paradigm for designing and creating complex mechanical devices and systems as well as their integrated electronics using batch fabrication techniques.

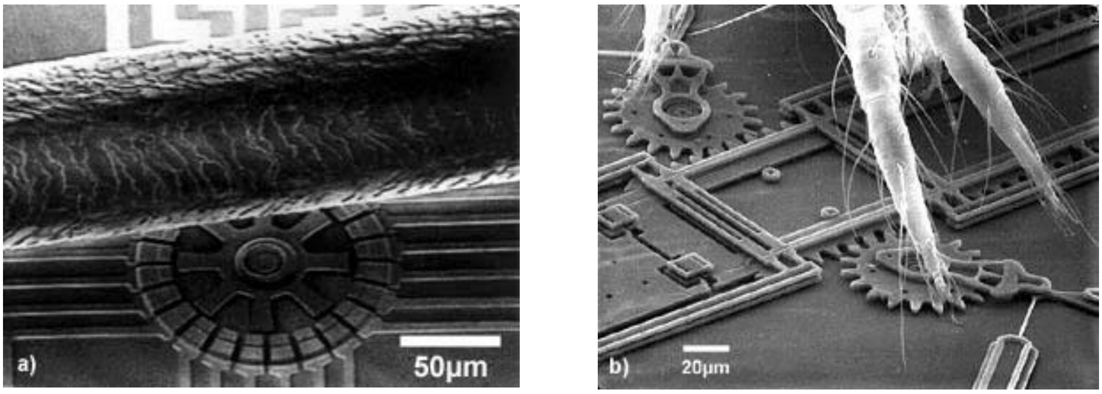


Figure 2. (a) A MEMS silicon motor together with a strand of human hair [1], and (b) the legs of a spider mite standing on gears from a micro-engine [2 - Sandia National Labs, SUMMiT *Technology, http://mems.sandia.gov].

From a very early vision in the early 1950's, MEMS has gradually made its way out of research laboratories and into everyday products. In the mid-1990's, MEMS components began appearing in numerous commercial products and applications including accelerometers used to control airbag deployment in vehicles, pressure sensors for medical applications, and inkjet printer heads. Today, MEMS devices are also found in projection displays and for micropositioners in data storage systems. However, the greatest potential for MEMS devices lies in new applications within telecommunications (optical and wireless), biomedical and process control areas.

MEMS has several distinct advantages as a manufacturing technology. In the first place, the interdisciplinary nature of MEMS technology and its micromachining techniques, as well as its diversity of applications has resulted in an unprecedented range of devices and synergies across previously unrelated fields (for example biology and microelectronics). Secondly, MEMS with its batch fabrication techniques enables components and devices to be manufactured with increased performance and reliability, combined with the obvious advantages of reduced physical size, volume, weight and cost. Thirdly, MEMS provides the basis for the manufacture of products that cannot be made by other methods. These factors make MEMS potentially a far more pervasive technology than integrated circuit microchips. However, there are many challenges and technological obstacles associated with miniaturization that need to be addressed and overcome before MEMS can realize its overwhelming potential.

Definitions and Classifications

This section defines some of the key terminology and classifications associated with MEMS. It is intended to help the reader and newcomers to the field of micromachining become familiar with some of the more common terms. A more detailed glossary of terms has been included in Appendix A.

Figure 3 illustrates the classifications of microsystems technology (MST). Although MEMS is also referred to as MST, strictly speaking, MEMS is a process technology used to create these tiny mechanical devices or systems, and as a result, it is a subset of MST.

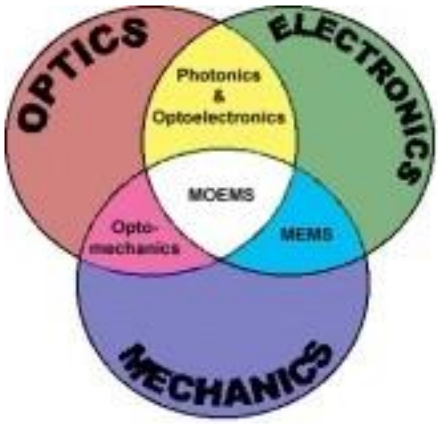


Figure 3. Classifications of microsystems technology

Micro-optoelectro mechanical systems (MOEMS) is also a subset of MST and together with MEMS forms the specialized technology fields using miniaturized combinations of optics, electronics and mechanics. Both their Microsystems incorporate the use of microelectronics batch processing techniques for their design and fabrication. There are considerable overlaps between fields in terms of their integrating technology and their applications and hence it is extremely difficult to categories MEMS devices in terms of sensing domain and/or their subset of MST. The real difference between MEMS and MST is that MEMS tends to use semiconductor processes to create a mechanical part. In contrast, the deposition of a material on silicon for example, does not constitute MEMS but is an application of MST.

Transducer

A transducer is a device that transforms one form of signal or energy into another form. The term transducer can therefore be used to include both sensors and actuators and is the most generic and widely used term in MEMS.

Sensor

A sensor is a device that measures information from a surrounding environment and provides an electrical output signal in response to the parameter it measured. Over the years, this information (or phenomenon) has been categorized in terms of the type of energy domains but MEMS devices generally overlap several domains or do not even belong in any one category. These energy domains include:

- Mechanical - force, pressure, velocity, acceleration, position
- Thermal - temperature, entropy, heat, heat flow
- Chemical - concentration, composition, reaction rate
- Radiant - electromagnetic wave intensity, phase, wavelength, polarization reflectance, refractive index, transmittance
- Magnetic - field intensity, flux density, magnetic moment, permeability
- Electrical - voltage, current, charge, resistance, capacitance, polarization [4,5,6,7]

Actuator

An actuator is a device that converts an electrical signal into an action. It can create a force to manipulate itself, other mechanical devices, or the surrounding environment to perform some useful function.

Applications

Today, high volume MEMS can be found in a diversity of applications across multiple markets (Table 1).

Table 1. Applications of MEMS [10].

Automotive	Electronics	Medical	Communications	Defence
Internal navigation sensors	Disk drive heads	Blood pressure sensor	Fibre-optic network components	Munitions guidance
Air conditioning compressor sensor	Inkjet printer heads	Muscle stimulators & drug delivery systems	RF Relays, switches and filters	Surveillance

Brake force sensors & suspension control accelerometers	Projection screen televisions	Implanted pressure sensors	Projection displays in portable communications devices and instrumentation	Arming systems
Fuel level and vapour pressure sensors	Earthquake sensors	Prosthetics	Voltage controlled oscillators (VCOs)	Embedded sensors
Airbag sensors	Avionics pressure sensors	Miniature analytical instruments	Splitters and couplers	Data storage
"Intelligent" tyres	Mass data storage systems	Pacemakers	Tuneable lasers	Aircraft control

As an emerging technology MEMS products are centred around technology-product paradigms rather than product-market paradigms. Consequently, a MEMS device may find numerous applications across a diversity of industries. For example, the MEMS inkjet printer head nozzle in widespread use today has developed from a nozzle originally used in nuclear separation. The commercialization of selected MEMS devices is illustrated in Table 2.

Table 2. Commercialization of selected MEMS devices [11].

Product	Discovery	Evolution	Cost Reduction/ Application Expansion	Full Commercialisation
Pressure sensors	1954-1960	1960-1975	1975-1990	1990-present
Accelerometers	1974-1985	1985-1990	1990-1998	1998
Gas sensors	1986-1994	1994-1998	1998-2005	2005
Valves	1980-1988	1988-1996	1996-2002	2002
Nozzles	1972-1984	1984-1990	1990-1998	1998
Photonics/displays	1980-1986	1986-1998	1998-2004	2004
Bio/Chemical sensors	1980-1994	1994-1999	1999-2004	2004
RF switches	1994-1998	1998-2001	2001-2005	2005
Rate (rotation) sensors	1982-1990	1990-1996	1996-2002	2002
Micro relays	1977-1982	1993-1998	1998-2006	2006

It is not within the scope of this report to detail all the current and potential applications within each market segment. Instead, a selection of the most established MEMS devices is detailed along with the most potentially significant future applications.

Established MEMS Applications

i) Automotive airbag sensor

Automotive airbag sensors were one of the first commercial devices using MEMS. They are in widespread use today in the form of a single chip containing a smart sensor, or accelerometer, which measures the rapid deceleration of a vehicle on hitting an object. The deceleration is sensed by a change in voltage. An electronic control unit subsequently sends a signal to trigger and explosively fill the airbag.

Initial air bag technology used conventional mechanical 'ball and tube' type devices which were relatively complex, weighed several pounds and cost several hundred dollars. They were usually mounted in the front of the vehicle with separate electronics near the airbag. MEMS has enabled the same function to be accomplished by integrating an accelerometer and the electronics into a single silicon chip, resulting in a tiny device that can be housed within the steering wheel column and costs only a few dollars (Figures 4 and 5).

The accelerometer is essentially a capacitive or piezoresistive device consisting of a suspended pendulum proof mass/plate assembly. As acceleration acts on the proof mass, micromachined capacitive or piezoresistive plates sense a change in acceleration from deflection of the plates. The sense plates can be seen in Figure 4.

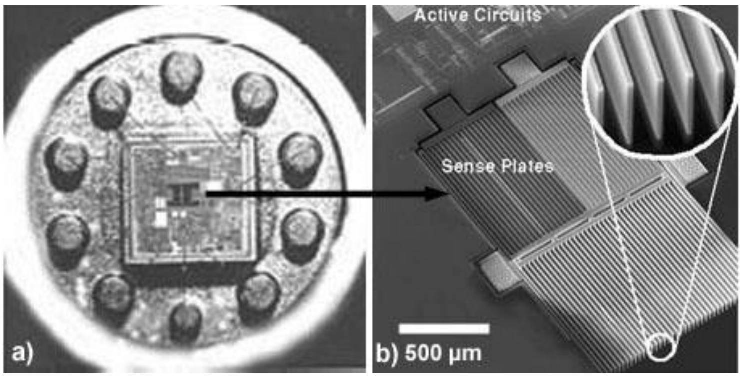


Figure 4. (a) The first commercial accelerometer from Analog Devices (1990); its size is less than 1 cm^2 (left) [12], and (b) capacitive sense plates, 60 microns deep (right) [13].

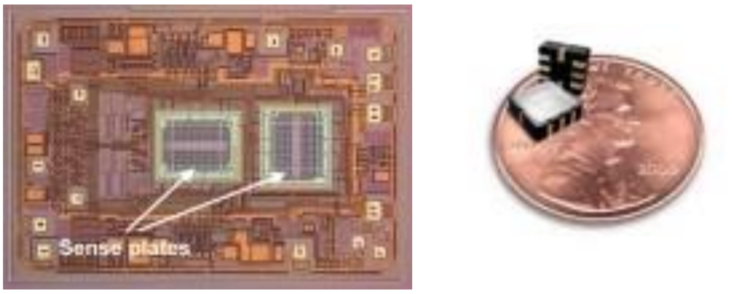


Figure 5. Modern day MEMS accelerometer (left), and the fully packaged device (right) [12].

The airbag sensor is fundamental to the success of MEMS and micromachining technology. With over 60 million devices sold and in operation over the last 10 years and operating in such a challenging environment as that found within a vehicle, the reliability of the technology has been proven. An example of this success is today's vehicles – the BMW 740i has over 70 MEMS devices including anti-lock braking systems, active suspension, appliance and navigation control systems, vibration monitoring, fuel sensors, noise reduction, rollover detection, seatbelt restraint and tensioning etc. As a result, the automotive industry has become one of the main drivers for the development of MEMS for other equally demanding environments. Some of the leading airbag accelerometer manufacturers include Analog Devices, Motorola, SensorNor and Nippondenso.

Accelerometers are not just limited to automotive applications. Earthquake detection, virtual reality video games and joysticks, pacemakers, high performance disk drives and weapon systems arming are some of the many potential uses for accelerometers.

ii) Medical pressure sensor

Another example of an extremely successful MEMS application is the miniature disposable pressure sensor used to monitor blood pressure in hospitals. These sensors connect to a patients intravenous (IV) line and monitor the blood pressure through the IV solution. For a fraction of their cost ($10), they replace the early external blood pressure sensors that cost over $600 and had to be sterilized and recalibrated for reuse. These expensive devices measure blood pressure with a saline-filled tube and diaphragm arrangement that has to be connected to an artery with a needle.

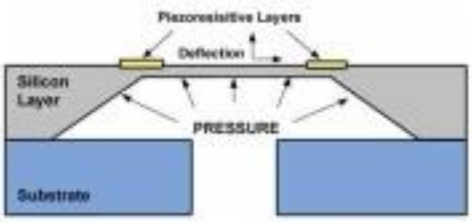


Figure 6. Schematic illustration of a piezoresistive pressure sensor.

The disposable sensor consists of a silicon substrate which is etched to produce a membrane and is bonded to a substrate (Figure 6). A piezoresistive layer is applied on the membrane surface near the edges to convert the mechanical stress into an electrical voltage. Pressure corresponds to deflection of the membrane. The sensing element is mounted on a plastic or ceramic base with a plastic cap over it, designed to fit into a manufacturer's housing (Figure 7). A gel is used to separate the saline solution from the sensing element.

As in the case of the MEMS airbag sensor, the disposable blood pressure sensor has been one of the strongest MEMS success stories to date. The principal manufacturers being Lucas Novasensor, EG & G IC Sensors and Motorola with over 17 millions units per year. More recently, the technology from the blood pressure sensor has been taken a step further in the development of the catheter-tip pressure sensor. This considerably smaller MEMS device is designed to fit on the tip of a catheter and measure intravascular pressure (its size being only 0.15 mm x 0.40 mm x 0.90 mm).

Pressure sensors are the biggest medical MEMS application to date with the accelerometer MEMS a distant second. Although the majority of these accelerometer applications remain under development, advanced pacemaker designs include a MEMS accelerometer device that measures the patient's activity. The technology, similar to that found in the airbag sensor, enables the patient's motion and activity to be monitored and signals the pacemaker to adjust its rate accordingly.

Figure 7. (a) Disposable blood pressure sensor connected to an IV line [14], (b) disposable blood pressure sensors (as shipped) [15], and (c) intracardial catheter-tip sensors for monitoring blood pressure during cardiac catheterisation, shown on the head of a pin [13].

iii) Inkjet printer head

One of the most successful MEMS applications is the inkjet printer head, superseding even automotive and medical pressure sensors. Inkjet printers use a series of nozzles to spray drops of ink directly on to a printing medium. Depending on the type of inkjet printer the droplets of ink are formed in different ways; thermally or piezoelectrically.

Invented in 1979 by Hewlett-Packard, MEMS thermal inkjet printer head technology uses thermal expansion of ink vapour. Within the printer head there is an array of tiny resistors known as heaters. These resistors can be fired under microprocessor control with electronic pulses of a few milliseconds (usually less than 3 microseconds). Ink flows over each resistor, which when fired, heat up at 100 million ºC per second, vaporizing the ink to form a bubble. As the bubble expands, some of the ink is pushed out of a nozzle within a nozzle plate, landing on the paper and solidifying almost instantaneously. When the bubble collapses, a vacuum is created which pulls more ink into the print head from the reservoir in the cartridge (Figure 8). It is worth noting there are no moving parts in this system (apart from the ink itself) illustrating that not all MEMS devices are mechanical.

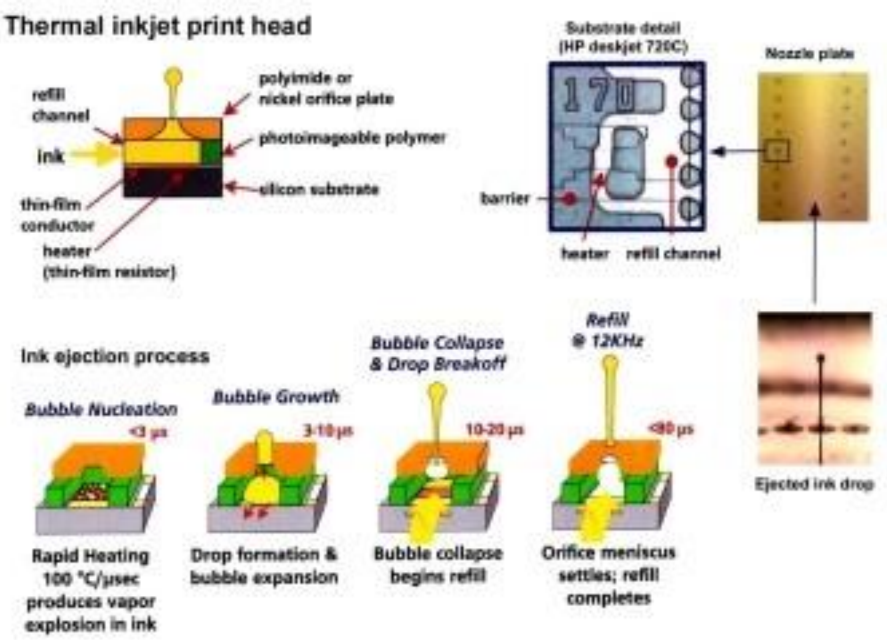
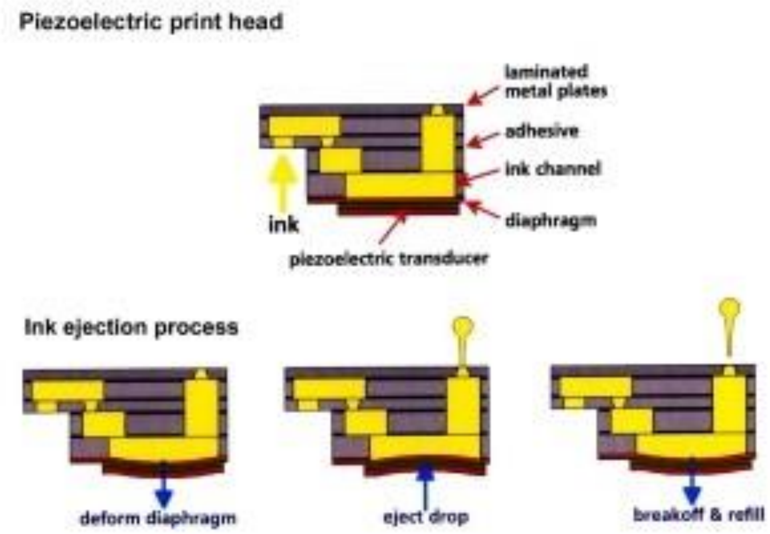


Figure 8. Thermal inkjet print technology [16].

A piezoelectric element can also be used to force the ink through the nozzles (Figure 9). In this case, a piezoelectric crystal is located at the back of the ink reservoir of each nozzle. The piezoelectric crystal element receives a very small electric charge causing it to vibrate. When it vibrates inwards it forces a tiny amount of ink out of the nozzle. As the element vibrates back out, it pulls some more ink into the reservoir to replace the ink that was sprayed out. Epson patented this technology but it is also used by the majority of the other leading printer companies.

MEMS has enabled more and more heating elements and piezoelectric crystals to be incorporated into a printer head. Early printers had 12 nozzles with resolutions of up to 92 dpi possible. Today, modern inkjet printers have up to 600 nozzles which can all fire a droplet simultaneously enabling 1200 dpi. Epson, Lexmark, Hewlett-Packard, Olivetti, Xerox and Canon all use a form of these MEMS in their inkjet printers. Over 350 million units were



sold in 2000.

Figure 9. Thermal inkjet print technology [16].

iv) Overhead projection display

One of the early MEMS devices used for a variety of display applications is the Digital Micro mirror Device (DMD) from Texas Instruments. The device contains over a million tiny pixel-mirrors each measuring 16 µm by 16 µm and capable of rotating by ±10º, over 1000 times a second (Figure 10). Light from a projection source impinges on the pupil of the lens (or mirror) and is reflected brightly onto a projection screen. DMD’s are used for displays for PC projectors, high definition televisions (HDTV’s) and for large venues such as digital cinemas where traditional liquid crystal technology cannot compete. MEMS has enabled the micro mirrors to be only 1 µm apart, resulting in an image taking up a larger percentage (89 percent) of space on the DMD chip's reflective surface, as compared to a typical LCD (12 to 50 percent). This reduces the pixilation and produces an overall sharper and brighter image. Today over 30 manufacturers use the DMD (Kodak being the largest) and over 500,000 systems have been shipped.

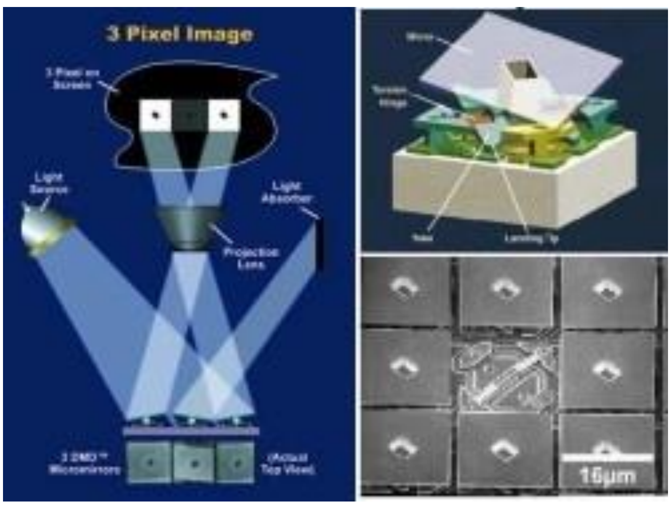


Figure 10. The MEMS Digital Micromirror Device (DMD) [17].

New MEMS Applications

The experience gained from these early MEMS applications has made it an enabling technology for new biomedical applications (often referred to as bioMEMS) and wireless communications comprised of both optical, also referred to as micro-optoelectromechanical systems (MOEMS), and radio frequency (RF) MEMS.

i) BioMEMS

Over the past few years some highly innovative products have emerged from bioMEMS companies for revolutionary applications that support major societal issues including DNA sequencing, drug discovery, and water and environmental monitoring. The technology focuses on microfluidic systems as well as chemical testing and processing and has enabled devices and applications such as 'lab-on-a-chip', chemical sensors, flow controllers, micronozzles and microvalves to be produced. Although many devices are still under development, microfluidic systems typically contain silicon micromachined pumps, flow sensors and chemical sensors. They enable fast and relatively convenient manipulation and analysis of small volumes of liquids, an area of particular interest in home-based medical applications where patients can use devices to monitor their own conditions, such as blood and urine analysis.

One example of a new bioMEMS device is the microtitreplate on which a number of cavities can be simultaneously filled accurately and repeatably by capillary force (Figure 11a). This is a relatively simple MEMS product in the form of a piece of plastic with high-aspect-ratio micromachined microchannels and is classified as a 'lab-on-a-chip' product. Its dimensions are only 20 mm x 37 mm x 3 mm and enables automatic filling of 96 microwells by the use of capillary action.

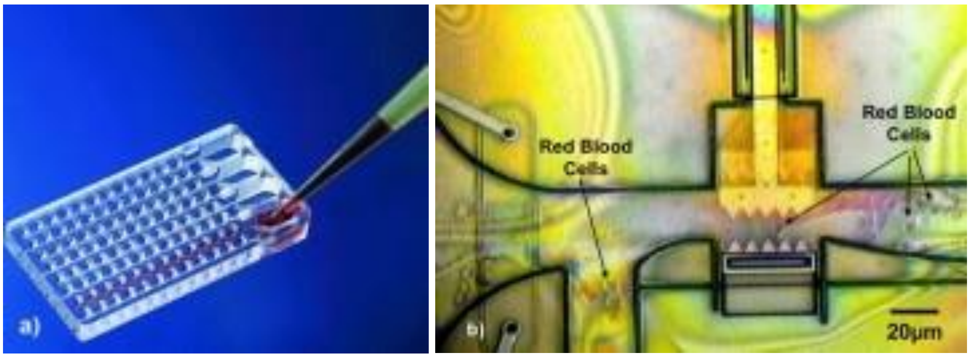


Figure 11. (a) Micromachined microtitreplate with 96 cavities filled by capillary force [18,19], and (b) a bioMEMS device actuated with 'microteeth' to trap, hold and release single red blood cells (unharmed). The little balls in the channels are red blood cells [2].

Future lab-on-a-chip technology may include implantable 'pharmacy-on-a-chip' devices to carefully release drugs into the body from tiny chambers embedded in a MEMS device, eliminating the need for needles or injections. The delivery of insulin is one such application, as is the delivery of hormones, chemotherapy drugs and painkillers. First generation devices are being developed which release their medication upon signals from an outside source, wired through the skin. Proposed second generation devices may be wireless and third generation MEMS chips could interact with MEMS sensors embedded in the body to respond to the body's own internal signals.

One of the most recent MEMS microfluidic devices to emerge from development laboratories incorporates a 'Pac-Man'-like microstructure that interacts with red blood cells (Figure 11b). The device from Sandia National Laboratories, U.S.A, contains silicon microteeth that open and close like jaws trapping and releasing a single red blood cell unharmed as it is pumped through a 20 µm channel. The ultimate goal of this device is to puncture cells and inject them with DNA, proteins, or pharmaceuticals to counter biological or chemical attacks, gene imbalances and natural bacterial or viral infections.

ii) MOEMS

Optical communications has emerged as the only practical means to address the network scaling issues created by the tremendous growth in data traffic caused by the rapid rise of the Internet. Current routing technology slows the information (or bit) flow by transforming optical signals into electronic information and then back into light before redirecting it. All optical networks offer far superior throughput capabilities and performance over traditional electronic systems.

The most significant MOEMS device products include waveguides, optical switches, cross connects, multiplexers, filters, modulators, detectors, attenuators and equalizers. Their small size, low cost, low power consumption, mechanical durability, high accuracy, high switching density and low cost batch processing of these MEMS-based devices make them a perfect solution to the problems of the control and switching of optical signals in telephone networks. An example of a MEMS optical connect is shown in Figure 12. Here a network of 256 MEMS micromirrors route information in the form of photons (the elementary particle that corresponds to an electromagnetic wave) to and from any of 256 input/output optical fibres.

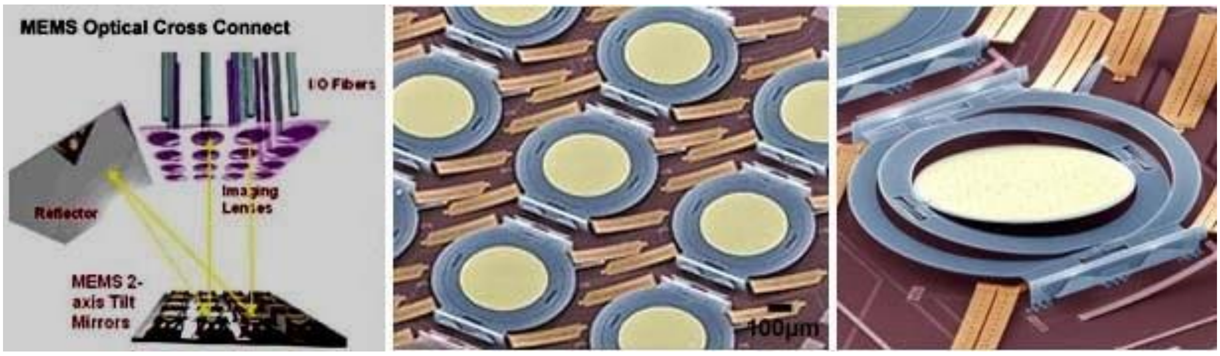


Figure 12. A MEMS optical cross connect consisting of an array of microscopic mirrors, each the size of a pin head and able to tilt in various directions to steer light [20,21].

MEMS fabrication processes have reached the stage where mass manufacture of such devices is now practical. A typical optical switch can cost over $1000, but using MEMS, the same level of functionality can be achieved for less than a dollar. Agere Systems (previously known as the microelectronics division of Lucent Technologies), Corning, JDS Uniphase and Sycamore Networks are some of the leading companies in this field.

iii) RF MEMS

RF MEMS is one of the fastest growing areas in commercial MEMS technology. RF MEMS are designed specifically for electronics in mobile phones and other wireless communication applications such as radar, global positioning satellite systems (GPS) and steerable antennae. MEMS has enabled the performance, reliability and function of these devices to be increased while driving down their size and cost at the same time (Figure 13).

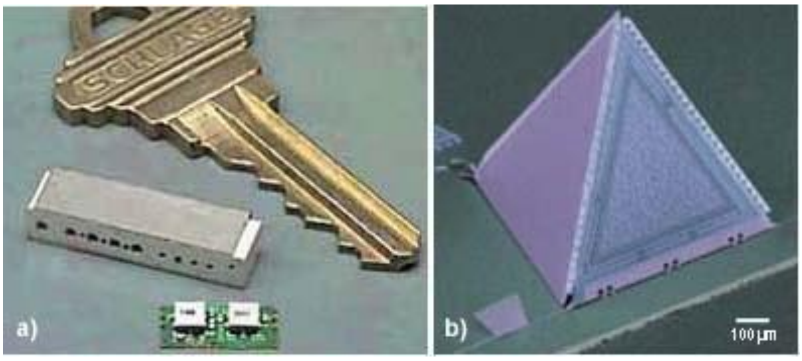


Figure 13. (a) A miniature acoustic resonator, shown in the foreground, is one-fifth the size of a traditional component used in mobile phones and other wireless communications devices [22], and (b) on-chip micro-microphones may make it possible to build radios on a chip [20,21].

The technology includes circuit tuning elements (capacitors/inductors, resonators, filters, microphones and switches). These low-loss ultra-miniature and highly integrative RF functions can and will eventually replace classical RF elements and enable a new generation of RF devices. As it can be seen today, if RF MEMS components continue to replace traditional components in today's mobile phones, then phones could become extremely small (the size of wristwatch is not too far away), require little battery power and may even be cheaper.

MEMS Market

The three most well known market studies are the Network of Excellence in Multifunctional Microsystems (NEXUS) study (1998), the System Planning Corporation (SPC) study (1999) and the Battelle study (1990) and there is discrepancy between each study [23, 24, 25 respectively]. The size of the MEMS market (M^3) is contingent on how MEMS is defined (M^3 is shorthand for MEMS, Microsystems and Micromachining and although it is not yet common, it is used as a reference for the entire MEMS market. Smaller M^3 figures are obtained if MEMS is considered as just micromachining, which is more elemental and at the device level. Alternatively, much larger M^3 figures arise if MEMS is examined at the system or subsystem level (as in the case of NEXUS). Depending on the study under review, the M^3 market today ranges from $4.2 billion to $14.2 billion. Much of the current market centres on read/write heads for computer disk drives, pressure sensors, inkjet printer heads and accelerometers. Table 3 provides the NEXUS worldwide M^3 market size in 1996 and forecasts for 2002 for existing MEMS product types.

Table 3. Worldwide M^3 market size in 1996 and 2002 for existing MEMS product types in $US millions [23].

Product Types	1996 Units (millions)	$ (millions)	2002 Units (millions)	$ (millions)
HDD heads	530	4500	1500	12000
Inkjet print heads	100	4400	500	10000

Heart pacemakers	0.5	1000	0.8	3700
In vitro diagnostics	700	450	4000	2800
Hearing aids	4	1150	7	2000
Pressure sensors	115	600	309	1300
Chemical sensors	100	300	400	800
Infrared imagers	0.01	220	0.4	800
Accelerometers	24	240	90	430
Gyroscopes	6	150	30	360
Magnetoresistive sensors	15	20	60	60
Microspectrometers	0.006	3	0.15	40
TOTAL	**1595**	**$13,033**	**6807**	**$34,290**

In the area of emerging MEMS products, Table 4 provides the NEXUS worldwide M^3 market size in 1996 and forecasts for 2002. Drug delivery systems (microfluidic microdosing systems), lab-on-a-chip devices and MEMS-based optical switches are predicted to reach billion dollar market segments by 2002.

Table 4. Worldwide M^3 market size in 1996 and 2002 for emerging MEMS product types in $US millions [23].

Product Types	**1996 Units (millions)**	**$ (millions)**	**2002 Units (millions)**	**$ (millions)**
Drug delivery systems	1	10	100	1000
Optical switches	1	50	40	1000
Lab on ship	0	0	100	1000
Magneto optical heads	0.01	1	100	500
Projection valves	0.1	10	1	300
Coil on chip	20	10	600	100
Micro relays		0.1	50	100
Micromotors	0.1	5	2	80
Inclinometers	1	10	20	70
Injection nozzles	10	10	30	30
Anti-collision sensors	0.01	0.5	2	20
Electronic noses	0.001	0.1	0.05	5
TOTAL	**33**	**$107**	**1045**	**$4,205**

A more recent market study by NEXUS/Roger Grace Associates, shown in Table 5, estimated the M^3 market to be $14.2 billion in 2000, increasing to $30.4 billion by 2004. This corresponds to a compounded annual growth rate (CAGR) of 21%. Telecommunications is forecast to be the major growth area, comprised of both optical MEMS and RF MEMS-based devices.

Table 5. Worldwide shipment of M^3 products by application sector for 2000-2004 in $US millions [23,26].

Application Sector	2000	2004	CAGR(%)
IT/Peripheral	$ 8,700	$13,400	11.5
Medical/Biochemical	2,400	7,400	32.5
Industrial/Automation	1,190	1,850	11.6
Telecommunications	130	3,650	128.1
Automotive	1,260	2,350	16.9
Environmental Monitoring	520	1,750	35.4
TOTAL	**$14,200**	**$30,400**	**21.0%**

Miniaturization Issues

As previously stated, MEMS is not about miniaturization; it is a manufacturing technology used to create tiny integrated microdevices and systems using IC batch fabrication techniques. Similarly, miniaturization is not just about shrinking down existing devices (although there have been some classic examples, namely the DENSO Micro-Car as shown in Figure 14); it's about completely rethinking the structure of a microsystem.

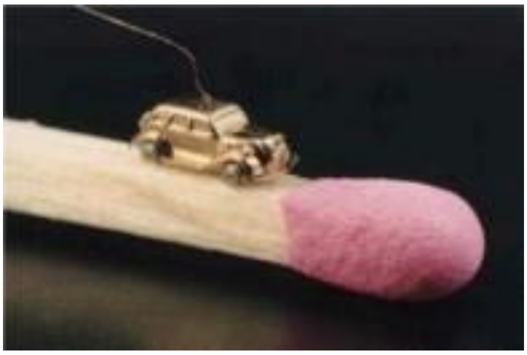


Figure 14. The DENSO Micro-Car is a miniature version of Toyota's first passenger car. Fabricated using MEMS, at 1/1000th the size of the original, it consists of a 0.67 mm magnetic-type working motor and when supplied with 3 V 20 mA of alternating current through a 18 µm copper wire, the engine runs at 600 rpm equivalent to 5-6 mm/s [27].

In order to manufacture a successful MEMS device basic physics and operating principles including scaling laws need to be fully understood and appreciated at both a macro and microlevel. Sometimes no advantages in terms of performance, size/weight, reliability and cost can be gained with a MEMS device. Increased surface area (S) to volume (V) ratios at microscales have both considerable advantages and disadvantages (Figure 15).

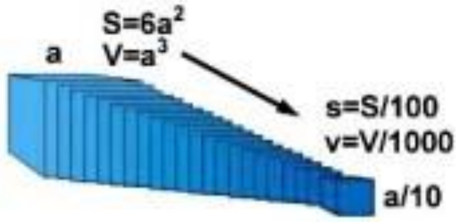


Figure 15. Effect of miniaturization on surface area and volume.

Some of these micro level issues include:

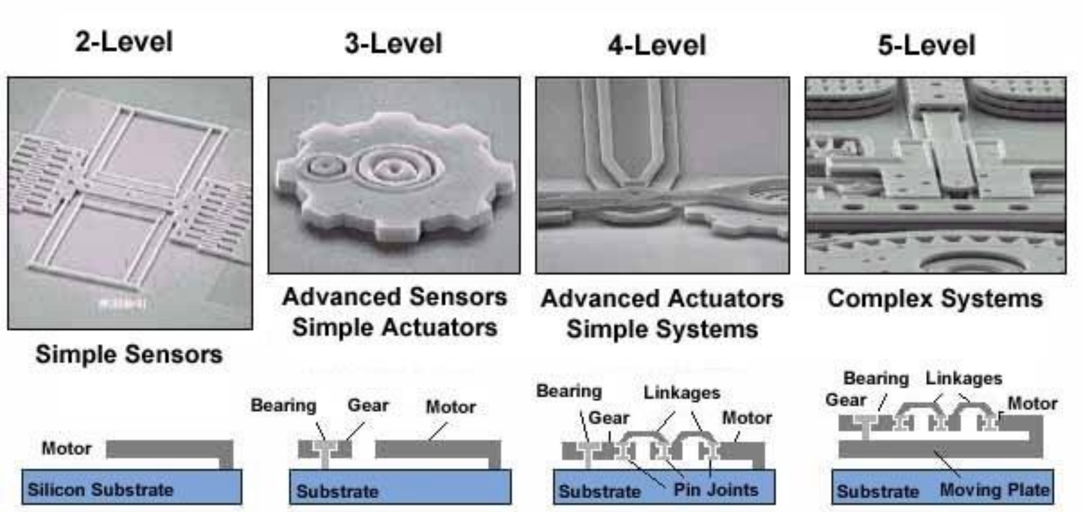
- Friction is greater than inertia. Capillary, electrostatic and atomic forces as well as stiction at a micro-level can be significant.
- Heat dissipation is greater than heat storage and consequently thermal transport properties could be a problem or, conversely, a great benefit.
- Fluidic or mass transport properties are extremely important. Tiny flow spaces are prone to blockages but can conversely regulate fluid movement.
- Material properties (Young's modulus, Poisson's ratio, grain structure) and mechanical theory (residual stress, wear and fatigue etc.) may be size dependent.
- Integration with on-chip circuitry is complex and device/domain specific. Lab-on-a-chip systems components may not scale down comparably.
- Miniature device packaging and testing is not straightforward. Certain MEMS sensors require environmental access as well as protection from other external influences. Testing is not rapid and is expensive in comparison with conventional IC devices.
- Cost – for the success of a MEMS device, it needs to leverage its IC batch fabrication resources and be mass-produced. Hence mass-market drivers must be found to generate the high volume production.

3. MEMS Fabrication Methods

MEMS fall into three general classifications; bulk micromachining, surface micromachining and high-aspect-ratio micromachining (HARM), which includes technology such as LIGA (a German acronym from Lithography, Galvanoformung, Abformung translated as lithography, electroforming and moulding).

Conventional macro scale manufacturing techniques e.g. injection molding, turning, drilling etc, are good for producing three dimensional (3D) shapes and objects, but can be limited in terms of low complexity for small size applications. MEMS fabrication, by comparison, uses high volume IC style batch processing that involves the addition or subtraction of two dimensional layers on a substrate (usually silicon) based on photolithography and chemical etching. As a result, the 3D aspect of MEMS devices is due to patterning and interaction of the 2D layers. Additional layers can be added using a variety of thin-film and bonding techniques as well as by etching through sacrificial 'spacer layers'. Figure 16 shows the potential complexity of a MEMS system by the addition of independent structural layers.

Figure 16. MEMS device complexity by structural layers [2].



Photolithography

Photolithography is the photographic technique to transfer copies of a master pattern, usually a circuit layout in IC applications, onto the surface of a substrate of some material (usually a silicon wafer).

The substrate is covered with a thin film of some material, usually silicon dioxide (SiO_2), in the case of silicon wafers, on which a pattern of holes will be formed (Figure 17). A thin layer of an organic polymer, which is sensitive to ultraviolet radiation, is then deposited on the oxide layer; this is called a photo resist. A photo mask, consisting of a glass plate (transparent) coated with a chromium pattern (opaque), is then placed in contact with the photo resist coated surface. The wafer is exposed to the ultraviolet radiation transferring the pattern on the mask to the photo resist which is then developed in a way very similar to the process used for developing photographic films. The radiation causes a chemical reaction in the exposed areas of the photo resist of which there are two types; positive and negative. Positive photo resist is strengthened by UV radiation whereas negative photo resists areweakened. On developing, the rinsing solution removes either the exposed areas or the unexposed areas of photoresist leaving a pattern of bare and photoresist-coated oxides on the wafer surface. The resulting photoresist pattern is either the positive or negative image of the original pattern of the photomask.

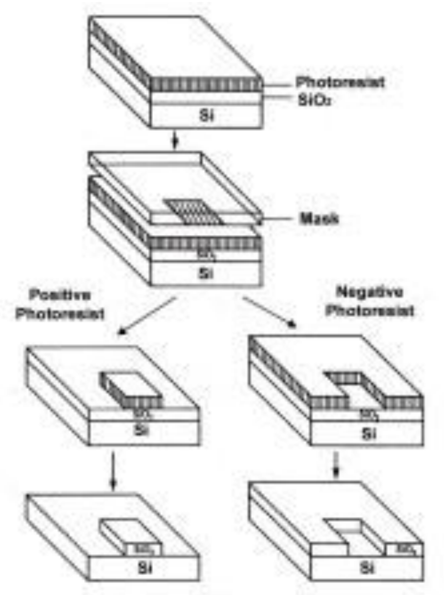


Figure 17. Photo resist and silicon dioxide patterns following photolithography [28].

A chemical (usually hydrochloric acid) is used to attack and remove the uncovered oxide from the exposed areas of the photo resist. The remaining photo resist is subsequently removed, usually with hot sulphuric acid which attacks the photo resist but not the oxide layer on the silicon, leaving a pattern of oxide on the silicon surface. The final oxide pattern is either a positive or negative copy of the photo mask pattern and serves as a mask in subsequent processing steps.

At this point MEMS diverges from traditional IC fabrication. In processing IC devices, the oxide pattern serves as a mask during the ‘doping’ of the wafer with impurities (such as boron or phosphorous) that alter the local conduction necessary for microelectronic devices. In MEMS, the oxide serves as a subsequent mask for either further additional chemical etching creating deeper 3D pits or new layers on which to build further layers, resulting in an overall 3D structure or device.

Materials for Micromachining

Substrates

The most common substrate material for micromachining is silicon. It has been successful in the microelectronics industry and will continue to be in areas of miniaturization for several reasons:

i) silicon is abundant, inexpensive, and can be processed to unparalleled purity

ii) silicon's ability to be deposited in thin films is very amenable to MEMS

iii) high definition and reproduction of silicon device shapes using photolithography are perfect for high levels of MEMS precision

iv) silicon microelectronics circuits are batch fabricated (a silicon wafer contains hundreds of identical chips not just one)

Other crystalline semiconductors including germanium (Ge) and gallium arsenide (GaAs) are used as substrate materials due to similar inherent features, but silicon is distinguished from other semiconductors in that it can be readily oxidized to form a chemically inert and electrically insulating surface layer of SiO_2 on exposure to steam.

The homogeneous crystal structure of silicon gives it the electrical properties needed in microelectronic circuits, but in this form silicon also has desirable mechanical properties. Silicon forms the same type of crystal structure as diamond, and although the interatomic bonds are much weaker, it is harder than most metals. In addition, it is surprisingly resistant to mechanical stress, having a higher elastic limit than steel in both tension and compression. Single crystal silicon also remains strong under repeated cycles of tension and compression.

The crystalline orientation of silicon is important in the fabrication of MEMS devices because some of the etchants used attack the crystal at different rates in different directions (Figure 18).

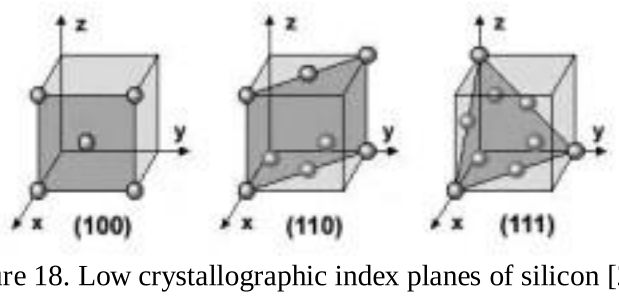


Figure 18. Low crystallographic index planes of silicon [29].

Silicon is dominant as a substrate for MEMS but research and development is ongoing with other non-semiconductor substrate materials including metals, glasses, quartz, crystalline insulators, ceramics and polymers. The ability to integrate circuitry directly onto the substrate is currently the underlying issue with today's MEMS substrate materials; hence the success of silicon.

Additive Films and Materials

The range of additive films and materials for MEMS devices is much larger than the types of possible substrates and includes conductors, semiconductors and insulators such as:

- silicon - single crystal, polycrystalline and amorphous
- silicon compounds (Si_xN_y, SiO_2, SiC etc.)
- metals and metallic compounds (Au, Cu, Al, ZnO, GaAs, IrO_x, CdS)
- ceramics ($Al_2 0_3$ and more complex ceramic compounds)
- organics (diamond, polymers, enzymes, antibodies, DNA etc.)

Bulk Micromachining

Bulk micromachining involves the removal of part of the bulk substrate. It is a subtractive process that uses wet anisotropic etching or a dry etching method such as reactive ion etching (RIE), to create large pits, grooves and channels. Materials typically used for wet etching include silicon and quartz, while dry etching is typically used with silicon, metals, plastics and ceramics.

Wet Etching

Wet etching describes the removal of material through the immersion of a material (typically a silicon wafer) in a liquid bath of a chemical etchant. These etchants can be isotropic or anisotropic.

Isotropic etchants etch the material at the same rate in all directions, and consequently remove material under the etch masks at the same rate as they etch through the material; this is known as undercutting (Figure 19 a and b). The most common form of isotropic silicon etch is HNA, which comprises a mixture of hydrofluoric acid (HF), nitric acid (HNO_3) and acetic acid (CH_3COOH). Isotropic etchants are limited by the geometry of the structure to be etched. Etch rates can slow down and in some cases (for example, in deep and narrow channels) they can stop due to diffusion limiting factors. However, this effect can be minimized by agitation of the etchant, resulting in structures with near perfect and rounded surfaces (Figure 19a) [4].

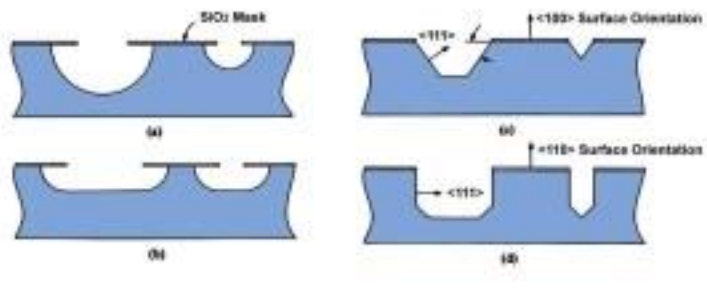


Figure 19. Isotropic etching with (a) and without (b) agitation, and anisotropic wet etching of (100) and (110) silicon (c and d respectively) [9].

Anisotropic etchants etch faster in a preferred direction. Potassium hydroxide (KOH) is the most common anisotropic etchant as it is relatively safe to use. Structures formed in the substrate are dependent on the crystal orientation of the substrate or wafer. Most such anisotropic etchants progress rapidly in the crystal direction perpendicular to the (110) plane and less rapidly in the direction perpendicular to the (100) plane. The direction perpendicular to the (111) plane etches very slowly if at all. Figures 19c and 19d shows examples of anisotropic etching in (100) and (110) silicon. Silicon wafers, originally cut from a large ingot of silicon grown from single seed silicon, are cut according to the crystallographic plane. They can be supplied in terms of the orientation of the surface plane.

Dopant levels within the substrate can affect the etch rate by KOH, and if levels are high enough, can effectively stop it. Boron is one such dopant and is implanted into the silicon by a diffusion process. This can be used to selectively etch regions in the silicon leaving doped areas unaffected.

Dry Etching

Dry etching relies on vapour phase or plasma-based methods of etching using suitably reactive gases or vapours usually at high temperatures. The most common form for MEMS is reactive ion etching (RIE) which utilizes additional energy in the form of radio frequency (RF) power to drive the chemical reaction. Energetic ions are accelerated towards the material to be etched within a plasma phase supplying the additional energy needed for the reaction; as a result the etching can occur at much lower temperatures (typically 150º - 250ºC, sometimes room temperature) than those usually needed (above 1000ºC). RIE is not limited by the crystal planes in the silicon, and as a result, deep trenches and pits, or arbitrary shapes with vertical walls can be etched [4].

Deep Reactive Ion Etching (DRIE) is a much higher-aspect-ratio etching method that involves an alternating process of high-density plasma etching (as in RIE) and protective polymer deposition to achieve greater aspect ratios (Figure 20).

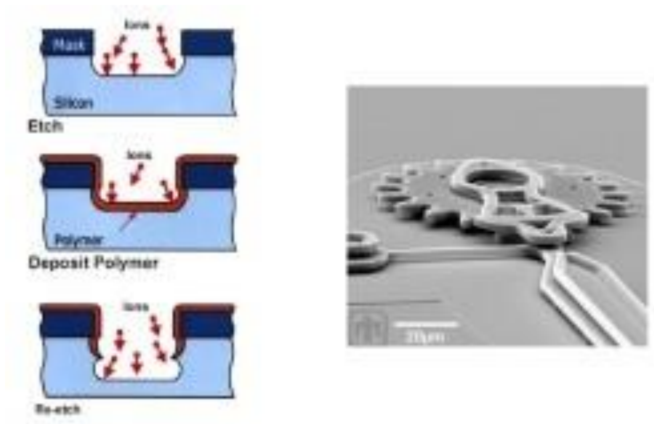


Figure 20. Deep Reactive Ion Etching (DRIE) [2,3].

Etch rates depend on time, concentration, temperature and material to be etched. To date there are no universally accepted master equations to predict etch performance and behavior.

3.4 Surface Micromachining

Surface micromachining involves processing above the substrate, mainly using it as a foundation layer on which to build. It was initiated in the 1980's and is the newest MEMS production technology. Material is added to the substrate in the form of layers of thin films on the surface of the substrate (typically a silicon wafer). These layers can either by structural layers or act as spacers, later to be removed, when they are known as sacrificial layers. Hence the process usually involves films of two different materials: a structural material out of which the free standing structure is made (generally polycrystalline silicon or polysilicon, silicon nitride and aluminium) and a sacrificial material, deposited wherever either an open area or a free standing mechanical structure is required (usually an oxide).

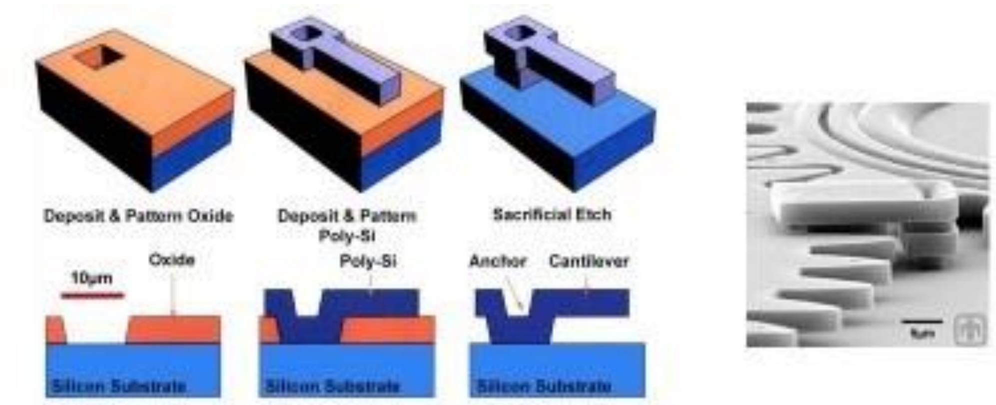


Figure 21. Surface micromachining of a cantilever beam using a sacrificial layer [2,3].

These layers (or thin films) are deposited and subsequently dry etched in sequence, with the sacrificial material being finally wet etched away to release the final structure. Each additional layer is accompanied by an increasing level of complexity and a resulting difficulty in fabrication. A typical surface micro machined cantilever beam is shown in Figure 21. Here, a sacrificial layer of oxide is deposited on the silicon substrate surface using a pattern and photolithography. A polysilicon layer is then deposited and patterned using RIE processes to form a cantilever beam with an anchor pad. The wafer is then wet etched to remove the oxide (sacrificial) layer releasing and leaving the beam on the substrate. More complex MEMS structures can be achieved using structural polysilicon and sacrificial silicon dioxide, including sliding structures, actuators and free moving mechanical gears. Figures 22 shows the process flow for the fabrication of a micromotor by the commercially available Multi-User MEMS Process (MUMPS).

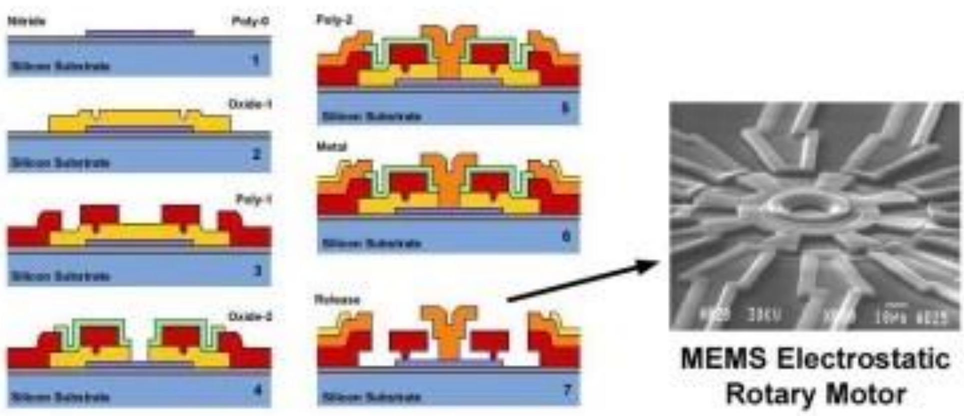


Figure 22. Surface micromachining of a MEMS micromotor using the Multi-User MEMS Process (MUMPS) [30].

The levels of complexity achievable with MEMS has already been shown in Figure 16. In this case, five mechanical levels of micromachined polysilicon can be achieved using Sandia Ultra-Planar Multi-Level Technology (SUMMiT).

The success of the surface micromachining process depends on the ability to successfully remove all of the sacrificial layers to free the structural elements so that they can be actuated. This step is responsible for curtailing the yield (percentage of the devices on a wafer that function properly) and reliability of fabricated MEMS due to the phenomenon known as stiction. Stiction refers to the sticking of structural elements either to the substrate or the adjacent elements. Capillary forces from rinsing liquids, as well as electrostatic and van der Waals forces can also produce permanent adhesion after the system has dried.

3.4.1 Fusion Bonding

In order to form more complex and larger MEMS structures, micromachined silicon wafers can be bonded to other materials in a process known as fusion bonding. It is a technique that enables virtually seamless integration of multiple layers and relies on the creation of atomic bonds between each layer either directly (with heating and pressure in the case of glass to wafer bonding), or through a thin film of silicon dioxide (Figure 23). The resulting composite has very low residual stress due to matching coefficients of thermal expansion from each layer. In addition, the mechanical strength of the bond is comparable to that of the adjoining layers resulting in a very strong composite fabrication technique for enclosed cavities and channels. High-aspect ratio structural layers can also be bonded to silicon substrates in a similar manner. Photoresist and polymethylmethacrylate (PMMA) are used as MEMS fusion bonding media and have proved very successful for the bonding of polyimide [4].

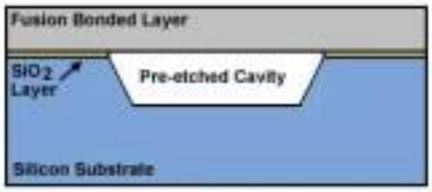


Figure 23. Formation of sealed cavity using fusion bonding

High-Aspect-Ratio Micromachining

High-aspect-ratio micromachining (HARM) is a process that involves micromachining as a tooling step followed by injection molding or embossing and, if required, by electroforming to replicate microstructures in metal from molded parts. It is one of the most attractive technologies for replicating microstructures at a high performance-to-cost ratio and includes techniques known as LIGA. Products micro machined with this technique include high-aspect-ratio fluidic structures such as molded nozzle plates for inkjet printing and micro channel plates for disposable microtitreplates in medical diagnostic applications. The materials that can be used are electroform able metals and plastics, including acrylate, polycarbonate, polyimide and styrene.

LIGA

LIGA is an important tooling and replication method for high-aspect-ratio microstructures. The technique employs X-ray synchrotron radiation to expose thick acrylic resist of PMMA under a lithographic mask (see Figure 24 below). The exposed areas are chemically dissolved and, in areas where the material is removed, metal is electroformed, thereby defining the tool insert for the succeeding moulding step. LIGA is capable of creating very finely defined microstructures up to 1000 µm high.

LIGA is limited by the need to have access to an X-ray synchrotron facility. A compromise which combines some features of LIGA with surface micromachining eliminating the need for exposure to X-rays has been developed and is known as SLIGA (Sacrificial LIGA) [31]. It replaces the thick PMMA photo resist with polyimide as the electroplating mould, thus enabling compatible conventional IC batch processing. HARM production methods have provided radically new ways to produce micro machined parts for MEMS devices at relatively low cost. In particular, techniques such as SLIGA enable the production of MEMS components with much lower manufacturing infrastructures in terms of investment, facilities and access to advanced materials and technology.

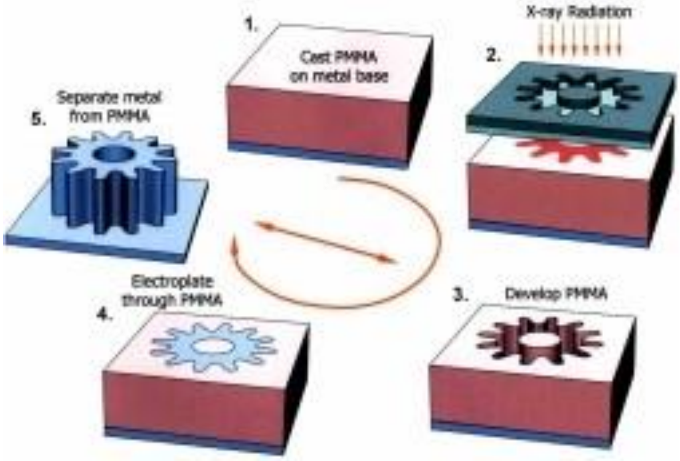


Figure 24. The LIGA process [3].

Other microreplication techniques can be combined to generate a preform for the tool insert. These include laser ablation, ultra-violet (UV) lithography and mechanical micromachining, which includes electric discharge machining (EDM) and diamond milling. EDM is a relatively new approach that uses machine shop production techniques and offers the capability to make parts out of most conductive materials. Unfortunately, as a spark erosion technique, it is slow and not ideal for batch processing but has found many applications for MEMS prototype production. For example, EDM was used for the micromachining of the DENSO Micro-car previously shown in Figure 14.

Laser Micromachining

Most laser micromachining processes are not parallel and hence not fast enough for effective MEMS fabrication. Nonetheless, they have utility in specialty micromachining or making moulds. Excimer laser micromachining is used particularly for the micromachining of organic materials (plastics, polymers etc.) as material is not removed by burning or vaporization. Hence, material adjacent to the machined area is not melted or distorted by heating effects. Lasers have found other applications in MEMS but only in a limited capacity; laser drilling, laser annealing and etching are the most common forms.

Computer Aided Design

Computer Aided Design (CAD) is generally used in MEMS for the design of photolithographic masks. This is a straightforward process as MEMS structures are relatively large in comparison to the sub-micron structures usually associated with silicon chip components. As well as using CAD for mask design, CAD and finite element analysis (FEA) are important simulation tools for the design of MEMS applications. Unfortunately, to date there is a lack of adequate advanced software based design tools to fully model, analyse and simulate MEMS microstructures as well as integrated MEMS/IC devices. This has acted as a barrier to the development of MEMS devices and systems.

One of the most successful and commercially available software design tools today is MEMCAD, a package from Microcosm Technologies in North Carolina, USA. The MEMCAD system defines device layout and process, constructs the three dimensional geometry of the device, assembles a detailed 3D model and analyses device performance as well as device sensitivity to manufacturing and design variations. MEMS Pro, a package from Tanner Research in California, enables designers of MEMS to simulate the growth/deposition, implantation/diffusion and etch steps in a MEMS fabrication process.

Assembly and System Integration

The MEMS fabrication process essentially uses the same process as the microelectronics industry as shown in Figure 25.

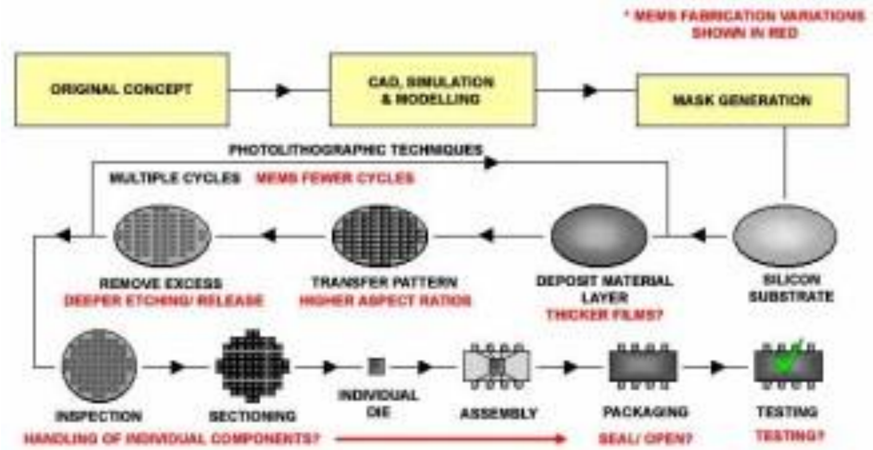


Figure 25. Similarities between IC and MEMS microfabrication processes [3].

Despite the fact that MEMS uses some of the same tools as those used with ICs, the greatest challenge facing the MEMS industry is system integration between the miniature mechanical systems and the electronic interface. For the cost-effective production of MEMS devices it is necessary to combine complex mechanical structures together with microelectronics to form integrated mechanical and electrical systems on a single chip that can be batch fabricated with high yield and no additional or subsequent assembly (Figure 26).

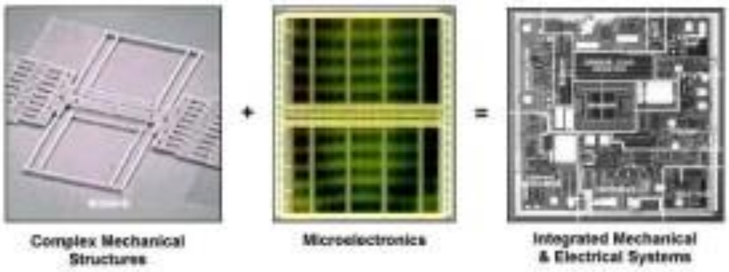


Figure 26. Integration of mechanical structures and microelectronics [2].

Despite certain successful high volume applications such as the airbag accelerometer and the disposable blood pressure sensor, high yields are difficult with MEMS devices due to their mechanical complexity and their integration with the necessary microelectronics. Assembling and packaging complex microscopic parts is also extremely difficult. As conventional automated assembly and packaging is not suited to such a microlevel, to date, many MEMS devices require individual handling. As a result, the final cost of a device may be up to 100 times the cost of the actual component. For their successful commercial production these challenges have to be overcome.

Over the years different approaches have been developed for the integration of the electronic interface. These include hybrid integration using conventional wire bonding and flip-chips (described later in Section 3.8) and monolithic integration. Monolithic integration offers superior system integration performance to hybrid systems but at an overall higher price in terms of involved technology and processing. Monolithic integration can be carried out in three ways:

i) IC before MEMS

Monolithic integration by IC first has proved to be successful and relatively cheap; an example is the technology in Texas Instrument's DMD (Figure 10). The process relies heavily on bulk micromachining and the addition of new layers through electroplating. It is a relatively simple integrated system but suffers from residual stresses within the device materials. To date, refractory metals need to be used within the IC components in order to withstand the high temperature annealing cycles required to relieve the stress in structural polysilicon.

ii) Mixed MEMS-IC fabrication

A typical example of MEMS and microelectronics being fabricated side by side is the airbag accelerometer (Figures 4 and 5). Monolithic processing of this device as well as the reduced number of parts enable a very compact device with high reliability at a very low cost. The trade-off lies within its complexity as this process leads to a very rigid and constrained process flow which is expensive, thus requiring very high volumes.

iii) MEMS fabricated prior to IC

The most promising monolithic integration technique includes fabricating the MEMS device prior to the microelectronics. Using technology known as iMEMS (Integrated Micro-electromechanical Systems) patented by Sandia National Laboratories, USA, MEMS components are fabricated in trenches on a silicon substrate and then the standard electronics are processed onto the same substrate as shown in Figure 27 [2].

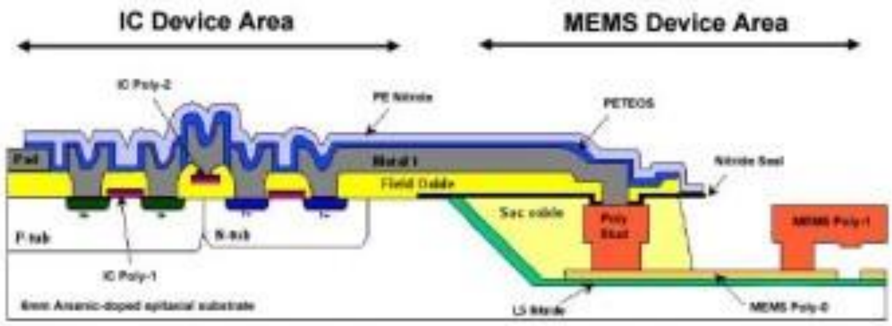


Figure 27. Integrated MEMS/IC (iMEMS) technology developed at Sandia National Laboratories for the monolithic integration of IC control circuits and MEMS sensors and actuators on the same silicon chip. To handle the differences in surface topography, the MEMS components are fabricated in a shallow trench below the wafer surface prior to IC processing [2].

A significant improvement in device functionality and a high level of integration can be obtained by integrating the control circuits and MEMS devices on the same silicon chip. Benefits of trench integration include smaller, faster, less costly, lower power and higher sensitivity integrated systems. There are no real trade-offs with the technology except the potential for more parasitic noise from interconnects on the chip.

Packaging

The proper operation of MEMS devices depends critically upon the 'clean' environment provided by the package and is considered an enabler for the commercialisation of MEMS. Packaging of microsensors presents special problems as part of the sensor requires environmental access while the rest may require protection from environmental conditions and handling (Figure 28).

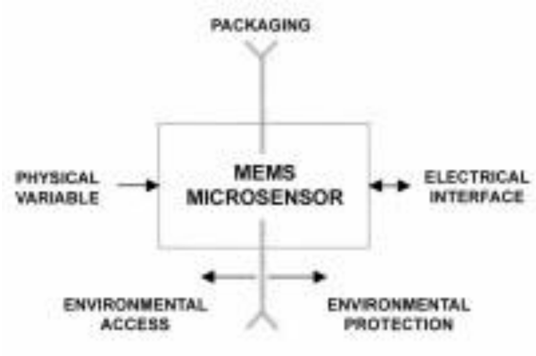


Figure 28. Schematic illustration of the packaging role of a MEMS microsensor [32].

Although there is no generic package for a MEMS device, the package should:

- provide protection and be robust enough to withstand its operating environment
- allow for environmental access and connections to physical domain (optical fibres, fluid feed lines etc.)
- minimize electrical interference effects from inside and outside the device
- dissipate generated heat and withstand high operating temperatures (where necessary)
- minimize stress from external loading
- handle power from electrical connection leads without signal disruption

The most commonly used packages for sensors are usually based on derivatives of conventional semiconductor packages including plastic, ceramic and metal can packages (Figure 29).

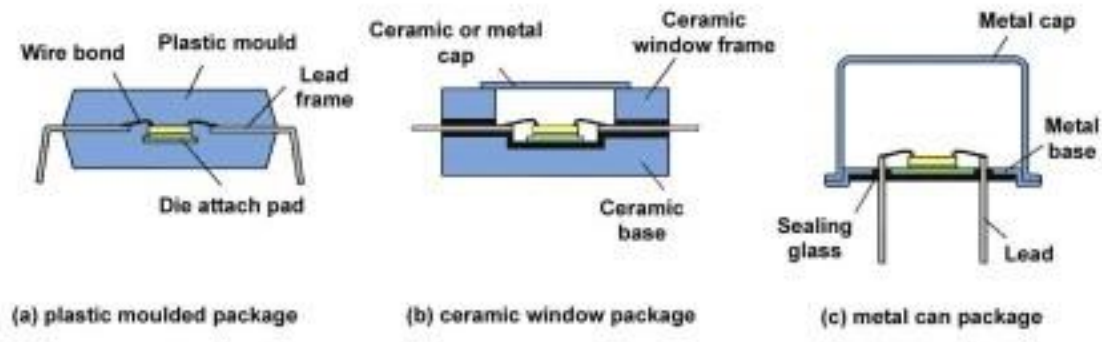


Figure 30. Types of traditional IC packaging [32].

Each of these packages has been adapted in one form or another for the packaging of silicon sensors. Since the substrate on many integrated circuits requires an electrical connection to bias it, sensor dies are usually mounted to a die attach pad in the package using a conductive bond. The die attach pad is typically joined to a metal lead frame with wire bonds providing the electrical connections to the lead frame fingers. Various bonding media include AuSi eutectic bonding, epoxy bonding (conductive or insulating depending on filler material) and glass usually loaded with silver. The package is subsequently formed by plastic moulding (as in the case of moulded plastic packages), sealed ceramic or metal caps (ceramic packages), or with a brazed metal cap to the base of a metal package.

Wire bonding is still the most common technique for electrically connecting the die and consists of two main technologies; ultrasonic and thermosonic, their difference being in the mechanical stress applied to the die, the minimum spacing, the used wire alloys and the possibility of wire adjustment.

In flip-chip (FC) technology the chips are bonded face down to a substrate via bumps; materials include solder, gold, copper and nickel. On heating, the bump material melts and simultaneously forms all the electrical and mechanical connections between the chip and the substrate.

Multi-chip Modules

Multi-chip modules (MCMs) enable the integration and packaging of MEMS devices on a single substrate using traditional thick-film technology. Using ceramics, silicon and printed circuit board laminates as substrate materials, a variety of die types can be attached to, or embedded within, the substrate surface. The dies can be interconnected by wire bonds, flip chips or direct metallisation. The close proximity of each die allows for improved system performance by providing low-noise wiring and in some cases eliminating unnecessary interconnections. Three-dimensional variations of this technology are emerging in which dies and their holding substrates are stacked up on top of each other.

Passivation and Encapsulation

In order to protect MEMS devices from external contamination as well as enable them to dissipate generated heat, thin-film coatings can be deposited on the components. In a process called passivation using plasma enhanced chemical vapour deposition (PECVD), thin-film coatings of usually silicon dioxide or silicon nitride increase wear resistance and electrical insulation.

Encapsulation is used to protect the sensor die against adverse influences from the environment like contaminants, mechanical vibration and shock. Common encapsulants are epoxies, silicones and polyurethanes. These materials need to adhere well to the substrate, be crack free and minimize induced mechanical stress as well as stresses due to mismatching of thermal expansion coefficients.

3.9 Foundry Services

Despite the many similarities between IC and MEMS fabrication, MEMS makers, or foundries, are still in their adolescence. The widening variety and increasing complexity of MEMS products make the MEMS foundry business extremely problematic. Although the fabrication technology is similar, the technology is on a different scale. MEMS are 3D products in comparison to the 2D level of IC's. Furthermore, unlike a standard IC foundry, which performs one or two standard processes, a MEMS foundry performs a wide variety of processes.

From an economic standpoint MEMS foundries share a common characteristic with semiconductor foundries in that they are often more cost-effective than internal manufacturing. This is because there is an enormous economy of scale as MEMS foundries can leverage the cumulative volume from multiple products from multiple companies to achieve high equipment utilization rates. The most important difference though is that MEMS produces a mechanical structure that moves and that is significantly more complex and sensitive than traditional 'stationery' IC structures.

Expansion of the MEMS market has been restricted by the need for specialized MEMS engineering knowledge. Until recently, the majority of global research and development investment has been limited to only a few MEMS foundries. A couple of years ago Cronos Integrated Microsystems of North Carolina was seen as the leading MEMS foundry in the field. A spin-off from MCNC and sponsored heavily by DARPA, it developed MUMPS, offering low-cost manufacturing solutions for prototype and small-series MEMS applications. Other pioneering foundries that were able to leverage the large scale investment already made in silicon semiconductor fabrication include the Metal Oxide Implementation Service (MOSIS), operated by the Information Sciences Institute at University of Southern California; and Sandia National Laboratories, USA, with their SUMMiT technology. Smaller original foundries still exist but in technology specific areas: MEMSCAP (France) – IC based; SensorNor (Norway) – bulk micromachining and fusion bonding; GEMAC (Germany) – bulk micromachining; and Bosch (Germany) – DRIE process. But of these labs, none are able to handle mass production, certainly on the scale usually associated with the IC chip industry. The lack of market demand for MEMS devices is one of the factors holding the technology back; the devices can not be manufactured in numbers high enough to bring the price of MEMS chips down to the point where they make economic sense.

In 1999, the MEMS industry witnessed unprecedented growth and wealth creation as major venture capital and corporate funding took place. Today, it is no longer necessary to build a separate fabrication facility to create a MEMS product or invest hundred of millions of dollars to become a MEMS player. A newly created infrastructure of smaller foundries is now available to support both emerging and proven MEMS-based applications. Although the biggest of these foundries are the risk-taking producers of specialized and niche chips such as Motorola, Sony, Analog Devices and Texas Instruments, there are also many smaller start-up MEMS foundries which offer more specialized services such as packaging, testing, reliability analysis etc. Not only do these foundries offer the obvious manufacturing technology and services to outside customers but they offer the concept of 'shared learning' in that lessons learned when the foundry puts into volume production one product can be applied to the subsequent volume production of another product. This can occur even when the products are completely different because there will still be sharing of specific process modules. Today, there are more than 40-50 MEMS makers or foundries worldwide (though none has broken away from the pack as in the case, for example, of Intel with computer chips).

4. MEMS Transducers

Microsensors and microactuators are at the very core of a MEMS device or system. A microsensor detects changes in the system's environment; an 'intelligent' part processes the information detected by the sensor and makes a decision in the form of a signal; and a microactuator acts on this signal to create some form of changes in the environment. Microelectronic components make up most of the intelligent part of the device and, as an established technology, will not be discussed here.

Sensors and actuators are broadly termed transducers and are essentially devices that convert one form of energy into another. Many of the MEMS sensors and actuators described in this section have been developed within the microelectronics industry and do not all involve any special micromachining techniques; they are based on conventional integrated circuits that, through inherent mechanisms, sense light, temperature etc. However, many of these can be enhanced by the use of MEMS.

Basic MEMS mechanisms and structures consist of both in-plane and out-of-plane mechanisms as well as structural members to couple energy between the actuator and sensors as well as with the physical interface of a mechanical system. Mechanisms such as joints, linkages, gears and hinges are very typical.

This section concentrates on the phenomena that can be sensed or acted upon with MEMS devices with a brief description of the basic sensing and actuation mechanisms. It is important to note that although these devices are mechanical and have been categorized in terms of their sensing domain (e.g. thermal, chemical, radiation), there are many overlaps, and forms of mechanical transducer can be commonly found as intermediate mechanisms in other devices.

Mechanical Transducers

Mechanical Sensors

There is a tremendous variety of direct mechanical sensors that have been or could be micromachined depending on their sensing mechanism (usually piezoresistive, piezoelectric or capacitive) and the parameters sensed (typically strain, force and displacement).

i) Piezoresistive sensors

As a result of the piezoresistive effect (defined as the change in resistivity of the material with applied strain), changes in gauge dimension result in proportional changes in resistance in the sensor. The piezoresistive effect in semiconductors is considerably higher than in traditional metals, making silicon an excellent strain sensor. MEMS piezoresistors are readily manufactured using bulk silicon doped with p-type or n-type impurities.

ii) Piezoelectric sensors

Piezoelectric sensors utilize the piezoelectric effect in which an applied strain (or force) on a piezoelectric crystal results in a potential difference across the crystal. Similarly, if the crystal is subjected to a potential difference, a displacement, or strain, is produced. The effect can be used to sense mechanical stress (i.e. displacement) and as an actuation mechanism, although displacements are small even for large voltages. Common piezoelectric materials used for MEMS applications include quartz, lead zirconate titanate (PZT), polyvinylidene fluoride (PVDF) and ZnO, PVDF and ZnO being the most common. Silicon is not piezoelectric; hence a thin film of a suitable material must be deposited on the devices.

iii) Capacitive sensors

Capacitive (or electrostatic) sensing is one of the most important (and widely used) precision sensing mechanisms and includes one or more fixed conducting plates with one or more moving conducting plates. Capacitive sensing relies on the basic parallel-plate capacitor equation shown below. As capacitance is inversely proportional to the distance between the plates, sensing of very small displacements is extremely accurate.

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

where: $_0$ = permittivity of free space = 8.854×10^{-12} Fm^{-1}

$_r$ = relative permittivity of material between the plates

A = overlapping plate area (m)

d = plate separation (m)

iv) Resonant sensors

MEMS resonant sensors consist of micromachined beams or bridges which are driven to vibrate at their resonant frequency. They can be attached to membranes or designed to adhere to a particular substance (as in the case of a biosensor). Movement of the membrane or increased build-up of the binding substance will affect the resonant frequency and can be monitored using implanted piezoresistors.

Types of mechanical sensor include:

a) Strain gauge - a strain gauge is a conductor or semiconductor that is fabricated on or bonded directly to the surface to be measured. An example of a polysilicon strain sensor unable to be fabricated by any other method than MEMS is an implantable piezoresistive strain gauge to measure forces in heart and brain tissue.

b) Accelerometer - accelerometers sense acceleration by using a suspended proof mass on which external acceleration can act (Figure 30). Upon acceleration (or deceleration), a force (F=ma) is generated on the proof mass resulting in displacement. The force or displacement is usually measured by piezoresistive and capacitive methods.

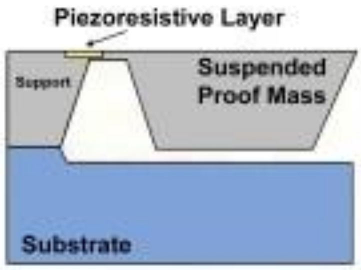


Figure 30. Suspended proof mass in a piezoresistive accelerometer (not to scale).

c) Gyroscope – a gyroscope is a device that measures the rotation rate and detects inertial angular motion. As a result it can be found, for example, in transportation, navigation and missile guidance applications. It relies on measuring the influence of the Coriolis force on a body in a rotating frame. MEMS gyroscopes typically use vibrating structures because of the difficulty of micromachining rotating parts with sufficient useful mass.

d) Pressure sensor - MEMS pressure sensors are usually based around thin membranes with sealed gas or vacuum-filled cavities on one side of the membrane and the pressure to be measured on the other side. Piezoresistive and capacitive membrane deflection measurement techniques are most commonly used in commercial pressure sensors.

Mechanical Actuators

i) Electrostatic actuation

The fundamental actuation principle behind electrostatic actuators is the attraction of two oppositely charged plates. Their use is extensive in MEMS devices, since it is relatively simple to fabricate closely spaced gaps with conductive plates on opposite sides. For a parallel plate capacitor, the energy (W) stored at a given voltage (V) is equal to:

$$W = \frac{1}{2}CV^2$$

where: C=capacitance between the plates

And the force between the plates is:

$$F = \frac{\partial W}{\partial x} = \frac{1}{2}\frac{\partial C}{\partial x}V^2$$

Comb-drive-type actuators make use of a large number of fine interdigitated fingers that are actuated by applying a voltage between them (Figure 31). As the capacitance is related to area, the greater the number of fingers, the larger the force that can be generated by the actuator.

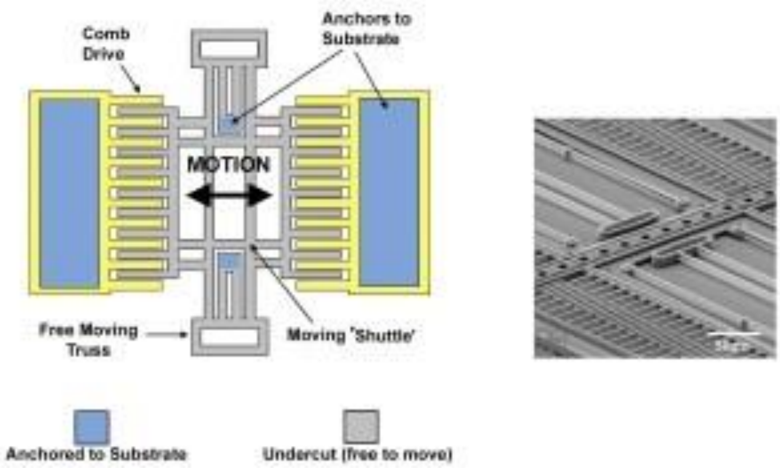


Figure 31. Comb-drive electrostatic actuator concept [2,33].

Electrostatic rotary motors are another good example of the success of MEMS sacrificial oxide/polysilicon techniques. They rely on a central freely-moving rotor with surrounding capacitive plates that can be driven in correct phase to cause the rotor to turn. Harmonic or ‘wobble’ motors rely on the principle of a rotor turning in a slightly larger stator ring, such that it ‘wobbles’ around the central axis as it rotates (Figure 32). Reduction of sliding friction and increased electrostatic forces can be achieved with these motors.

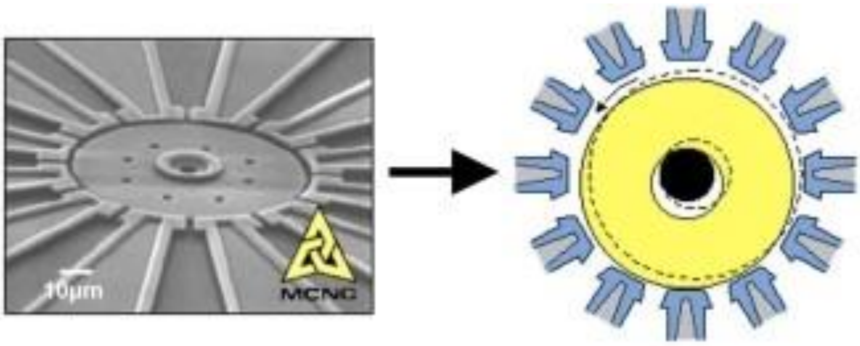


Figure 32. A MEMS electrostatic ‘wobble’ motor [30].

ii) Piezoelectric actuation

As previously described, the piezoelectric effect can be used in both sensors and actuators. In piezoelectric actuation, the electrically induced displacement (or strain) is proportional to the applied potential difference. Despite small displacements, relatively high forces (in the region of tens of MPa) can be achieved using lower voltages than those required for comparable electrostatic actuation. It should be noted, however, that it is dependent on the geometry of the device components. The main disadvantages of piezoelectric actuation include high complexity of fabrication, as well as small actuation displacements. Larger displacements can be achieved using multiple piezoelectric layers known as piezoelectric bimorphs. Most MEMS piezoelectric actuation is used where small strains are required (for example, the tip of a scanning tunnelling microscope) [4].

Radiation Transducers

Radiation Sensors

Radiation sensors cover ionising radiation as well as visible light, infra-red (IR) and ultra-violet (UV) radiation. Current ionising radiation sensors for high-energy particles and X-rays include Geiger-Müller (GM) tubes and scintillators and although they have not been realized using MEMS, their miniaturization is potentially feasible. Sensors for visible, IR and UV radiation are generally categorized as either direct or indirect. Direct optical sensors detect photons and result in an electronic signal. Indirect sensors convert the optical signals into an intermediate energy form (e.g. thermal or chemical), which is then measured electrically. There are a wide variety of both direct and indirect sensors and only the most common will be described here.

i) Photodiodes

A photodiode is a semiconductor device for measuring light intensity based on the photoconductive effect (increase in conductivity of a semiconductor on exposure to light). Photodiodes are junction-based photoelectrodes which have a p-n junction. When visible or near infra-red light falls on the device, additional charge carriers are generated resulting in increased current flow.

ii) Charge-coupled devices

Charge-coupled devices (CCDs) are one of the most common photodetectors used in handheld video recorders and many other consumer applications. They consist of a metal gate (electrode) above a dielectric and a semiconductor substrate. This forms a metal oxide semiconductor (MOS) capacitor, the charge on which arises from photogenerated carriers. CCDs can be linear or made up of arrays of metal-insulator-semiconductor sensors arranged so that photo-generated charge can be stored and transferred between elements by an appropriate variation of control voltages applied to surface electrodes (memory/signal processing approach).

iii) Pyroelectric sensors

Pyroelectric detectors are an example of indirect optical sensors and are essentially capacitors whose charge can be altered by illumination or temperature changes. By converting incident light into heat, which is then measured, pyroelectric sensors have a wide range of applications in surveillance, military, security consumer markets etc. e.g. human motion detectors. Pyroelectric sensors use piezoelectric and ferroelectric materials (varying dielectric constant with applied voltage). ZnO is the most common in MEMS devices.

Radiation (Optical) Actuators

The two most common forms of optical actuation include light emitting diodes and light modulators such as liquid crystal displays and reflective micromechanical light modulators (technology used in Texas Instrument’s DMD projection system).

Optical devices can either be active or passive; active devices include laser emitting diodes, photodiodes and optical switches. Passive devices include couplers, mirrors, wavelength division multiplexers, polarisers etc. Their application is important in both optical MEMS devices and integrated optics to enable the control and analysis of optical acquired data. A brief selection of optical MEMS components includes:

- optical waveguides to route optical energy from one region to another. MEMS techniques are commonly employed to enable waveguide-to-photodiode coupling.
- fibre-optic couplers incorporate micromachined grooves and channels as mechanical couplings for fibre-optic components. Anisotropic wet etching, DRIE and HARM methods are typically used.
- micromirrors with flawless surfaces can be achieved using anisotropic etching to yield perfect crystal plane surfaces.

Thermal Transducers

Thermal Sensors

i) Thermo-mechanical sensors

Thermo-mechanical sensing (and actuation) utilize the fact that all materials have a coefficient of thermal expansion. Consequently, if two different materials are sandwiched together and undergo a temperature change, movement in the sandwich assembly would occur. This is the basis for the common bimetallic (or thermal bimorph) sensing and actuation.

ii) Thermoresistive sensors

Thermoresistive sensors rely on the fact that the resistivity, , of most materials changes with temperature and is shown by the equation $\rho = R(1 + aT = bT^2)$ where R is the resistivity of the material at a reference temperature, T (ºC), and a and b are constants specific to the material being used. The rate of change of resistance with temperature is known as the temperature coefficient of resistance. Most common materials exhibit an increase in resistance with temperature (e.g. platinum is particularly linear with temperature). Certain materials – for example, carbon, some ceramics and most semiconductors used in thermoresistors or ‘thermistors’ – exhibit a decrease in resistance with increasing temperature. They are not as linear as platinum, but often cheaper to fabricate and easier to integrate with circuitry in MEMS devices.

iii) Thermocouples

The thermocouple is probably the most common temperature transducer. It consists of a junction between two different materials and measures the temperature-dependent voltage that arises across the junction. Semiconductor materials often exhibit a better thermoelectric effect than metals. Thermocouples have been used in a wide variety of MEMS sensors in an array arrangement referred to as a thermopile.

Thermal Actuators

Thermal actuation in MEMS is usually as a direct result of incorporating tiny heaters, or resistors. These resistors can be controlled to locally heat specific areas or layers as in the case of a bilayer actuator. As already detailed, basic thermal actuation utilizes the difference in thermal coefficients for expansion of two bonded materials and is referred to as thermal bimorph actuation. A typical thermal bimorph actuator is shown in Figure 33.

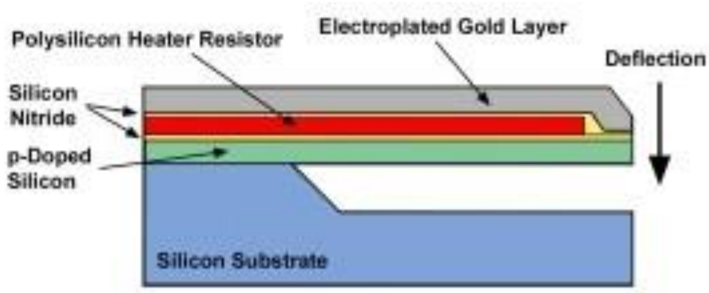


Figure 33. Example of a MEMS thermal bimorph actuator [34].

This can be applied to a volume of fluid (liquid or gases) in sealed cavities with a thin membrane as a wall. By incorporating a heater the liquid can be heated causing it to expand and deform the membrane outwards. Large forces can be achieved using thermally actuated devices but power consumption can be high and it can take time for material to cool to its original activation state.

i) Shape memory alloy actuation

Shape memory alloys (SMAs) exhibit considerable changes in their length (contraction) when heated. These include titanium/nickel alloys, of which some, once mechanically deformed, would return to their original undeformed state when heated. Being conductive they can be heated simply by passing a current through them.

Magnetic Transducers

Magnetic Sensors

Most MEMS magnetic sensors are based on the Hall effect. They rely on the production of an electric field across a material through which an electric current is flowing and where a magnetic field is acting. The force applied to the charge carriers by the electric field exactly balances a force from the magnetic field called the Lorentz force. Other ways to sense magnetic fields use optical sensors that rely on the magneto-optical effect or materials that exhibit magnetic anisotropy (shape, stress and crystalline anisotropy are particularly common in MEMS magnetic applications). Magnetic coils are not common in MEMS as they tend to be 2D, which is not useful for many applications.

The most sensitive magnetic sensors include superconducting quantum interference devices (SQUIDS). The devices can detect diminutive magnetic fluxes produced by the electric currents in heart and brain tissue. Advances in superconducting thin films as well as MEMS techniques have accelerated growth with these devices.

Most of today’s magnetic sensors are silicon based, not only because of the ease of fabrication and their ability to be readily integrated with circuitry, but also because their high volume demand necessitates lower cost.

Magnetic Actuators

Magnetic actuation is based on the fact that a current-carrying conductor generates a magnetic field. If this conductor is a wire (or coil) and interacts with another external magnetic field (e.g. from a similar conductor or coil) a mechanical force is produced.

Despite the success of magnetic actuation on a macroscale, such as motors or solenoids, MEMS magnetic devices are still relatively unestablished. This is due to the fact that 3D coils are very difficult to fabricate by MEMS. A notable exception is the magnetic read/write heads for computer disk drives. This device can be classified as both a sensor and actuator in that it reads from and writes to magnetic media.

Choice of magnetic material is limited to those that can be easily micromachined and do not suffer from high power consumption and heat dissipation. Thin film permanent magnets can be fabricated using MEMS; LIGA is particularly common for polymers such as polyimide which can be loaded with a magnetic powder and electroplated. Although attempts have been made to fabricate MEMS magnetic actuators with wire-bonded coils, often in MEMS devices, magnetic actuators compete with electrostatic devices which are stronger for the same volume.

i) Magnetostrictive Actuators

These rely on the magnetostrictive effect, which is the change of shape or size of a ferromagnetic material induced by a magnetic field, for example, the contraction of a nickel rod under a longitudinal magnetic field.

Chemical and Biological Transducers

Chemical and Biological Sensors

Chemical and biological sensors encompass a large and wide variety of devices that interact with solids, gases and liquids of all types and are therefore extremely diverse and interdisciplinary. They are different from previously described sensors in that they must directly interact with a chemical medium to connect the chemical and electrical domains. Hence they require ‘openings’ within their packaging to enable this interaction (like pressure sensors).

Most chemical and biological sensors do not require extremely sophisticated micromachining but can require considerable interdisciplinary knowledge and sophistication for their actual use. Chemical sensors must be very highly selective in order to make such identifications among compounds without falsely responding to potential interfering species.

Chemical sensors can be categorized in many ways including passive chemical sensors, work function based systems and electrochemical transducers. Passive chemical sensors include:

- Chemiresistors measure the resistance of a chemically sensitive layer between two electrical contacts. Sensitivity can be increased using more micromachined electrodes.

- Chemicapacitors are similar to chemiresistors but the capacitance of the sensitive layer is measured. Chemicapacitors have found application in sensing humidity.
- Chemomechanical sensors rely on direct chemical-to-mechanical transduction (for example, the expansion of a thin-film polymer in the presence of a substance being analysed).
- Calorimetric sensors measure heat generated by chemical reactions.

i) Work function based sensors

This class of sensors, including the ion sensitive field effect transistor (ISFET) and the metal oxide semiconductor field effect transistor (MOSFET), utilizes metal-insulator-semiconductor junctions and the fact that the work function of the material at the interfaces can be chemically modulated. The ISFET was developed as a direct result of the fact that metal-oxide-semiconductor transistors were so sensitive to surface contaminants during their manufacture. As a large proportion of chemical sensors are based on the ISFET, a more detailed description of their operation is outlined.

ISFETs sense the concentration or activity level of a particular ion in solution. The ISFET is a derivative of a common electronic component called a MOSFET. This consists of a silicon semiconductor substrate (doped with impurities to make it p-type) and two electrical contacts (source and drain) doped with impurities so that negatively charged electrons are the main carriers in these small n-type silicon regions. A small distance separates source from drain (Figure 34). Overlaying the substrate between the source and drain is a silicon dioxide insulator which itself is overlaid with a metal electrode called a gate. When a potential is applied to the gate of the MOSFET, the induced electrical field changes the freedom with which the current flows between the source and the drain. In the case of an ISFET however, there is no gate electrode and the insulator is in direct contact with an electrolyte solution to be measured. With the ISFET, electric current flows from the source to the drain via a channel. As in the MOSFET the channel resistance depends on the electric field perpendicular to the direction of the current. Also it depends on the potential difference over the gate oxide. Therefore the source-drain current is influenced by the interface potential at the oxide/aqueous junction. When SiO_2 is used as the insulator, the chemical nature of the interface oxide is reflected in the measured source-drain current. With the selection of other appropriate insulator material, such as silicon nitride or aluminium oxide, hydrogen ions will reside at the surface of the insulator in proportion to the pH. Their positive charge produces an electric field that modulates the current between the source and drain. In order to quantify this effect, the control voltage is measured that must be applied (via a reference electrode) to maintain the drain-source current at a constant value.

The chemical sensitivity of the ISFET is completely controlled by the properties of the electrolyte/insulator interface. One significant problem in the design and fabrication of ISFETs is ensuring that the selective membrane adheres to the device. If the integrity of the membrane is compromised, then the device is useless.

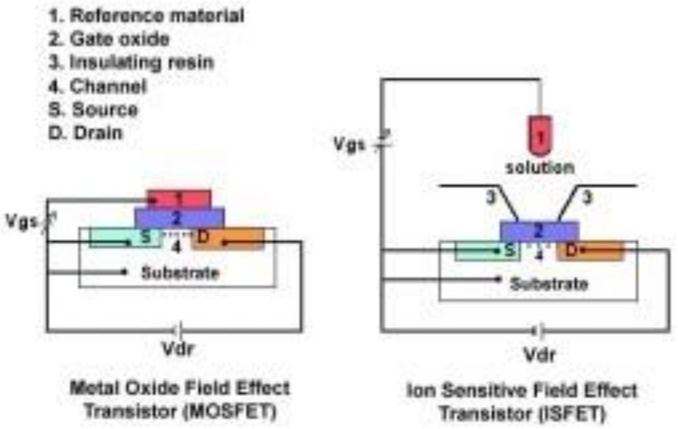


Figure 34. Schematic diagram of an MOSFET and ISFET [35].

ii) Biosensors

Biosensors is the term used for a whole class of sensors that utilize a biochemical reaction to determine a specific compound. A biosensor is generally a transducer combined with an immobilized enzyme or cell to monitor a specific change in the microenvironment. Typically, an enzyme, antibody, polysaccharide or nucleic acid is used to interact with the substance to be measured. The sensor itself can vary but a form of ISFET is typically used. The probe tip is immersed in a liquid phase and is in contact with the process either directly or through a membrane. They have not seen widespread use because as a class they exhibit many disadvantages including oxidization reactions with product, extreme sensitivity and the need for regular recalibration (not ideal for implantable devices).

One of the most promising applications of an amperometric enzyme-based biosensor is the glucose oxidase based sensor for monitoring glucose levels in the blood. This is particularly important for diabetes and also in the fermentation process.

Chemical Actuators

There is certainly potential to fabricate chemical actuators using MEMS, but to date, there has been little work in this area with the exception of a few devices using microelectrodes. These electrochemical transducers are based on the simple electrochemical electrode concept in which current is transducer from the circuit domain into the chemical domain through oxidation or reduction of chemical species at the electrode surface. These structures are amongst the simplest (they can be as simple as a region of bare metal in solution) and play a major role in biological interfacing (e.g. neurophysiologic probes).

4.6 Micro fluidic Devices

MEMS has many applications in micro fluidics with many of the key building blocks such as flow channels, pumps and valves fabricated using mature micromachining techniques. Chemical analysis, drug delivery, biological sensing, environmental monitoring and many other applications typically incorporate MEMS micro fluidic devices. It should be noted that in MEMS fluidic devices the type of flow (laminar or turbulent), effect of bubbles, capillary forces, fluidic resistance and capacitance all have an effect on their final design.

i) Flow channels

A wide variety of micro fluidic channels have been fabricated using bulk micromachining (wet and dry etching), surface micromachining and moulding techniques (Figure 35).

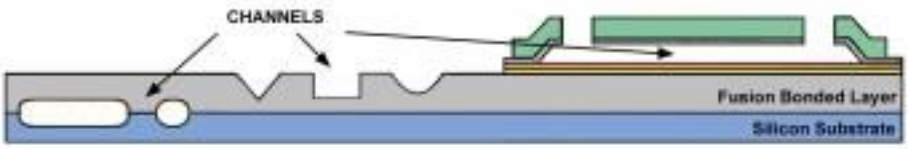


Figure 35. Selection of MEMS channels for microfluidic applications [36,37,38].

ii) Flow sensors

MEMS flow sensors can be fluid-dependent flow or fluid-independent. In a very basic form, fluid-dependent flow sensors measure the flow rate by heating a fluid ‘upstream’ and then recording its temperature ‘downstream’. The flow rate is proportional to the temperature difference and transit time of the two actions. Fluid-independent flow sensors measure pressure or force exerted on an object by the fluid. Figure 36 shows an example of a MEMS bulk drag-force flow sensor. Using a piezoresistive sensing mechanism, flow measurements are fairly linear; direction and magnitude can be sensed by this method. In addition, fluid-independent flow sensors do not involve any form of heating and hence are more suited to biological fluid applications.

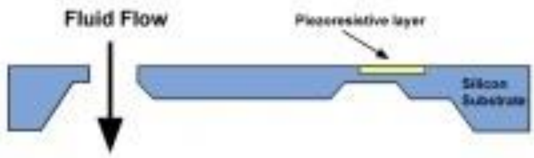


Figure 36. Micromachined mechanical (drag-force) flow sensor [39].

iii) Valves

Valves are generally classified as either active or passive depending on whether or not they have an external power or control source. One of the simplest MEMS valves is the passive check valve shown in Figure 37.

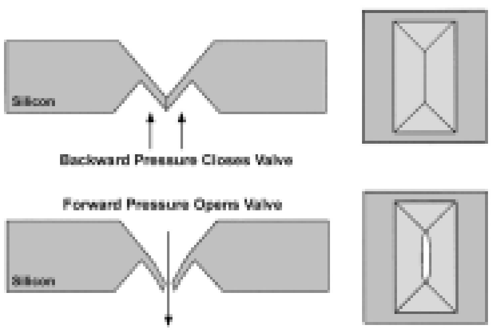


Figure 37. Basic concept of passive silicon check valve [40].

Active MEMS valves can be actuated by many methods including thermal, piezoelectric, electrostatic and shape memory alloy means. Thermal actuation is the most common.

iv) Pumps

Pumps are generally an important part of micro fluidic devices. However, MEMS pumps are very sensitive to fine particles which often cause contamination and leakage of the device. Membrane, rotary and ultrasonic pumps are the most common types of MEMS pumps.

v) Rotary pumps

Figure 38 shows the basic concept of a magnetic rotary micro pump. LIGA is commonly used as a fabrication technique for micro machined PMMA gears in MEMS micro fluidic systems. These gears can be driven for example using electroplated NiFe bars mounted on one or both of the gears. Fluid is pumped by the action of the turning gears.

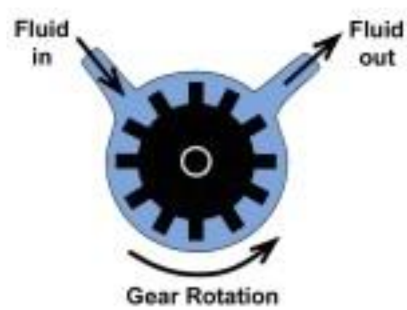


Figure 38. Basic concept of magnetic rotary micropump [41].

vi) Droplet generators

The majority of droplet generators in commercial MEMS microfluidic devices are inkjet printer heads as previously described in Section 2.4.1. These rely on either thermal or piezoelectric actuation to eject ink droplets, thermal actuation being the most common. Piezoelectric ally actuated valves offer the advantage of very high forces, but very small movement for even very large voltages. They also find use in automotive fuel-injection valves and spray nozzles.

FABRICATION OF OUT-OF-PLANE POLYMER MICROLENSES

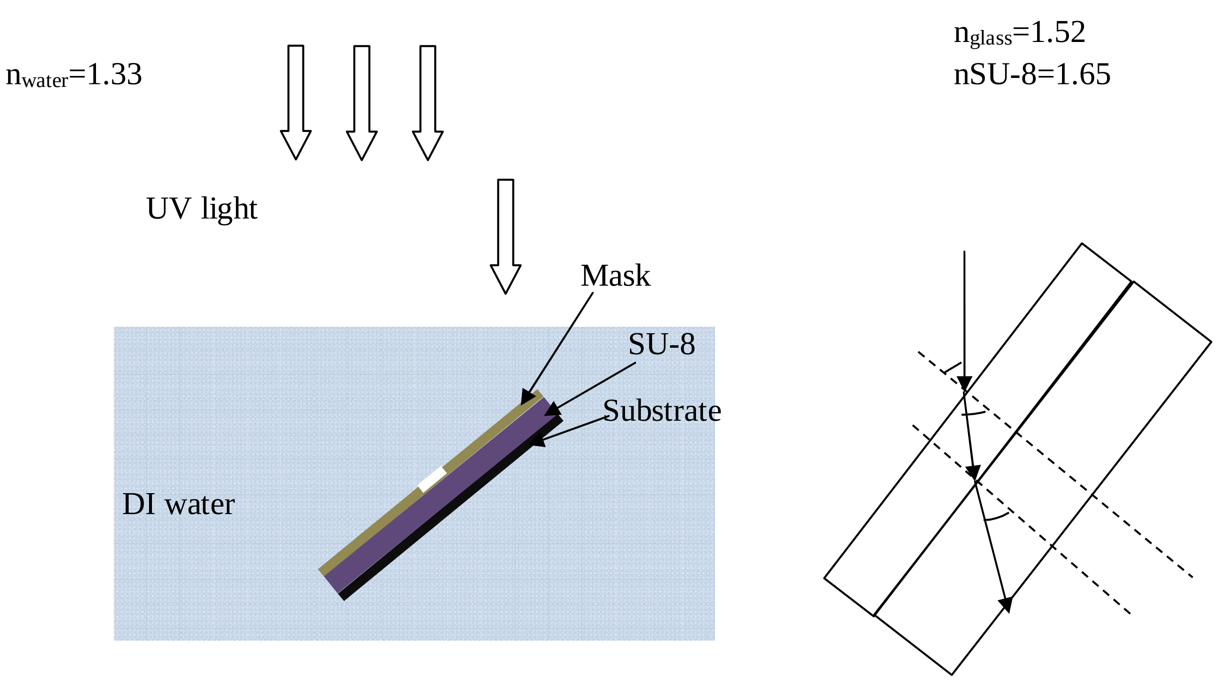
UV lithography method to directly fabricate out-of-plane microlens with negative tone photoresist SU-8 .
An out-of-plane microlens array with nearly-spherical micrlens pixels was successfully fabricated with this method. However, there are two disadvantages with the previous technology. First, the use of an ultra- thick (>500m) SU-8 photoresist layer and multiple tilted UV exposures made this process a time consuming one. It took more than two days to finish the whole process and expensive photo-lithography process equipments was necessary.
Secondly, microlenses can only be made of SU-8 polymer which is essentially a photo sensitive material and has limited optical transparency. It has been observed that aged SU-8 polymer turns to reddish color. A fast and low cost out-of-plane microlens fabrication technology which can be used to make microlenses with a broad selection of materials is therefore highly desirable.

PDMS is a silicone based elastomer. It was introduced into micro fabrication in late 90s [20]. Because it is in a liquid state before curing and has a very low surface energy (essential ford molding process), PDMS has quickly become arguably the most popular material in micro and nano-molding processes. The PDMS molding process has also been adopted into micro lens fabrication [60]. However, the reported micro lens fabrication processes using PDMS are all for in-plane microlens fabrication. Unlike in-plane micro lenses whose relief structures are on the substrate plane, out-of-plane micro lens has relief structure on the sidewall. This makes the molding of out-of-plane micro lens very challenging since the lens structures may easily be damaged during the demolding process. PDMS, because of its unique properties, is a great candidate for out-of-plane molding and replication process. Before curing, PDMS pre-polymer is in relatively low-viscosity liquid state, so it can conformally cover the three-dimensional microstructures. After curing, the polymerized PDMS has good elasticity, which makes it possible to deform during the demolding process and come back to the original shape after demolding. So the negative mold can be released while keeping the SU-8 structure on the master intact.

Fabrication of SU-8 Master Mold

The fabrication of an out-of-plane micro lens master mold was done using a tilted UV lithography process with the widely used negative tone photo resist SU-8. Details of the fabrication process has been reported by Yang and Wang .

UV lithography in water medium



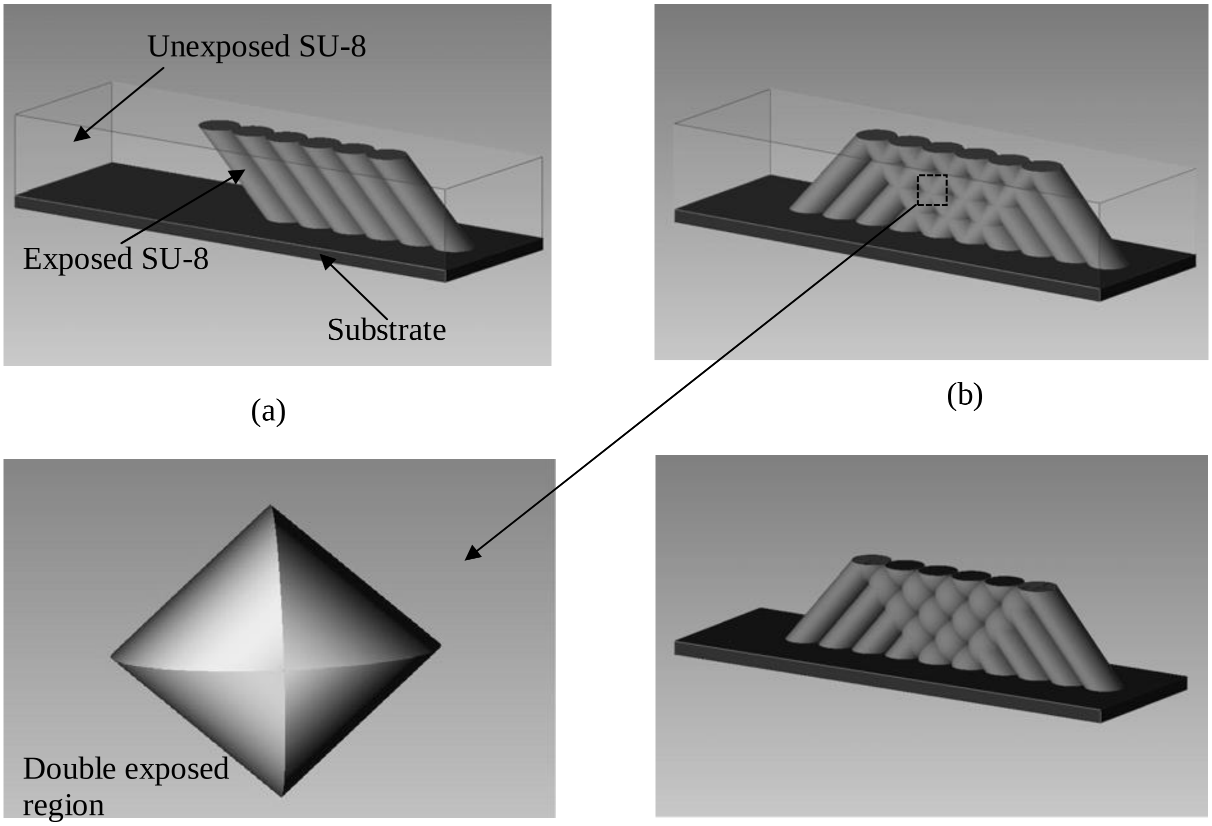
To perform the tilted UV lithography process, we chosed to use a water immersion lithography method similar to the one reported by Sato et al [62]. Comparing to prism assisted tilted UV lithography [6] [59], the water immersion approach is relatively easy to set up, and the maximum inclined angle can reach 56.2^{o} which is sufficient for out-of-plane microlens fabrication because only +/- 45^{o} inclined angles are required. Before exposure, silicon substrate spin-coated with SU-8 was fixed together with a chromium mask using a homemade clutch. As shown schematically in Figure 2-1, the clutch set was immersed in deionized (DI) water in a tilted position. The relationship between the resulting structure inclined angle and the tilted angle of the clutch set can be calculated using Snell's law. The following equation can be derived:

Where , n_{SU} =1.65 , n_{glass} =1.52, n_{water} =1.33, are the refractive indices of uncured SU-8, glass (soda lime), and water respectively. In our fabrication process, the final structures should have -/+ 45^{o} inclined angles with respect to the substrate.

Therefore, the clutch should be held at 61.26^{o} angle with respect to the horizontal plane during exposure. Since SU-8 has strong absorption to short wavelength UV light, short wavelength UV light may be absorbed only in the top layer and cause exposure non- uniformity throughout the whole photoresist thickness. For better exposure results, a piece of 1cm thick PMMA sheet (Plexiglas Grade G, Altuglas International, Philadelphia, PA) was used as an optical fileter to eliminate short wavelength spectrum of the UV light source. This PMMA sheet can block most of the UV light with wavelength shorter than 400nm. With the filter, SU-8 was only exposed by the *g-line* (436nm) and the *h-line* (405nm). Absorption of the *g-line* is much lower than that of the *h-line*, the exposure is dominated by the *h-line*. All exposure dosage mentioned in this chapter is measured at the *h-line*, unless otherwise stated.

The fabrication process for micro lenses made of cured SU-8 is graphically illustrated in Figure 2-2.

(1) **Substrate preparation and spin-coating:** A 4 inch silicon wafer with one side polished was cleaned in acetone, isopropyl alcohol (IPA) and DI water successively. After dehydration at 180^{o}C for 30 minutes, about 16g of SU-8 100 was dispensed onto the wafer and spincoated at 460 rpm for 30 seconds to obtain an 1100µm thick SU-8 layer. Since the layer was relatively thick, no edge beads were observed after letting the sample set at room temperature for 20min. To reduce the bubble generation during the spin-coating process, SU-8 was poured onto the wafer directly from the bottle with care, and formed bubbles were pricked by a sharp needle.



(c) (d)

Figure 2-2 SU-8 out-of-plane microlens fabrication process

(2) Soft bake: The spin-coated SU-8 was soft baked on a well-leveled hot plate to eliminate the solvent. The hot plate has a heating part underneath the wafer which helps drive the solvent from the bottom to the top and, thus, keep the top layer soft. This is important for thick SU-8 layer soft bake since a dried top layer can prevent remaining solvent from being evaporated. To reduce the stress in the thick SU-8 layer and achieve better lithography results, multi-step ramping and stepping soft bake process is used. Figure 2-3 shows the multi-step baking process used in this fabrication. The SU-8 layer was slowly ramped up to 110°C in multi steps and kept at 110°C for 10 hrs (for a thick SU-8 layer, the rule of thumb for soft bake time is about 1hr per100µm). The

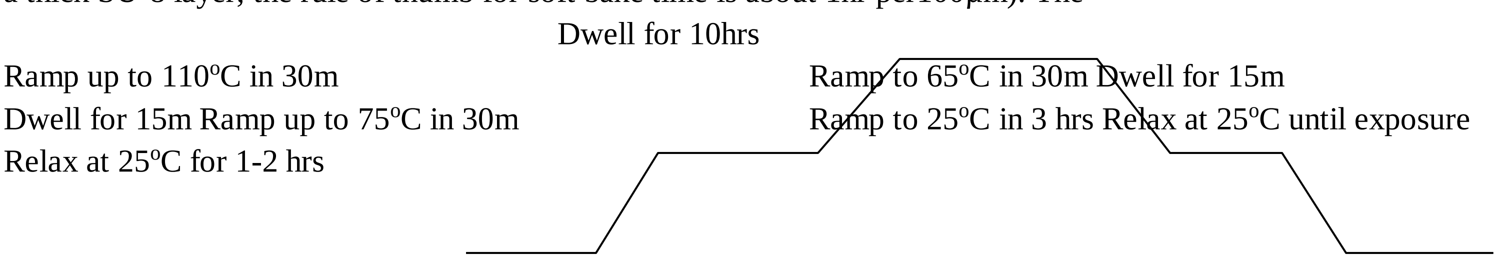
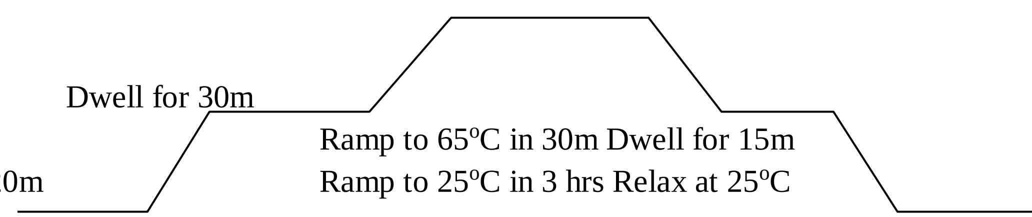


Figure 2-3 Multi step soft baking process

SU-8 layer was then slowly cooled down to 65^{0}C. Since the glass transition temperature of uncured SU-8 is about 60^{o}C, the cooling at around and below glass transition temperature should be done in a very slow rate to greatly reduce the internal stress in the thick SU-8 layer. 20^{o}C per hour was used in this process. After the soft bake, surface inspection was performed. It was found that the SU-8 surface had relatively smooth surface, height deviation across the whole 4- inch wafer was less than 30µm for an 1100µm layer.

(3) Tilted UV exposure: The wafer a chromium mask were fixed together in a rotatable home- made clutch (a drop of glycerol was applied between the mask and the wafer to serve as index matching fluid) and immersed in a DI water container for the first 45^{o} tilted UV exposure as described in the previous section (Figure 2-2 (a) shows the result after first exposure). After about 2 minutes relaxing, the whole set was put in an opposite direction for the -45^{o} exposure (Figure 2-2 (a) shows the result after second exposure). At each intersection area of two exposure beams, a four faced double exposed region was obtained as shown in Figure 2-2 (c). 4.5 J/cm^{2} exposure dosage at 405nm was used for each exposure. The dosage was experimentally optimized so that even the double exposed regions were still slightly under exposed, which was important for resulting of microlens with smooth surface. All UV exposures were performed using an Oriel UV exposure station (Newport Stratford, Inc. Straford, CT).

Figure 2-4 Multi step post bake proces



(4) Post bake: After exposure, the SU-8 layer was post-baked to accelerate the polymerization process. Similar to the soft baking process, rapid heating and cooling should also be avoided during post baking process. As shown in Figure 2-4, the sample was slowly heated up to 96ºC and kept there for 30m and then slowly cooled down to room temperature. To reduce the residual stress even more, a post bake at a lower temperature for a much longer time could also be employed.

(5) Development: After post bake, the whole sample was developed in SU-8 developer (PGMEA, propylene glycol methyl ether acetate). Because of the thickness of our SU-8 layer, a two-step development process was performed. As the first step, the sample was held facing- down in the developer for about 1 hr to solve most of the unexposed SU-8. Then, the sample was held face-up in a fresh developer solution for about 40 minutes with very mild agitation. Since the double exposed region was slight under exposed, the sharp edges of the four-faced region were smoothed out during the development process and eventually spherical microlens pixels with smoothed surfaces were formed as shown in Figure 2-2 (d). The developed sample was then rinsed in fresh SU-8 developer and dried in the hood under mild airflow. For microlens fabrication, IPA rinsing step which is widely used in SU-8 development process should be avoided since milky white spots formed on the partially polymerized SU-8 microlens surface can
cause great deterioration of its optical performance.

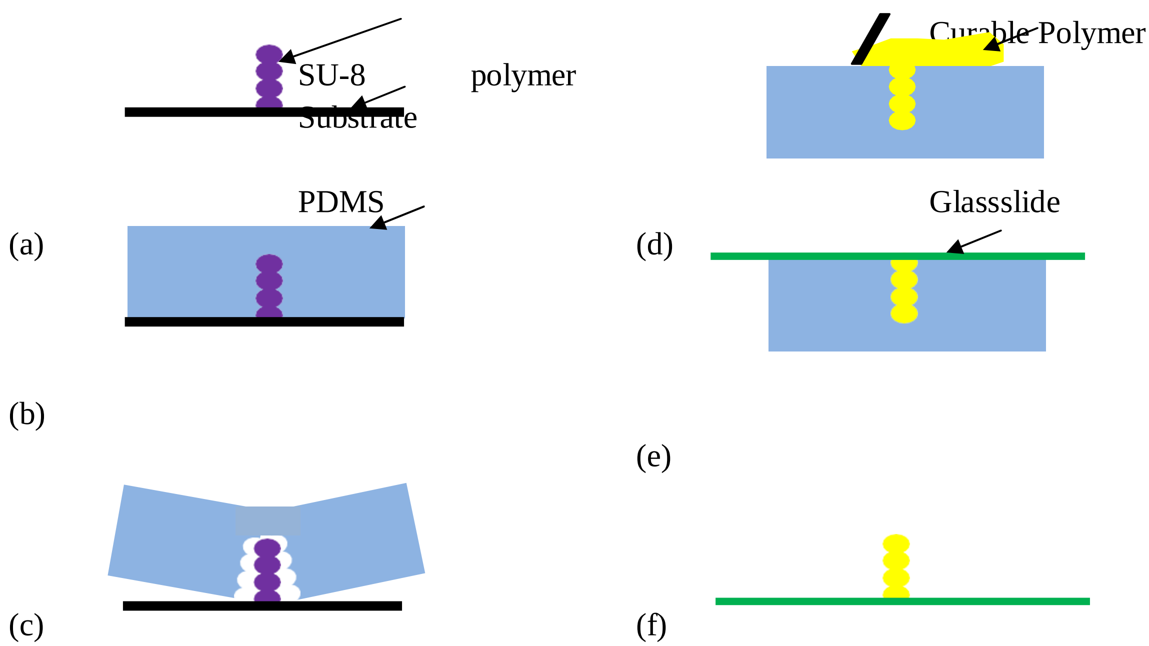
(6) Flood exposure and hard bake: After being dried, the sample with SU-8 out-of-plane microlens arrays is then flood exposed under the UV exposure station and baked at 95ºC for 1 hr. This treatment gave the final structures better mechanical stress. However, it was found during experiment that fully cross-linked SU-8 polymer turned to reddish color, which may negatively affect the optical performed of the microlens if SU-8 microlenses were directly used. For molding and replication process, the effect of this color change is negligible. SU-8 master mold fabrication was finished after hard bake process.

Out-of-plane Microlens Replication

PDMS molding process was used to make the negative mold from the SU-8 microlens array. Other curable polymers could then be used to cast out-of-plane microlens replica from the PDMS mold. In this work, a solvent-free UV curable polymer (NOA 73, Norland Products Inc., Cranbury, NJ) was used as an example curable polymer for demonstration purpose.

The microlens replication process is schematically shown in Figure 2-5. SU-8 out-of-plane microlens array was ready for PDMS molding after hard bake (Figure 2-5. (a)). PDMS pre- polymer mixture (Sylgard 184 Dow Corning) was prepared by mixing the base with curing agent in a 10:1 ratio. After being thoroughly stirred to ensure complete mixing, the PDMS pre-polymer mixture was placed in a vacuum chamber for 20 minutes to eliminate air bubbles. The PDMS pre-polymer mixture was then poured on the SU-8 master mold to form a 3mm thick PDMS layer. The PDMS covered wafer was then placed in a vacuum chamber for 20 minutes again to evaporate air bubbles and ensure that PDMS conformally covered the microstructures on the master mold. PDMS was then cured at 85°C for 3 hours (Figure 2-5 (b)). Since SU-8 mold master with out-of-plane microlens array had micro relief structure on the sidewall, one would

Figure 2-5 Out-of-plane microlens replication process: (a)-(c) PDMS molding, (d)-(f) curable polymer casting



have expected that demolding process might damage the master mold. However, the excellent flexibility of PDMS facilitated the demolding and made this whole process possible. Before being peeled off from SU-8 master, the PDMS mold was pulled sideways to be separated from the SU-8 microlens surface.

The whole PDMS negative mold could then be peeled off from the master with ease (Figure 2-5 (c)). A calculated amount of UV curable resin (NOA 73) was then poured onto the PDMS negative mold. After vacuum treatment, excessive resin was scraped off using a clean razor blade (Figure 2-5 (d)). Comparing to other NOA series product, NOA 73 resin had low viscosity (130cps, from NOA 73 datasheet), which was very important for the resin to flow into the three-dimensional micro cavities in the PDMS mold.

A microscope slide was then covered on the PDMS mold filled with UV curable resin (Figure 2-5 (e)) and exposed under a mercury lamp (Newport Cooperation, 9mw at 365nm) for 300s. After peeling off PDMS negative mold, out-of-plane microlens array replicas made of NOA 73 UV curable polymer was fabricated on glass slide (Figure 2-5 (f)). The whole replication process took less than 5 hours (not including the fabrication of SU-8 master mold). Because the PDMS mold is reusable, multiple replications can be done use the same negative mold. In the following operations, each replication process can be completed in less than 30 minutes.

Optical Analysis

Optical analysis is important to study the performance of the optical detection system and optimize itsdesign. Optical simulation was done using Zemax EE (ZEMAX Development Corp., Tucson, AZ). In our system, the output multimode fiber core diameter was 200μm, which is more than 200 times greater than typical fluorescent light wavelength. Therefore enough transverse modes can be supported in the output fiber and geometrical ray tracing method can be used to evaluate the light coupling efficiency .

An optical system as shown in Figure 3-2 was built in Zemax. A sample cell/bead emitting fluorescent light was modeled as a point light source [73, 74]; an imaginary aperture stop was placed in front of the microlens to define the optical rays which were traced during the simulation; microlens was modeled as a spherical lens with diameter of 450μm and radius of curvatures of 380μm for both surfaces; a circular image surface with numerical aperture (N.A.) of 0.2 was defined in Zemax to model the optical fiber with same N.A..

During the simulation, Zemax randomly generated a group of rays from the point light source to fill the aperture stop; those rays were then bent by the microlens and reached the plane where the output fiber end face was; part of the rays missed the defined output fiber end face and was obviously not supported by the output fiber; among those rays that did hit the acceptance end of the optical fiber, some came in at an angle larger than the optical fiber's numerical aperture and were also be dropped; only those rays that hit the optical fiber acceptance end at an angle within its numerical aperture were supported by the output fiber and contributed to the final detection signal. By comparing the number of rays that were supported by the output fiber to the original rays filling the aperture stop, the light coupling efficiency was calculated. The optimization function built in Zemax automatically compared coupling efficiency for different microlens focal lengths, light source to lens distances, lens to optical fiber distances, etc and decided the best value for those parameters.

For comparison purposes, the light source to output fiber direct light coupling efficiency was also studied. The direct coupling system was similar to the microlens aided system shown in Figure 3-2, however, there was no focusing microlens and the optical fiber was moved to the microlens position. The aperture stop size remained the same to ensure that the same total amount of rays was used in the coupling efficiency calculation for both systems. Under the same

simulation conditions, a snap shot on the output fiber end face was taken in both systems (Figure 3-3). Each small dot in the center areas of both pictures represents a ray which was supported by the output fiber and contributed to the final optical signal. It is obvious to see that microlens aided system has much higher coupled ray density (Figure 3-3 (a)) than the direct coupling system (Figure 3-3 (b)), thus a higher coupling efficiency was achievable.

With a comprehensive consideration of fluid dynamics (personal communication with Dr. Udoetok), optical simulation results and fabrication feasibility, the critical feature dimensions were decided as following: all three inlets were 1000□m in both height and width; the injection nozzle was 100m by 10m; three slopes were inclined 30o with respect to the substrate plane; the outlet channel was 500m by 500m; the microlens array was placed about 450□m away from the outlet channel center; microlens pixel diameters ranging from 250□m to 450□m were tried; the distance from the output fiber to the microlens back surface was estimated at about mm for the highest coupling efficiency.

Although the distance between the microlens and the sample cell light source was optimized, practically, it was very difficult to maintain the sample cells right at the center of the outlet channel. It is thus very important to study how the sample cells being off from the outlet center can affect the coupling efficiency.Two types of offset were studied. The first one was the longitudinal offset caused by the slight asymmetry of two sheath flows from right and left sides. When the sheath flow from one side is stronger, sample cells, instead of being focused at the center, are pushed to the opposite side.

system and the microlens aided system. For the direct coupling system, the coupling efficiency stays low but slight increases as the light source moves toward the output fiber. In contrast, with the microlens as the focusing element, the coupling efficiency is much higher. Coupling efficiency drops from about 60% to about 25% when point light source moves 90□m closer to the microlens and drops to about 40% when the point light source moves 90m away.

The other common offset was radial offset related to the hydro-focusing in vertical direction. Non-sufficient vertical hydrodynamic force may cause sample cells being focused in a position lower than the center of the flow. Detection system with microlens is very sensitive to radial offset, coupling efficiency drops to nearly 0 for only 60m offset from the center. In the meantime, direct coupling system is not so sensitive to radial offset, but the overall coupling efficiency is low.

It should be mentioned that only fluorescent signal was considered in this optical analysis. The intensity distribution function for the scattering light may be greatly different from the light intensity distribution from a fluorescent bead. More sophisticated light source model should be used to analyze the coupling efficiency for scattering light. Also, since fluorescent bead is modeled as a point source, this analysis works better for fluorescent beads with diameter smaller than the diffraction limit of the optical detection system (about 1.5 μm). For larger beads, the point source assumption may cause error to the coupling efficiency, however, the efficiency trend remains the same and the result can be used as a reference for the system design