A (not so) short introduction to MEMS

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Chapter 1

Why MEMS?

1.1 What is MEMS and comparison with microelectronics

Micro Electro Mechanical Systems or MEMS is a term coined around 1989 by Prof. R. Howe [1] and others to describe an emerging research field, where mechanical elements, like cantilevers or membranes, had been manufactured at a scale more akin to microelectronics circuit than to lathe machining. But MEMS is not the only term used to describe this field and from its multicultural origin it is also known as Micromachines, a term often used in Japan, or more broadly as Microsystem Technology (MST), in Europe.
However, if the etymology of the word is more or less well known, the dictionaries are still mum about an exact definition. Actually, what could link an inkjet printer head, a video projector DLP system, a disposable bio-analysis chip and an airbag crash sensor - yes, they are all MEMS, but what is MEMS?
It appears that these devices share the presence of features below 100 μm that are not machined using standard machining but using other techniques globally called micro-fabrication technology. Of course, this simple definition would also include microelectronics, but there is a characteristic that electronic circuits do not share with MEMS. While electronic circuits are inherently solid and compact structures, MEMS have holes, cavity, channels, cantilevers, membranes, etc, and, in some way, imitate 'mechanical' parts.
This has a direct impact on their manufacturing process. Actually, even when MEMS are based on silicon, microelectronics process needs to be adapted to cater for thicker layer deposition, deeper etching and to introduce special steps to free the mechanical structures. Then, many more MEMS are not based on silicon and can be manufactured in polymer, in glass, in quartz or

even in metals...
Thus, if similarities between MEMS and microelectronics exist, they now clearly are two distinct fields. Actually, MEMS needs a completely different set of mind, where next to electronics, mechanical and material knowledge plays a fundamental role.

1.2 Why MEMS technology

1.2.1 Advantages offered

The development of a MEMS component has a cost that should not be misevaluated but the technology has the possibility to bring unique benefits. The reasons that prompt the use of MEMS technology can be classified broadly in three classes:

- miniaturization of existing devices, like for example the production of silicon based gyroscope which reduced existing devices weighting several kg and with a volume of $1000\,\mathrm{cm}^3$ to a chip of a few grams contained in a $0.5\,\mathrm{cm}^3$ package.
- development of new devices based on principles that do not work at larger scale. A typical example is given by the biochips where electrical field are use to pump the reactant around the chip. This so called electro-osmotic effect based on the existence of a drag force in the fluid works only in channels with dimension of a fraction of one mm, that is, at micro-scale.
- development of new tools to interact with the micro-world. In 1986 H. Rohrer and G. Binnig at IBM were awarded the Nobel price in physics for their work on scanning tunneling microscope. This work heralded the development of a new class of microscopes (atomic force microscope, scanning near-field optical microscope...) that shares the presence of micromachined sharp micro-tips with radius below 50 nm. This micro-tool was used to position atoms in complex arrangement, writing Chinese character or helping verify some prediction of quantum mechanics. Another example of this class of MEMS devices at a slightly larger scale would be the development of micro-grippers to handle cells for analysis.

By far miniaturization is often the most important driver behind MEMS development. The common perception is that miniaturization reduces cost, by decreasing material consumption and allowing batch fabrication, but an important collateral benefit is also in the increase of applicability. Actually, reduced mass and size allow placing the MEMS in places where a traditional system won't have been able to fit. Finally, these two effects concur to increase the total market of the miniaturized device compared to its costlier and bulkier ancestor. A typical example is brought by the accelerometer developed as a replacement for traditional airbag triggering sensor and that is now used in many appliances, as in digital cameras to help stabilize the image or even in the contact-less game controller integrated in the latest handphones.

However often miniaturization alone cannot justify the development of new MEMS. After all if the bulky component is small enough, reliable enough, and particularly cheap then there is probably no reason to miniaturize it. Micro-fabrication process cost cannot usually compete with metal sheet punching or other conventional mass production methods.
But MEMS technology allows something different, at the same time you make the component smaller you can make it better. The airbag crash sensor gives us a good example of the added value that can be brought by developing a MEMS device. Some non-MEMS crash sensors are based on a metal ball retained by a rolling spring or a magnetic field. The ball moves in response to a rapid car deceleration and shorts two contacts inside the sensor. A simple and cheap method, but the ball can be blocked or contact may have been contaminated and when your start your engine, there is no easy way to tell if the sensor will work or not. MEMS devices can have a built-in self-test feature, where a micro-actuator will simulate the effect of deceleration and allow checking the integrity of the system every time you startup the engine. Another advantage that MEMS can bring relates with the system integration. Instead of having a series of external components (sensor, inductor...) connected by wire or soldered to a printed circuit board, the MEMS on silicon can be integrated directly with the electronics. Whether it is on the same chip or in the same package it results in increased reliability and decreased assembly cost, opening new application opportunities.

As we see, MEMS technology not only makes the things smaller but often makes them better.

1.2.2 Diverse products and markets

The previous difficulty we had to define MEMS stems from the vast number of products that fall under the MEMS umbrella. The MEMS component currently on the market can be broadly divided in six categories (Table 1.1), where next to the well-known pressure and inertia sensors produced by different manufacturer like Motorola, Analog Devices, Sensonor or Delphi we

have many other products. The micro-fluidic application are best known for the inkjet printer head popularized by Hewlett Packard, but they also include the burgeoning bioMEMS market with micro analysis system like the capillary electrophoresis system from Agilent or the DNA chips.
Optical MEMS includes the component for the fiber optic telecommunication like the switch based on a moving mirror produced by Sercalo. They also include the optical switch matrix that is now waiting for the recovery of the telecommunication industry. This component consists of 100s of micro-mirror that can redirect the light from one input fiber to one output fiber, when the fibers are arranged either along a line (proposed by the now defunct Optical Micro Machines) or in a 2D configuration (Lambda router from Lucent).
Moreover MOEMS deals with the now rather successful optical projection system that is competing with the LCD projector. The MEMS products are based either on an array of torsional micro-mirror in the Texas Instrument Digital Light Processor (DLP) system or on an array of controllable grating as in the Grating Light Valve (GLV) from Silicon Light Machines.
RF MEMS is also emerging as viable MEMS market. Next to passive components like high-Q inductors produced on the IC surface to replace the hybridized component as proposed by MEMSCAP we find RF switches and soon micromechanical filters.
But the list does not end here and we can find micromachined relays (MMR) produced for example by Omron, HDD read/write head and actuator or even toys, like the autonomous micro-robot EMRoS produced by EPSON.

In 2002 these products represented a market of about 3.2B$, with roughly one third in inkjet printer nozzle, one third in pressure sensor and the rest split between inertia sensors, RF MEMS, optical MEMS, projection display chip and bioMEMS [2]. Of course the MEMS market overall value is still small compared to the 180B$ IC industry - but there are two aspects that still make it very interesting:

- it is expected to grow at an annual rate of 18% for the foreseeable future, much higher than any projection for IC industry;

- MEMS chips have a large leveraging effect, and in the average a MEMS based systems will have 8 times more value than the MEMS chip price (e.g., a DLP projector is about 10 times the price of a MEMS DLP chip).

This last point has created very large difference between market studies, whether they reported market for components alone or for systems. The

Product category	**Examples**
Pressure sensor	Manifold pressure (MAP), tire pressure, blood pressure...
Inertia sensor	Accelerometer, gyroscope, crash sensor...
Microfluidics / bioMEMS	Inkjet printer nozzle, micro-bio-analysis systems, DNA chips...
Optical MEMS / MOEMS	Micro-mirror array for projection (DLP), micro-grating array for projection (GLV), optical fiber switch, adaptive optics...
RF MEMS	High Q-inductor, switches, antenna, filter...
Others	Relays, microphone, data storage, toys...

Table 1.1: MEMS products example

number cited above are in the average of other studies and represent the market for the MEMS components alone.

1.2.3 Economy of MEMS manufacturing and applications

However large the number of opportunities is, it should not make companies believe that they can invest in any of these fields randomly. For example, although the RF MEMS market seems to be growing fuelled for the appetite for smaller wireless communication devices, it seems to grow mostly through internal growth. Actually the IC foundries are developing their own technology for producing, for example, high-Q inductors, and it seems that an external provider will have a very limited chance to penetrate the market.
Thus, market opportunities should be analyzed in detail to eliminate the false perception of a large market, taking into consideration the targeted customer inertia to change and the possibility that the targeted customer himself develop MEMS based solution. In that aspect, sensors seems an easy target being simple enough to allow full development within small business unit and having a large base of customers - however, an optical switch matrix is riskier because its value is null without the system that is built by a limited number of customers, which most probably have the capabilities to develop in-house the MEMS component anyway.

Some MEMS products already achieve high volume and benefit greatly from the batch fabrication technique. For example more than 100 millions MEMS accelerometers are sold every year in the world - and with newer use coming, this number is still growing fast. But large numbers in an open market invariably means also fierce competition and ultimately reduced prices. Long are gone the days where a MEMS accelerometer could be sold 10$ a piece - it is now less than 2$ and still dropping. Currently, the next target is a 3-axis accelerometer in a single package for about 4$, so that it can really enter the toys industry. Note that there may be a few exceptions to this rule. Actually, if the number of unit sold is also very large, the situation with the inkjet printer nozzle is very different. Canon and Hewlett Packard developed a completely new product, the inkjet printer, which was better than earlier dot matrix printer, creating a captive market for its MEMS based system. This has allowed HP to repeatedly top the list of MEMS manufacturer with sales in excess of 600M$. This enviable success is unfortunately most probably difficult to emulate.

But these cases should not hide the fact that MEMS markets are essentially niche markets. Few product will reach the million unit/year mark and currently among the more than 300 companies producing MEMS only a dozen have sales above 100m$/year. Thus great care should be taken in balancing the research and development effort, because the difficulty of developing new MEMS from scratch can be daunting and the return low. For example, although Texas Instrument is now reaping the fruit of its Digital Light Processor selling between 1996 and 2004 more than 4 millions chips for a value now approaching 200m$/year, the development of the technology by L. Hornbeck took more than 10 years [3]. Few startup companies will ever have this opportunity.

Actually it is not clear for a company what the best approach for entering the MEMS business is, and we observe a large variety of business model with no clear winner. For many years in microelectronics industry the abundance of independent foundries and packaging companies has made fabless approach a viable business model. However it is an approach only favored by a handful of MEMS companies, and it seems for good reasons. A good insight in the polymorphism of MEMS business can be gained by studying the company MemsTech, now a holding listed on the Kuala Lumpur Mesdaq (Malaysia) and having office in Detroit, Kuala Lumpur and Singapore.

Singapore is actually where everything started in the mid-90's for MemsTech with the desire from an international company (EG&G) to enter the MEMS sensor market. They found a suitable partner in Singapore at the Institute of Microelectronics (IME), a research institute with vast experience in IC technology.

This type of cooperation has been a frequent business model for MNC willing to enter MEMS market, by starting with ex-house R&D contract development of a component. EG&G and IME designed an accelerometer, patenting along the way new fabrication process and developing a cheap plastic packaging process. Finally the R&D went well enough and the complete clean room used for the development was spun-off and used for the production of the accelerometer.
Here, we have another typical startup model, where IP developed in research institute and university ends up building a company. This approach is very typical of MEMS development, with a majority of the existing MEMS companies having been spun-off from a public research institute or a university.
A few years down the road the fab continuously produced accelerometer and changed hands to another MNC before being bought back in 2001 by its management. During that period MemsTech was nothing else but a component manufacturer providing off-the-shelf accelerometer, just like what Motorola, Texas Instrument and others are doing.
But after the buyout, MemsTech needed to diversify its business and started proposing fabrication services. It then split in two entities: the fab, now called Sensfab, and the packaging and testing unit, Senzpak. Three years later, the company had increased its 'off-the-shelf' product offering, proposing accelerometer, pressure sensor, microphones and one IR camera developed in cooperation with local and overseas university.
This is again a typical behaviour of small MEMS companies where growth is fuelled by cooperation with external research institutions. Still at the same time MemsTech proposes wafer fabrication, packaging and testing services to external companies. This model where products and services are mixed is another typical MEMS business model, also followed by Silicon Microstructures in the USA, Colybris in Switzerland, MEMSCAP in France and some other. Finally, in June 2004 MemsTech went public on the Mesdaq market in Kuala Lumpur.
The main reason why the company could survives its entire series of avatar, is most probably because it had never overgrown its market and had the wisdom to remain a small company, with staff around 100 persons. Now, with a good product portfolio and a solid base of investor it is probably time for expansion.

1.3 Major drivers for MEMS technology

From the heyday of MEMS research at the end of the 1960s, started by the discovery of silicon large piezoresisitive effect by C. Smith[4] and the demon-

stration of anisotropic etching of silicon by J. Price[5] that paved the way to the first pressure sensor, one main driver for MEMS development has been the automotive industry. It is really amazing to see how many MEMS sensor a modern car can use! From the first oil pressure sensors, car manufacturer quickly added manifold and tire pressure sensors, then crash sensors, one, then two and now up to five accelerometers. Recently the gyroscopes made their apparition for anti-skidding system and also for navigation unit - the list seems without end.
Miniaturized pressure sensors were also quick to find their ways in medical equipment for blood pressure test. Since then biomedical application have drained a lot of attention from MEMS developer, and DNA chip or micro-analysis system are the latest successes in the list. Because you usually sell medical equipment to doctors and not to patients, the biomedical market has many features making it perfect for MEMS: a niche market with large added value.
Actually cheap and small MEMS sensors have many applications. Digital cameras have been starting using accelerometer to stabilize image, or to automatically find image orientation. Accelerometers are also being used in new contactless game controller or mouse.
These two later products are just a small part of the MEMS-based system that the computer industry is using to interface the arid beauty of digits with our human senses. The inkjet printer, DLP based projector, head-up display with MEMS scanner are all MEMS based computer output interfaces. Additionally, computer mass storage uses a copious amount of MEMS, for example, the hard-disk drive nowadays based on micromachined GMR head and dual stage MEMS micro-actuator. Of course in that last field more innovations are in the labs, and most of them use MEMS as the central reading/writing element.
The telecommunication industry has fuelled the biggest MEMS R&D effort so far, when at the turn of the millennium, 10 s of companies started developing optical MEMS switch and similar components. We all know too well that the astounding 2D-switch matrix developed by Optical Micro Machines (OMM) and the 3D-matrix developed in just over 18 months at Lucent are now bed tale stories. However within a few years they placed optical MEMS as a serious contender for the future extension of the optical network, waiting for the next market rebound. Wireless telecommunications are also using more and more MEMS components. MEMS are slowly sipping into handphone replacing discrete elements one by one, RF switch, microphone, filters - until the dream of a 1 mm^3 handphone becomes true (with vocal recognition for numbering of course!). The latest craze seems to be in using accelerometers (again) inside handphone to convert them into game controller, the ubiqui-

tous handphone becoming even more versatile.
Large displays are another consumer product that may prove to become a large market for MEMS. Actually, if plasma and LCD TV seems to become more and more accepted, their price is still very high and recently vendors start offering large display based on MEMS projector at about half the price of their flat panel cousin. Projector based system can be very small and yet provide large size image. Actually, for the crown of the largest size the DLP projecting system from TI is a clear winner as evidenced by the digital cinema theaters that are burgeoning all over the globe. For home theater the jury is still debating - but MEMS will probably get a good share at it and DLP projector and similar technologies won't be limited to PowerPoint presentation.
Finally, it is in the space that MEMS are finding an ultimate challenge and already some MEMS sensors have been used in satellite. The development of micro (less than 100kg) and nano (about 10kg) satellites is bringing the mass and volume advantage of MEMS to good use and some project are considering swarms of nanosatellite each replete with micromachined systems.

1.4 Mutual benefits between MEMS and microelectronics

The synergies between MEMS development and microelectronics are many. Actually MEMS clearly has its roots in microelectronics, as H. Nathanson at Westinghouse reported in 1967 the "resonant gate transistor" [6], which is now considered to be the first MEMS. This device used the resonant properties of a cantilevered beam acting as the gate of a field-effect transistor to provide electronic filtering with high-Q. But even long after this pioneering work, the emphasis on MEMS based on silicon was clearly a result of the vast knowledge on silicon material and on silicon based microfabrication gained by decades of research in microelectronics. Even quite recently the SOI technology developed for ICs has found a new life with MEMS.
But the benefit is not unilateral and the MEMS technology has indirectly paid back this help by nurturing new electronic product. MEMS brought muscle and sight to the electronic brain, enabling a brand new class of embedded system that could sense, think and act while remaining small enough to be placed everywhere.
As a more direct benefit, MEMS can also help keep older microelectronics fab running. Actually MEMS devices most of the times have minimum fea-

tures size of a several μm, allowing the use of older generation IC fabrication equipment that otherwise will have just been dumped. It is even possible to convert a complete plant and Analog Devices has redeveloped an older BiC-MOS fabrication unit to successfully produce their renowned smart MEMS accelerometer. Moreover, as we have seen, MEMS component often have small market and although batch fabrication is a must, a large part of the MEMS production is still done using 4"(100 mm) and 6" (150 mm) wafers - and could use 5-6 years old IC production equipment.
But this does not mean that equipment manufacturer cannot benefit from MEMS. Actually MEMS fabrication has specific needs (deeper etch, double side alignment, wafer bonding, thicker layer...) with a market large enough to support new product line. For example, firms like STS and Alcatel-Adixen producing MEMS deep RIE or EVGroup and Suss for their wafer bonder and double side mask aligner have clearly understood how to adapt their know-how to the MEMS fabrication market.

Chapter 2

Fundamentals of MEMS design and technology

2.1 Physical scaling laws

The large decrease in size during miniaturization, that in some case can reach 1 or 2 orders of magnitude, has a tremendous impact on the behavior of micro-object when compared to their larger size cousin. We are already aware of some of the most visible implications of miniaturization. Actually nobody will be surprised to see a crumb stick to the rubbed surface of a plastic rod, whereas the whole bread loaf is not. Everybody will tell that it works with the crumb and not with the whole loaf because the crumb is lighter. Actually it is a bit more complicated than that.
The force that is attracting the crumb is the electrostatic force, which is proportional to the amount of charge on the surface of the crumb, which in turn is proportional to its surface. Thus when we shrink the size and go from the loaf to the crumb, we not only decrease the volume and thus the mass but we also decrease the surface and thus the electrostatic force. However, because the surface varies as the square of the dimension and the volume as the cube, this decrease in the force is relatively much smaller than the drop experienced by the mass. Thus finally not only the crumb mass is smaller, but, what is more important, , the force acting on it becomes proportionally larger - making the crumb really fly!

To get a better understanding, we can refer to Figure 2.1 and consider a cube whose side goes from a length of 10 to a length of 1. The surface of the bigger cube is $6 \times 10 \times 10 = 600$ whereas its volume is $10 \times 10 \times 10 = 1000$. But now what happen to the scaled down cube? Its surface is $6 \times 1 \times 1 = 6$ and has been divided by 100 but its volume is $1 \times 1 \times 1 = 1$ and has been

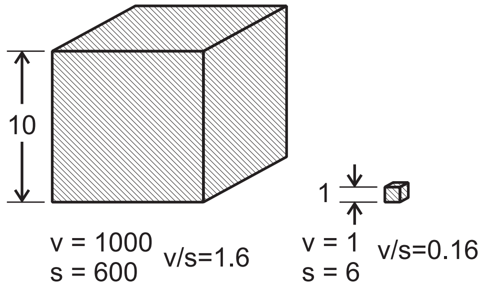


Figure 2.1: Scaling effect on volume, surface and volume/surface ratio.

divided by 1000. Thus the volume/surface ratio has also shrunk by a factor of 10, making the surface effect proportionally 10 times larger with the smaller cube than with the bigger one. This decrease of volume/surface ratio has profound implications for the design of MEMS. Actually it means that at a certain level of miniaturization, the surface effect will start to be dominant over the volume effects. For example, friction force (proportional to surface) will become larger than inertia (proportional to mass hence to volume), heat dissipation will become quicker and heat storage reduced: energy storage will become less attractive than energy coupling... This last example is well illustrated by one of the few ever built micromachines, the EMRoS microrobot from Epson. The EMRoS (Epson Micro Robot System) is not powered with a battery (which stores energy proportional to its volume and becomes less interesting at small scale) but with solar cells whose output is clearly proportional to surface.
Then of course we can dwell into a more elaborate analysis of nature laws and try to see apart from geometrical factor what happens when we shrink the scale? Following an analysis pioneered by W. Trimmer [7], we may describe the way physical quantities vary with scale as a power of an arbitrary scale variable, s. We have just seen that volume scale as s^3, surface as s^2 and the volume/surface ratio as s^1. In the same vein we may have a look at different forces and see how they scale down (Table 2.1).

From this table it appears that some forces that are insignificant at large scale becomes predominant at smaller scale. For example we see that gravity, which scales as s^4 (that is decrease by a factor 10,000 when the scale is shrunk by 10) will be relatively weak at micro-scale. However a more favorable force will be the tension force, which decrease as s^1 making it an important (and often annoying for non-fluidic application) force at micro-scale. The table also reveals that the electrostatic force will become more interesting than the magnetic force as the scale goes down. Of course this simple description is more qualitative than quantitative. Actually if we know that as the size

Force	Scaling law
Surface tension	s^1
Electrostatic, Pressure, Muscle	s^2
Magnetic	s^3
Gravitational	s^4

Table 2.1: Scaling of nature forces.

shrinks the electrostatic force will finally exceed the magnetic force, a more detailed analysis is needed to find if it is at a size of 100 µm, 1 µm or 10 nm. In that particular case it has been shown that the prediction becomes true when the dimensions reach a few µm, right in the scale of MEMS devices. This has actually been the driver behind the design of the first electrostatic motors by R. Howe and R. Muller [8].

A more surprising consequence of miniaturization is that, contrary to what we would think at first, the relative manufacturing accuracy is sharply decreasing. This was first formalized by M. Madou [10] and it is indeed interesting to see that the relative accuracy of a MEMS device is at a few % not much better than standard masonry. Actually, if it is true that the absolute accuracy of MEMS patterning can reach 1 µm, the MEMS size is in the 10 µm-100 µm, meaning a relative patterning accuracy of 1%-10% or even less. We are here very far from single point diamond turning or the manufacturing of large telescope mirror that can both reach a relative accuracy of 0.0001%. So, ok, we have a low relative accuracy, but what does that mean in practice? Let's take as an example the stiffness of a cantilever beam. From solid mechanics the stiffness, k, depends on the beam cross-section shape and for a rectangular cross-section it is proportional to

$$k = \frac{E}{4}\frac{hw^3}{L^3}, \tag{2.1}$$

where E is the elasticity modulus, h is the beam thickness, w its width and L its length. For a nominal beam width of 2 µm with an absolute fabrication accuracy of ±0.2 µm the relative accuracy is ±10%. The stiffness for bending along the width direction varies as a power of 3 of the width and will thus have a relative accuracy of ±30%. For a stiffness nominal value of 1 N/m, it means that the expected value can be anywhere between 0.7 N/m and 1.3 N/m - this is almost a variation by a factor of two! Our design needs to be tolerant to such variation, or the yield will be very low. In this particular case, one could improve the relative accuracy by taking advantage of the relatively constant absolute fabrication accuracy and increase the beam width nominal value to 4 μm - of course it also means doubling its length if one wants to keep the same spring constant.

2.2 The principles of design and reliability

Since the first days of pressure sensor development, MEMS designers have had to face the complexity of designing MEMS. Actually if IC design relies on an almost complete separation between fabrication process, circuit layout design and packaging, the most successful MEMS have been obtained by developing these three aspects simultaneously (Figure 2.2).

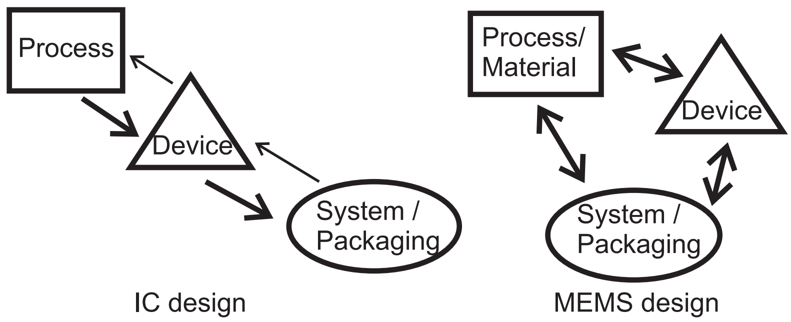


Figure 2.2: IC and MEMS design paradigms.

Actually MEMS fabrication process is so much intertwined with the device operation that MEMS design often involve a good deal of process development. If it is true that some standard processes are proposed by a few foundries (e.g, SOI process, and 3 layer surface micromachining by MEMSCap, epitaxy with buried interconnect by Bosch...), there is in MEMS nothing as ubiquitous as the CMOS process.
The success of the device often depends on physics, material property and the choice of fabrication techniques. Actually some industry observers are even claiming that in MEMS the rule is "One Product, One Process" - and many ways to achieve the same goal. Actually we are aware of at least five completely different processes that are currently used to fabricate commercial MEMS accelerometer with about the same characteristics and price - and for at least two companies the accelerometer is their only MEMS product.
And what about packaging then, the traditional back-end process? In MEMS it can account for more than 50% of the final product price and obviously should not be ignored. Actually the designer has to consider the packaging

aspect too, and there are horror stories murmured in the industry where products had to be completely redeveloped after trials for packaging went unsuccessful. The main issues solved by MEMS packaging are less related with heat dissipation than with stress, hermetic sealing and often chip alignment and positioning. If chip orientation for IC is usually not a concern, it becomes one for single-axis MEMS accelerometer where the chip has to be aligned precisely with respect to the package. This may imply the use of alignment mark, on the MEMS and in the package. In other case the chip may need to be aligned with external access port. Actually MEMS sensors often need an access hole in the package to bring air or a liquid in contact with the sensing chip, complicating substantially the packaging. One of the innovative approaches to this problem has been to use a first level packaging during the fabrication process to shield the sensitive parts, finally linking the back-end with the front-end. Even for MEMS that do not need access to the environment, packaging can be a complex issue because of stress.
MEMS often use stress sensitive structure to measure the deformation of a member and the additional stress introduced during packaging could affect this function. Motorola solved this problem with its line of pressure sensor by providing calibration of the device after packaging - then any packaging induced drift will be automatically zeroed.
This kind of solution highlights the need to practice design for testing. In the case of Motorola this resulted in adding a few more pins in the package linked to test point to independently tweak variable gain amplifier. This cannot be an afterthought, but need to be taken into consideration early. How will you test your device? At wafer level, chip level or after packaging? MEMS require here again much different answers than ICs.
Understandably it will be difficult to find all the competence needed to solve these problems in one single designer, and good MEMS design will be teamwork with brainstorming sessions, trying to find the best overall solution. MEMS design cannot simply resume to a sequence of optimized answer for each of the individual process, device and packaging tasks - success will only come from a global answer to the complete system problem.

An early misconception about MEMS accelerometer was that these small parts with suspension that were only a few µm wide would be incredibly fragile and break with the first shock. Of course it wasn't the case, first because silicon is a wonderful mechanical material tougher than steel and then because the shrinking dimension implied a really insignificant mass, and thus very little inertia forces. But sometime people can be stubborn and seldom really understand the predictive nature of the law of physics, preferring to trust their (too) common sense. Analog Device was facing the hard task to convince the army that their MEMS based accelerometer could be used

in military system, but it quickly appeared that it had to be a more direct proof than some equations on a white board. They decided to equip a mortar shell with an accelerometer and a telemetry system, and then fired the shell. During flight, the accelerometer measured a periodic signal, that was later traced back to the natural wobbling of the shell. Then the shell hit his target and exploded. Of course the telemetry system went mum and the sensor was destroyed. However, the 'fragile' sensing part was still found in the debris... and it wasn't broken.
In another example, the DLP chip from Texas Instrument has mirrors supported by torsion hinge 1 μm wide and 60 nm thick that clearly seems very prone to failure. TI engineers knew it wasn't a problem because at this size the slippage between material grains occurring during cyclic deformation is quickly relieved on the hinge surface, and never build-up, avoiding catastrophic failure. But, again, they had to prove their design right in a more direct way. TI submitted the mirrors of many chips through 3 trillions (10^{12}) cycles, far more that what is expected from normal operation... and again not a single of the 100 millions tested hinges failed.
Of course, some designs will be intrinsically more reliable than other and following a taxonomy introduced by P. McWhorter, at Sandia National Laboratory [11], MEMS can be divided in four classes, with potentially increasing reliability problems.

Class	**I**	**II**	**III**	**IV**
Type	No moving parts	Moving parts, no rubbing and impacting parts	Moving parts, impacting surfaces	Moving parts, impacting and rubbing surfaces
Example	Accelerometer, Pressure sensor, High-Q inductor, Inkjet nozzle...	Gyroscopes, Resonator, Filter...	TI DLP, Relay, Valve, Pump...	Optical switch, scanner, locking system

Table 2.2: Taxonomy for evaluating MEMS devices reliability

By looking at this table it becomes clearer why developing the Texas Instrument DLP took many more years than developing accelerometer - the reliability of the final device was an issue and for example, mirrors had originally a tendency to stick to the substrate during operation. TI had to go through a series of major improvements in the material and in the design to increase the reliability of their first design.

2.3 MEMS design tools

As we have seen miniaturization science is not always intuitive. What may be true at large scale may become wrong at smaller scale. This translates into an immediate difficulty to design new MEMS structure following some guts feeling. Our intuition may be completely wrong and will need to be backed up by accurate modeling. However simulation of MEMS can become incredibly complex and S. Senturia describes a multi-tiered approach that is more manageable [12] as shown in Figure 2.3.

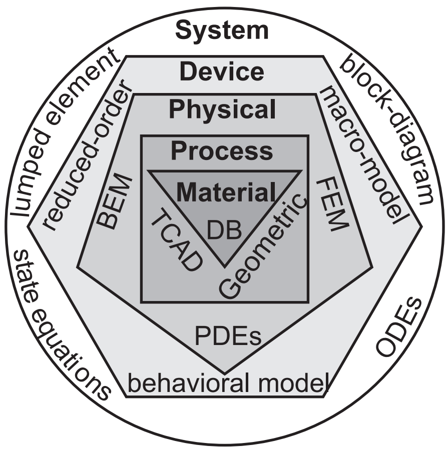


Figure 2.3: MEMS multi-tiered simulation (adapted from [12] and expanded).

Some simulation tools like Intellisuite by Intellisense or Coventorware by Coventor have been specifically devised for MEMS. They allow accurate modeling using meshing method (FEM, BEM) to solve the partial different equation that describe a device in different physical domains. Moreover, they try to give a complete view of the MEMS design, which, as we said before, is material and process dependent, and thus they give access to material and process libraries. In this way it is possible to build quickly 3D model of MEMS from the mask layout using simulated process. However MEMS process simulation is still in its infancy and the process simulator is used as a simple tool to build quickly the simulation model from purely geometrical consideration, but cannot yet be used to optimize the fabrication process. One exception will be the simulation of anisotropic etching of silicon

and some processes modeled for IC development (oxidation, resist development...) where the existing TCAD tools (SUPREM, etc) can be used.
Complete MEMS devices are generally far too complex to be modeled entirely ab initio, and generally reduced models have to be used. For example, behavioral simulation is used by MEMSPro from MemsCap where ANSYS is used to generate the reduced model, which then is run in circuit-analysis software like Spice. Sugar from C. Pister's group at UC Berkeley is also based on lumped analysis of behavioral model, but the decomposition of the structure in simpler element is left to the designer. Still, although the actual tendency is to use numerical modeling extensively, it is our opinion that no good device modeling can be devised without a first analytic model based on algebraic equation. Developing a reduced order model based on some analytic expression help our intuition regains some of its power. For example, seeing that the stiffness varies as the beam width to the cube makes it clearer how we should shrink this beam: if the width is divided by a bit more than two, the stiffness is already ten times smaller. This kind of insight is invaluable. The analytic model devised need of course to be verified with a few examples using numerical simulation.

Finally the system level simulation is often not in the hand of the MEMS designer, but here block diagram and lumped model can be used, with only a limited set of key state variable. This model may then include the electronics and the MEMS device will be represented by one or more blocks, reusing the equation derived for the behavioral model.

2.4 MEMS system partitioning

At the early stage of MEMS design an important question to be answered will be: hybrid or monolithic? Actually the decision to integrate the MEMS with its electronics or to build two separate chips has a tremendous impact on the complete design process. Most MEMS observer will advocate the use of separate chips and only in the case of a definite advantage (performance, size, cost) should a MEMS be integrated together with its electronics.
From past industry examples, only a handful of companies, like Analog Device for its range of accelerometer or Motorola for its pressure sensors, have promoted the integrated process - and all are big companies having market reaching millions of chips. The hybrid approach in the other hand is used by many more companies on the market. For example Figure 2.4 shows a hybrid solution from SensoNor, the pressure sensor SP15.

The MEMS chip on the left is wire bonded to the ASIC on the right and both are mounted in a lead frame before encapsulation in the same package.

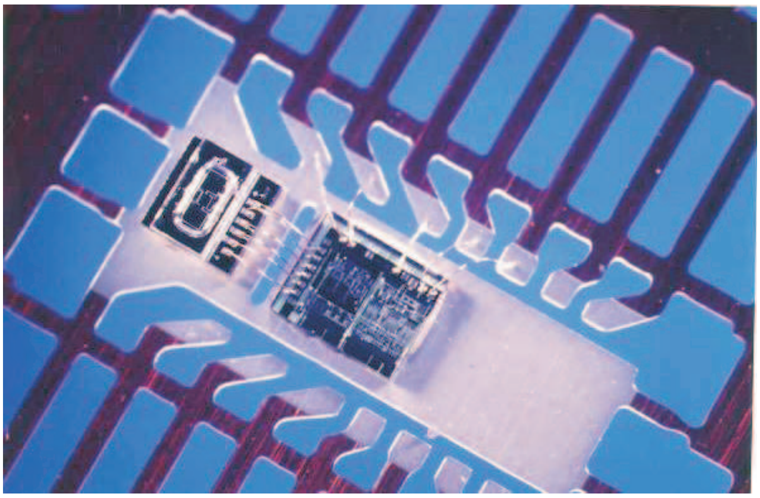


Figure 2.4: Hybrid integration in a pressure sensor (Courtesy SensoNor AS - An Infineon Technologies Company).

The advantage of this solution is that both chips can use the best process without compromise and may achieve a better overall yield. However compactness and reliability suffers from the additional elements and the packaging becomes slightly more complicated. Moreover the electronic is somewhat further from the sensing element and this may introduce additional noise if the signal is small. It is this last argument that has pushed AD to develop its integrated accelerometer range.

2.5 Mechanical structure

Most MEMS required the development of special micro-mechanical elements to achieve standard mechanical function like linkage, suspension, articulation, etc. For example the fundamental inability to miniaturize hinge mentioned earlier force to use flexible micro-joint with excellent wear characteristic but usually restricting rotation.

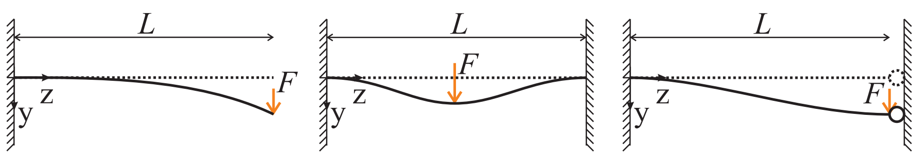


Figure 2.5: Beams with different boundary conditions (cantilever, clamped-clamped beam, clamped-guided beam) in bending .

Type	**Deflection**	**Max deflection**	**Spring constant**
Cantilever	$y = \frac{Fz^2}{6EI}(3L - z)$	$y(L) = \frac{FL^3}{3EI}$	$\frac{3EI}{L^3}$
Clamped-clamped beam	$y = \frac{F}{192EI}(12Lz^2 - 16z^3)$	$y(L/2) = \frac{FL^3}{192EI}$	$\frac{192EI}{L^3}$
Clamped-guided beam	$y = \frac{F}{12EI}(3Lz^2 - 2z^3)$	$y(L) = \frac{FL^3}{12EI}$	$\frac{12EI}{L^3}$

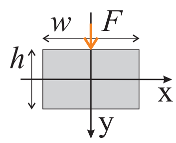
Table 2.3: Characteristics of beams in bending.

Type	**Compliance**	**Buckling**	**Linearity**
clamped-clamped	++	-	-
crab-leg	controlable	0	0
folded-beam	+	+	+

Table 2.4: Characteristics of typical MEMS suspensions.

The suspension, where the traditional fabrication of coils is generally to complex to be considered, has also seen many original development based on the elastic properties of beams. Actually the elasticity of a simple beam is well known[9] and we list in Table 2.3 for the different cases in Figure 2.5 the deflection and spring constant.

There E is representing the Young's modulus for the material of the beam and I is the second moment of inertia for the beam cross-section, which is given by $I = \int\int x^2 dA = wh^3/12$ for a beam with a rectangular cross-section as shown in the inset.



But of course these beams are not enough and need usually to be combined to provide suspension with added flexibility. Actually for choosing a suspension there are usually four main characteristics to watch: the spring constant in the direction of use, the compliance in the other directions (it needs to be low to keep the motion in the desired direction) , the tolerance to internal stress (long beam may buckle during fabrication) and its linearity during large deformation. There is of course a trade-off to be observed and different designs have been pursued (Figure 2.6) which have the characteristics shown in Table 2.4. As we see here the folded beam suspension is versatile and particularly suitable for process where there is a risk

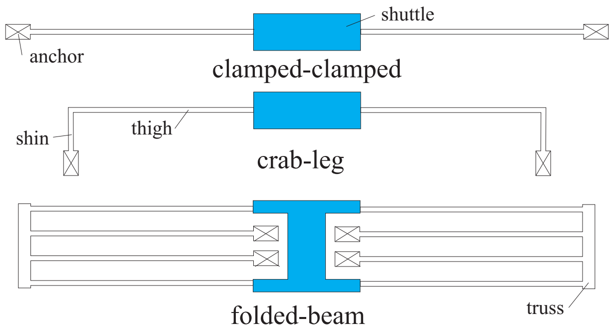


Figure 2.6: Layout of different type of suspension.

of buckling (it will stand large internal stress, as those appearing in surface micromachining) but more compact design may be suitable with other process. For example a clamped-clamped beam is an excellent choice in process with little or no internal stress like DRIE micromaching.
In the case of suspension made of combined beams the computation of the spring constant may be complicated but often existing symmetries allow to decompose the suspension into elementary beams connected in series and in parallel. For two beam connected in series, the equivalent spring constant is simply the sum of the two beams spring constants whereas if the two beams are in series, the resulting spring constant is the inverse of the sum of the inverse of the spring constants - in fact the spring constant behaves in a similar way as capacitor in electronic circuit. For example, it could be noted that the clamped-guided beam is in fact two cantilevers of half length connected in series, and the spring constant for the former can easily be deducted from the spring constant of the later.

Of course the force on the beam is not always concentrated and in some application, particularly in fluidic application, the beam is subject to a uniform pressure, q. In that case there is no real 'spring constant' that can be defined (there is no force, q is a pressure per unit of length in N/m) but the deflection can still be obtained and is given in Table 2.5 corresponding to the cases shown in Figure 2.7.

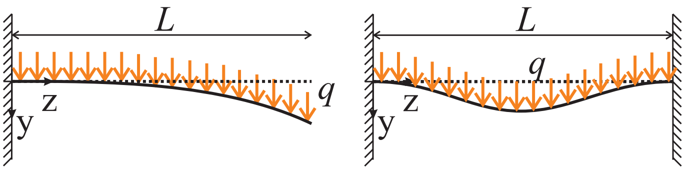


Figure 2.7: Beams under pressure.

Type	Deflection	Max deflection
Cantilever	$y = \frac{qz^2}{24EI}(z^2 - 4Lz + 6L^2)$	$y(L) = \frac{qL^4}{8EI}$
Clamped-clamped beam	$y = \frac{qz^2}{24EI}(z^2 - 2Lz + L^2)$	$y(L/2) = \frac{qL^4}{384EI}$

Table 2.5: Deflection of beams under pressure.

Type	Max Deflection	Spring constant
Round (Force)	$y_C = \frac{Fr^2}{16\pi D}$	$k = \frac{16\pi D}{r^2}$
Round (Pressure)	$y_C = \frac{qr^4}{64D}$	
Square (Force)	$y_C = \frac{\alpha_F F a^2}{Et^3}$	$k = \frac{Et^3}{\alpha_F a^2}$
Square (Pressure)	$y_C = \frac{\alpha_P q a^4}{Et^3}$	

Table 2.6: Deflection of round and square membrane (Plate constant $D = Et^3/[12(1-\nu^2)]$, $\alpha_F = 0.014$ (ν =0.3), $\alpha_P = 0.061$ (ν =0.3).)

In addition to beams, MEMS often uses membranes for which the equation are usually more complicated. We will give the case of round and square membranes clamped at the edge (Figure 2.8), which will show the general dependence of the characteristics with the geometry (Table 2.6).

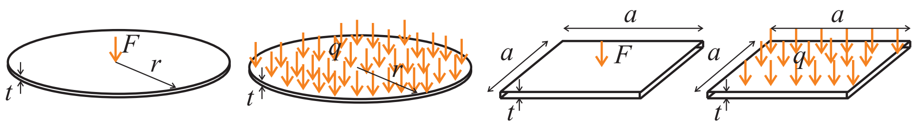


Figure 2.8: Deflection of membranes.

Of course the case of pressure is of particular interest to sensors (pressure sensors), where in addition to the deflection the knowledge of stress will be required.

2.6 Sensors technology

Sensing is certainly a quality that we associate with living being. A stone does not sense, but can a silicon circuit do it? Of course, the answer is yes, and MEMS have increased tremendously the number of physical parameters

that are sensed by silicon.
Sensing can be formally defined by the ability to transform energy in the environment to energy inside a system. An example will be to convert the air temperature to an electrical signal by using a thermo-couple. At the heart of the sensor is the ability to perform the energy transformation, a process usually called transduction. MEMS sensor ability to measure different parameters as pressure, acceleration, magnetic field, force, chemical concentration, etc is based on a limited number of transduction principles compatible with miniaturization.

The oldest MEMS sensor that gained huge popularity was the pressure sensor and it was based on the piezoresistive effect. Piezoresistivity can be described by the change of resistance of a material when it is submitted to stress. This effect is known since the 19th century in metals, but it was only in the mid 1950s that it was recognized that semiconductor and particularly silicon had huge piezoresistive coefficient compared to metal[4]. The MEMS designer will place resistors obtained by doping silicon where the stress variation is maximal, for example at the edge of a membrane in the case of a pressure sensor. Then a simple Wheatstone bridge circuit (Figure 2.9) could be used to convert the resistance change δR to a voltage difference. Actually, it is simple to show that if there is a single variable resistor in the bridge and if $\Delta R << R$ then

$$V_{out} \approx \frac{V_{in}}{4R}\Delta R.$$

Moreover, if a judicious choice of variable resistors allows reaching the configuration shown in the right (where the variation of two variable resistors is opposite to the variation of the two other but with the same magnitude), then the sensitivity of the bridge increases fourfold and we exactly have

$$V_{out} = \frac{V_{in}}{R}\Delta R.$$

For resistors with large aspect ratio in plane it is possible to write the relative change of resistance as :

$$\frac{\Delta R}{R} = \pi_l\sigma_l + \pi_t\sigma_t$$

where π_i is the piezoresistive coefficient and σ_i the stress component repectively, along the direction parallel to the current flow (l longitudinal) or perpendicular to it (t transverse). However the anisotropy in silicon, and actually in most crystals, makes it difficult to obtain the piezoelectric coefficients. Actually, all the physical parameters of silicon, like Young's modulus

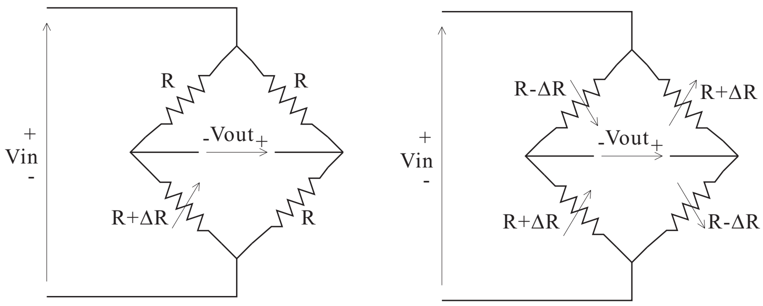


Figure 2.9: Resistors in a Wheastone bridge with (left) one variable resistor, or (right) four variable resistors.

or conductivity, depends on the direction with respect to the crystal axes in which they are measured. Thus, a complete treatment of piezoresistivity will involve complex mathematical object called tensors. Moreover, the piezoresistive coefficients in silicon depend on the type (n- or p-type) and concentration of doping, being generally larger for p-type resistors, and also on temperature. However for the most important cases the expression can be found in the litterature and for example for p-type resistors placed in a n-type substrate along the (110) direction, that is, parallel to the wafer flat in (100) wafers, we have $\pi_l \approx 71.8 \cdot 10^{-11}\,\mathrm{Pa}^{-}1$ and $\pi_t \approx -66.3 \cdot 10^{-11}\,\mathrm{Pa}^{-}1$.

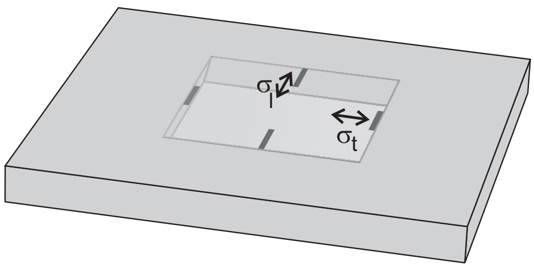
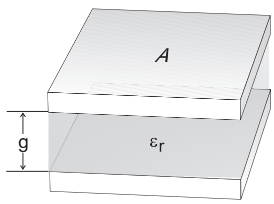


Figure 2.10: Typical position of piezoresistors for a square membrane on (100) Si wafer.

On a square membrane, for symmetry reasons, the stress in the middle of a side is essentially perpendicular to that side. Piezoresistor placed parallel or perpendicular to the side at that point will be, respectively, under transverse or longitudinal stress. If the membrane sides have been aligned with the (110) direction, the π_l and π_t are about the same magnitude but of opposite sign and the resistance of the two resistors under longitudinal stress in Figure 2.10 will increase when the membrane deforms while the resistance of the two resistors under transverse stress will decrease. It is thus possible to connect the four identical resistors in a full bridge configuration, as in Figure 2.9, and the bridge sensitivity simplifies to:

$$V_{out} \approx \frac{70 \cdot 10^{-11} V_{in}}{R} \sigma_{max}$$

where V_{in} is the bridge polarization voltage, σ_{max} the maximum stress in the membrane and R the nominal value of the piezoresistors. Although it seems advantageous this configuration is seldom used in practical devices because it suffers from a low manufacturability as the resistor positioning requires a very good accuracy. In general only one or two sensing resistors are used allowing simpler bridge balancing with trimmed external thick-film resistors. Piezoresitivity is not only used for pressure sensor but find also application in acceleration or force sensors. Unfortunately, the simplicity of the method is counterbalanced by a strong dependence on temperature that has to be compensated for most commercial products by more complex circuitry that the elementary Wheatstone bridge.



Capacitive sensing is independent of the base material and relies on the variation of capacitance happening when the geometry of a capacitor is changing. Capacitance is generally proportional to $C \propto \epsilon_0 \epsilon_r \frac{A}{g}$ where A is the area of the electrodes, g the distance between them and ϵ_r the permittivity of the material separating them (actually, for a plane capacitor as shown above, the proportionality factor is about 1). A change in any of these parameters will be measured as a change of capacitance and variation of each of the three variables has been used in MEMS sensing. For example, whereas chemical or humidity sensor may be based on a change of ϵ_r, accelerometers have been based on a change in g or in A. If the dielectric in the capacitor is air, capacitive sensing is essentially independent of temperature but contrary to piezoresitivity, capacitive sensing requires complex readout electronics. Still the sensitivity of the method can be very large and, for example, Analog Device used for his range of accelerometer a comb capacitor having a suspended electrode with varying gap. Measurement showed that the integrated electronics circuit could resolve a change of the gap distance of only 20 pm, a mere 1/5th of the silicon inter-atomic distance.

A third commonly used transduction mechanism is based on piezoelectricity. Piezoelectricity occurs when stress applied on a material induces the apparition of charge on its surface. Silicon does not present piezoelectricity but crystalline quartz has a large piezoelectric coefficient and other material like ZnO or PZT can be deposited in thin films possessing piezoelectric properties. The advantage of piezoelectricity is that it can be used to sense stress but also as an actuator too. Actually a difference of potential applied on two sides of a piezoelectric layer will induce its deformation. Thus piezoelectric material can be excited in vibration and the vibration sensed with the same structure. This has been the heart of the quartz watch since its invention in the 1970's, but it is also used for different inertial MEMS sensor like gyroscope.

Magnetic sensing, although less often used, has its supporters mainly because it is a non-contact sensing mechanism with a fairly long range. Its main application has to be found in the (giant)magnetoresistive effect used inside the hard-disk head. However other uses of magnetic sensing have been tested and for example some sensors have been based on the Hall effect taking advantage of the simplicity to manufacture this sensing element.

2.7 Actuator technology

Since the industrial revolution humans know that machines can perform task with more force and endurance that them. Bulldozers moving around with their huge engine and pushing big rocks with their powerful pneumatic actuators are probably a good example of what a big machine can do. But what will be the function of a micro-sized actuator?

Type		**Force**	**Stroke**	**Efficiency**	**Manuf.**
Electromagnetic		+	+	-	-
Electrostatic	Gap-closing	0	-	+	+
	Comb-drive	-	+	+	+
	SDA	0	+	+	0
Piezoelectric		+	-	+	-
Thermal	Bimorph	+	+	0	0
	Heatuator	0	0	0	+
	Shape memory alloy (SMA)	+	+	+	-
	Thermo-fluidic	+	-	0	0

Table 2.7: Comparison of common micro-mechanical actuators.

The main parameters useful to describe an actuator are its force and

its stroke. However we have seen previously that all forces decrease with the scale, thus we can not expect to move big rocks around - but only micro-rocks. The micro-actuators are currently used to act on micro-object, typically one part of a MEMS device, and generate forces in the micro to milli Newton range with a stroke from a few μm to several hundreds μm. It would be interesting to have enough force and stroke to allow actuator to help interface human and machine by providing force feedback for example, but micro-actuators are still unable to do that properly.
Still a wide range of possibilities exists to transform internal energy of a system (usually electrical energy) to energy in the environment (in the case of MEMS, generally mechanical energy). Sometime the conversion from electric energy to mechanical energy is direct but often another intermediate energy form is used. For example, the heatuator, a form of thermal actuator, uses current to generate heat which in turn becomes strain and displacement.
The MEMS actuators can be conveniently classified according to the origin of their main energy form. In Table 2.7 we compare the most common MEMS actuators, where Efficiency refers to the loss existing in the actuator conversion of electrical energy to mechanical energy and Manuf. is the manufacturability or the simplicity of micro-fabrication.

2.7.1 Magnetic actuator

Electromagnetic actuation is well known for providing the actuator used in house appliances, toys, watches, relays... The principle of electromagnetic motor is well known and it is tempting to miniaturize such a versatile device to use it in the micro-world. However an electromagnetic motor with its coils, armature and bearings prove a tremendous task for micro-fabrication and so far nobody has been able to batch produced a motor less than 1mm diameter.
Still magnetic actuation has many proponents and some version of magnetic linear actuator have been used in different devices. Such a mobile armature actuator is shown in Figure 2.11, where by increasing the current in the coil the mobile armature is attracted along the x direction to align with the fixed armature.

The magnetic force produced on the mobile armature is linked to the change of reluctance and is given approximately by [12] :

$$F_{ma} = \frac{(nI)^2}{2w}\left(\frac{\mu_0 A}{g_\mu + \mu_0 L/\mu}\right)$$

From this equation it is clear that the force is non linear with the current, and assuming a constant resistance for the coil, the force will also depend on

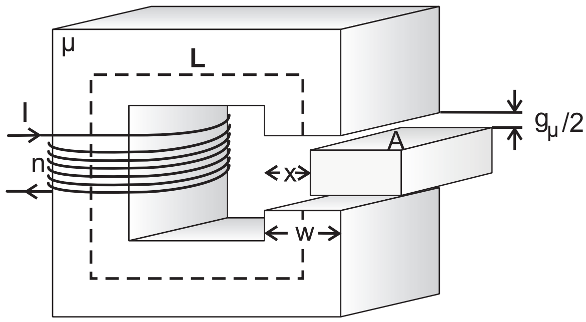


Figure 2.11: Mobile armature linear magnetic actuator.

the square of the coil voltage.
Although this force does not scale very favorably, the possibility to increase the current at small scale, because the heat can be dissipated more quickly, still allows producing relatively strong force. However the main difficulty preventing the widespread use of this type of actuator in a MEMS component is the fabrication of the coil. In that case the most convincing approach proposed so far are most probably those using a hybrid architecture, where the magnetic circuit is fabricated using micro-fabrication but the coil is obtained with more conventional techniques and later assembled with the MEMS part. Actually some design have shown that the coil does not need to be micro-fabricated at all and can be placed in the package, taking benefit of the long range action of the magnetic field.
Finally it should be noted that magnetic actuation can used in conjunction with ferro-magnetic material to provide bistable actuator where two positions can be maintained without power consumption. A permanent magnet placed in the package is used to maintain the magnetized ferro-magnetic material in place. Then, when we send a current pulse of the right polarity in a coil wound around the ferro-magnetic material we invert its magnetization and the actuator switch to its second state. NTT has been producing since at least 1995 a fiber optic switch based on a moving fiber with a ferro-nickel sleeve that has two stable positions in front of two output fibers [13]. The device will consume power only during the brief time where the current pulse is sent and can maintain its position for years.

2.7.2 Electrostatic actuator

A physical principle that leads itself well to integration with MEMS technology is electrostatics. Actually by applying a potential difference between two elements, they develop opposite charges and start attracting each other.

This principle has known several application among which, the comb-drive actuator, the gap-closing actuator and the scratch drive actuator are the most commonly used (Figure 2.12). From energy consideration it is easy to show that the force developed between two electrodes is proportional to the change (derivative) of their capacitance multiplied by the square of the voltage ($F_{elec} \propto dC/dx\, V^2$). Thus electrostatic actuators develop force basically non-linear with the voltage.

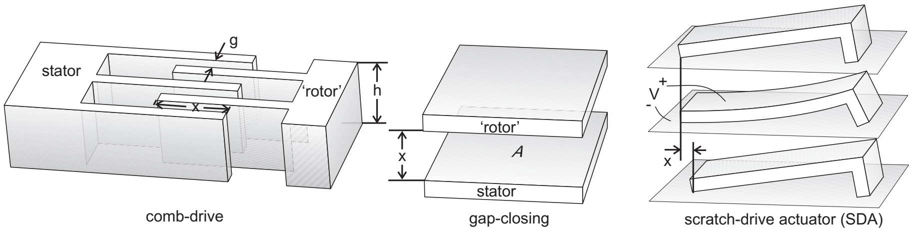


Figure 2.12: Different type of electrostatic actuators.

The comb-drive actuator was invented by W. Tang [14] at UC Berkeley and it generally allows motion in the direction parallel to the finger length. The force produced by n fingers in the rotor is approximately given by

$$F_{cd} \approx n\epsilon_0 \frac{h}{g} V^2$$

where we see the expected dependence with the square of the voltage and notice that it is independent of the displacement x. The proportionality factor is ϵ_0, a small quantity indeed, hinting to a small force generated per finger, in the order of a few 10 nN. Of course the number of fingers can reach 100 or more and the actuator aspect-ratio can be made larger (i.e., increase h/g) to increase the force proportionally. This actuator has been used repeatedly in MEMS component, for example in the original Analog Devices accelerometer or in the fiber optic switch from Sercalo.

The gap-closing actuator usually delivers a larger force (proportional to A) again non linear with the applied voltage, but additionally the force now depends on the displacement x.

$$F_{gc} \approx \epsilon_0 \frac{A}{2x^2} V^2$$

It can be shown that, when the actuator is used in conjunction with a spring (usually a bending beam) to retain the rotor electrode, the rotor electrode position can only be controlled over a limited range. Actually as soon as the rotor electrode has moved by one third of the original gap width, snap-in suddenly occurs and the rotor comes into contact with the stator. This behavior can be advantageous if the actuator is used for bi-stable operation, but preventive measures should be taken to avoid electrodes short-circuit. Actually, the actuator behind the Texas Instruments' DLP is a gap-closing electrostatic actuator working in torsion with the two stable states position fixed by resting posts.

The scratch drive actuator is a more recent invention by T. Akiyama [15] and although it is actuated by electrostatic force, the friction force is the real driving force. As we can see in the diagram, the electrostatic energy is stored in the SDA strain while its front part, the bushing, bends. When the voltage is released, the strain energy tends to decrease and the bushing returns to its rest orientation producing displacement. The main advantage of this actuator is that it is able to produce a rather large force (100 μN), which can be even increased by connecting multiple actuators together. Actually the SDA has been used as an actuator in the 2D optical switch matrix that was developed by Optical Micro Machines (OMM) and which received the stringent Telcordia certification.

2.7.3 Thermal actuator

The thermal energy used by this class of MEMS actuator comes almost invariably from the Joule effect when a current flows through a resistive element. These actuators are generally relatively strong and their main drawback is most probably their speed, although at micro-scale the heat is quickly radiated away and operating frequency up to 1 kHz can be achieved. Bimorph actuators are the most common type of thermal actuator. The bimaterial actuator, well known from the bimetallic version used in cheap temperature controller, and the heatuator (Figure 2.13) are both bending actuator where bending is induced by a difference of strain in two members connected together.

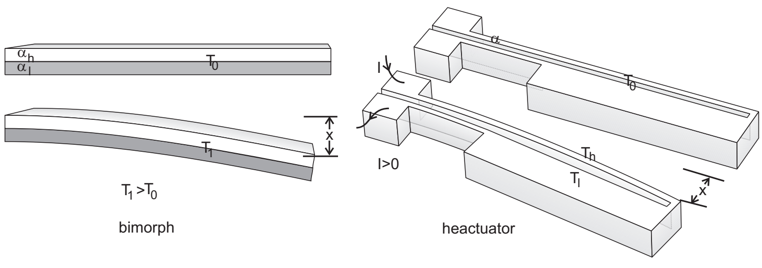


Figure 2.13: Thermal bimorph actuators.

The bimaterial actuator obtains this effect by using two different materials with different expansion coefficients that are placed at the same temperature.

The heatuator [16] uses a single material, simplifying its fabrication, and obtain a difference of strain by obtaining different temperature in the two arms. Actually as the current flow through the actuator the wider 'cold' arm will have a lower resistance and thus generate less heat than the other narrow 'hot' arm. It should be noted that the force produced by these two actuators decreases with the deformation. At maximum displacement all the energy is used to bend the actuator and no external force is produced. One heatuator can produce force in the 10 µN range and they can be connected together or made thicker to produce larger force.

The thermo-pneumatic actuator is another actuator where the expansion of a heated fluid can bulge a membrane and produce a large force. This principle has been used to control valve aperture in micro-fluidic components. In the extreme case, the heating could produce bubble resulting in large change of volume and allowing to produce force as in the inkjet printer head from Canon or HP.

Finally the shape memory effect is also controlled by temperature change and traditionally belongs to the class of thermal actuator. The shape memory effect appears in single crystal metal like copper and in many alloys among which the more popular are NiTi (nitinol) or $Ni_xTi_yCu_z$. In such shape memory alloys (SMA) after a high temperature treatment step, two solid phases will appear one at low temperature (martensite phase) and the other at high temperature (austenite phase). The alloy is rather soft and can be easily deformed at low temperature in the martensite phase. However, upon heating the alloy above its phase transition temperature it will turn to austenite phase and returns to its original shape. This process creates large recovery forces that can be used in an actuator. The temperature difference between the two phases can be as low as 10°C and can be controlled by changing the composition of the alloy. In principle the alloy can be 'trained' and will then shift from a high temperature shape to a low temperature shape and vice-versa when the temperature is changed. In practice, training is difficult and micro-actuators based on SMA are one way actuator, the restoring force being often brought by an elastic member, limiting the total deformation. The most common application of such material has been for various micro-grippers, but its use remains limited because of the difficulty in controlling the deposition of SMA thin-films.

2.8 Problems

1. We consider a micro-cantilever of length L, width w and thickness h bending under its own weight.

- What is the expression of the weight per unit of length of the cantilever assuming the material has a density of ρ?
- What is the general expression of the deflection at the tip of the cantilever?
- What is the length of a 2 μm thick silicon cantilever whose tip deflects by 2 μm? (Note: the density and Young's modulus of silicon are $\rho = 2.33 \cdot 10^3\,\mathrm{kg/m^3}$ and $E = 106\,\mathrm{GPa}$, the acceleration of gravity is g=9.81 m/s^2)
- What are the practical implication of this deflection for the cantilever?

2. A force sensor is based on a piezoresistor placed on a cantilever. For which of the layout in Figure 2.14 will the force sensitivity be the highest when the force is applied at the tip of the cantilever? (Note: we have $\pi_l = -31 \cdot 10^{-11}\mathrm{Pa}^{-1}$ and $\pi_t = -17 \cdot 10^{-11}\mathrm{Pa}^{-1}$.)

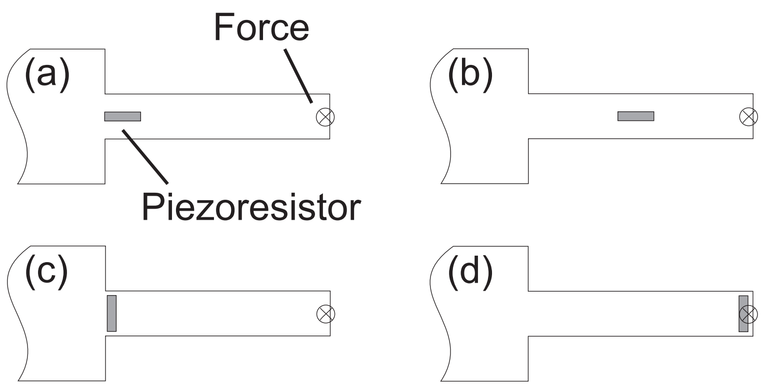


Figure 2.14: Design of force sensor.

Chapter 3

How MEMS are made

3.1 Overview of MEMS fabrication process

Micro-fabrication is the set of technologies used to manufacture structures with micrometric features. This task can unfortunately not rely on the traditional fabrication techniques such as milling, drilling, turning, forging and casting because of the scale. The fabrication techniques had thus to come from another source. As MEMS devices have about the same feature size as integrated circuits, MEMS fabrication technology quickly took inspiration from microelectronics. Techniques like photolithography, thin film deposition by chemical vapor deposition (CVD) or physical vapor deposition (PVD), thin film growth by oxidation and epitaxy, doping by ion implantation or diffusion, wet etching, dry etching, etc have all been adopted by the MEMS technologists. Standard book on microelectronics describe in details these techniques but, as MEMS and IC fabrication goals are different, some of these techniques have evolved as they were applied to MEMS and we will detail here their new capabilities. Moreover, MEMS has spurred many unique fabrication techniques that we will also describe in our panorama of MEMS fabrication introducing bulk micromachining, surface micromachining, LIGA, etc [17].

In general, MEMS fabrication tries to use batch process to benefit from the same economy of scale that is so successful in reducing the cost of ICs. As such, a typical fabrication process starts with a wafer (silicon, polymer, glass...) that may play an active role in the final device or may only be a substrate on which the MEMS is built. This wafer is processed with a succession of processes (Table 3.1) that add, modify or remove materials along precise patterns. The patterns (or the layout) is decided by the designer depending on the desired function but, for most materials, it is difficult to directly

Additive process	Modifying process	Substractive process
Evaporation	Oxydation	Wet etching
Sputtering	Doping	Dry etching
CVD	Annealing	Sacrificial etching
Spin-coating	UV exposure	Development
...	...	...

Table 3.1: Process classification.

deposit or modify them locally. Actually there are few processes equivalent to turning or milling in micromachining. Focused Ion Beam (FIB), where a beam of high energy ion can be scanned to remove most materials and deposit some, can perform even down to nanoscale but the sequential processing approach it requires (as opposed to batch processing) is absolutely not cost effective for production. Thus the problem of patterning a material is generally split in two distinct steps: first, deposition and patterning of a surrogate layer that can be easily modified locally and then transfer of the pattern to the material of interest.

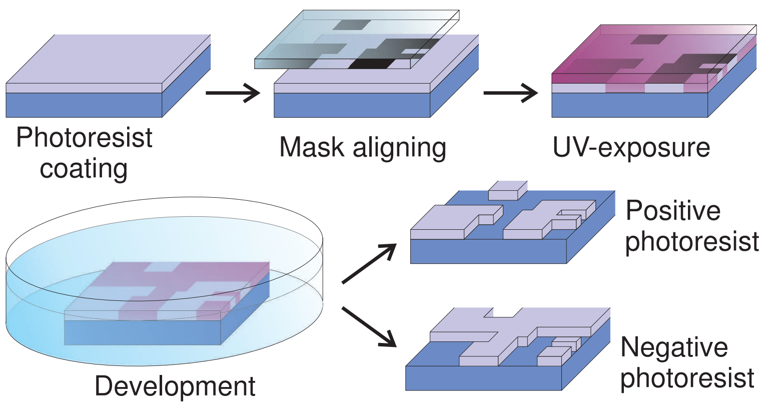


Figure 3.1: Photo-patterning in positive and negative photoresist.

In the most common process called photo-patterning, the surrogate layer used is a special polymer (called a photoresist) which is sensitive to UV-photon action (Figure 3.1). The photoresist is first coated on the substrate as a thin-film using, in general, a spinning process called spin-coating. In this process the photoresist is poured on the substrate which is then set to high-speed rotation, spreading the photoresist in a thin-film with very uniform thickness. The photoresist solvent is then evaporated by baking on a hotplate before the substrate is brought to the mask aligner tool, where the patterning process will take place. The photoresist film is exposed to UV radiation through a mask which has been precisely aligned with the substrate. The mask has clear and opaque regions according to the desired pattern, the clear regions allowing the photoresist to be exposed to UV radiation and modifying it locally. This exposure thus creates a latent image of the mask feature in the surrogate layer whose contrast may be enhanced by heat, which accelerates the chemical reaction initiated by the UV-exposure. To finish the process this latent imagehas to be revealed in a special chemical solution, the developper. Actually the exposure changes the solubility of the photoresist in the developper and the exact change of solubility depends on the type of photoresist used originally: for so called positive photoresist the exposed region becomes more soluble in the developper, while for negative photoresist the reverse happens and the exposed region becomes insoluble. After development the surrogate layer patterned over the whole surface of the wafer can be used for pattern transfer.

They are actually two main techniques that can be used to transfer the

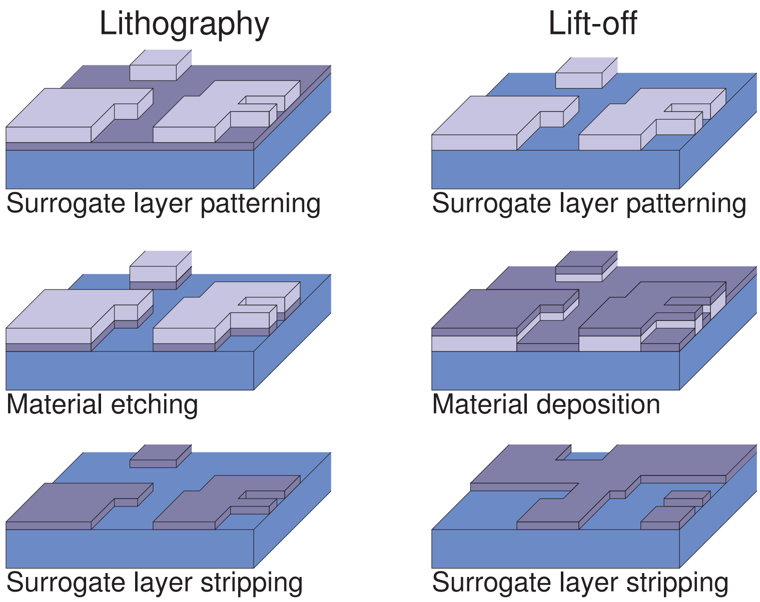


Figure 3.2: Pattern transfer by lithography and lift-off.

pattern: lithography and lift-off (Figure 3.2). In lithography the patterned layer allows exposing locally the underlying material. The exposed material is then etched physically or chemically before we finally remove the protec-

tive layer. For lift-off, we deposit the material on top of the patterned layer. Complete removal of this layer (called a sacrificial layer) leaves the material only in the open regions of the pattern.
Combination of photo-patterning and lithography is known as photolithography and is nowadays the most common techniques for micro-fabrication, lying at the roots of the IC revolution. An important steps is the fabrication of the photolithographic mask, which can clearly not itself use photolithography! Its fabrication is actually based on lithography on a transparent substrate, where the patterned layer is obtained with a photoresist film that has been exposed by a scanning beam (electron or laser). This process is slow, as the beam need to be scanned over the whole surface in a raster manner, but this is an acceptable trade-off for mask production, as photolithography needs a unique mask which is then used repeatedly to produce 1000's of wafers.

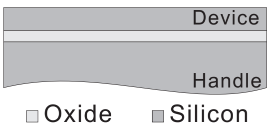
Recently we have seen the emergence of new patterning techniques, that try to reduce the cost attached to photo-patterning at small scale where there is a need to use deep-UV source with complex optics using immersion lens and systems under vacuum. The most promising ones are based on imprinting, where the desired pattern on a stamp is pressed against a protective resin film (hot-embossing, nano-imprint lithography, UV-NIL...). The resulting patterned layer can then be used with lithography or lift-off for pattern transfer.

MEMS fabrication does not end with wafer fabrication and there are, like in Electronics, back-end processes... with a twist. For example, when 'mechanical' parts (mobile elements, channels, cavities...) exist in the device, the processed wafer passes through a special step called 'release' to free these parts. This step is one of the last steps of the front-end process and may happen before or after the wafer has been diced in individual chips, just before the more traditional assembly, packaging and final tests.

3.2 The MEMS materials

The choice of a good material for MEMS application is no more based like in microelectronics on carrier mobility, but on more mechanical aspect: small or controllable internal stress, low processing temperature, compatibility with other materials, possibility to obtain thick layer, patterning possibilities... In addition, depending on the field of application, the material often needs to have extra properties. RF MEMS will want to be based on material with small loss tangent (for example high resistivity silicon), optical MEMS may need a transparent substrate, BioMEMS will need bio-compatibility, if not

for the substrate, for a coating adhering well to the substrate, sensor application will need a material showing piezoresistance or piezoelectricity, etc. Actually, because the issue of material contamination is much less important in MEMS than in IC fabrication, the MEMS designer often tries to use the material presenting the best properties for his unique application.
Still, from its microelectronics' root MEMS has retained the predominant use of silicon and its compounds, silicon (di)oxide (SiO_2) and silicon nitride (Si_xN_y). But actually, it was not purely coincidental, silicon is, as K. Petersen explained in a famous paper [18], an excellent mechanical material. Actually, silicon is almost as strong but lighter than steel, has large critical stress and no elasticity limit at room temperature as it is a perfect crystal ensuring that it will recover from large strain. Unfortunately it is brittle and this may pose problem in handling wafer, but it is rarely a source of failure for MEMS components. For sensing application silicon has a large piezoresistive coefficient, and for optical MEMS it is transparent at the common telecommunication wavelengths.
In addition silicon has a stable oxide easy to grow at elevated temperature that is transparent and thermally and electrically insulating. Actually this oxide has the smallest coefficient of thermal expansion of all known materials. Those properties are often put to good use during MEMS fabrication, where oxide support will be used to thermally insulate a pixel of an thermal camera for example.



Recently, a new substrate based on silicon and coming from IC industry has made its entry in the MEMS material list: the SOI (Silicon On Insulator) wafer. This substrate is composed of a thick silicon layer of several hundred μm (the handle), a thin layer of oxide of 1 or 2 μm and on top another silicon layer, the device layer. The thickness of this last layer is what differentiates the IC and the MEMS SOI wafers: in the first case it will reach at most a few μm where in the later case, the thickness can reach 100 μm or more. The high functionality of this material has allowed producing complete devices with very simple process, like the optical switch produced by Sercalo fabricated with its mobile mirror, actuator and fiber alignment feature with one single process step!
Another interesting compound is silicon nitride (Si_xN_y), which is stronger than silicon and can be deposited in thin layer with an excellent control of stress to produce 1 μm thick membrane of several cm^2. In general stoichiometric nitride film (Si_3N_4) will show tensile stress, but increasing the Si content will invariably ends in obtaining a compressive stress. A good control of stress is also obtained during deposition of poly-crystalline silicon. During LPCVD deposition, increasing the temperature from 560°C to

620°C lowers the as-deposited stress, changing the compressive stress usually present in polysilicon films to tensile stress [19]. A subsequent high temperature (>950°C) anneal result in layer with very low stress, making Poly-Si the material of choice for building multi-layered structure on silicon surface. For example the Sandia National Lab's 'Summit V' process stacks five layer of poly-silicon allowing an unparalleled freedom of design for complex MEMS structure. Closing the list of silicon compound we can add a newcomer, silicon carbide SiC. SiC has unique thermal properties (albeit not yet on par with diamond) and has been used in high temperature sensor.

But silicon and its derivative are not the only choice for MEMS, many other materials are also used because they posses some unique properties. For example, other semiconductors like InP have also been micromachined mainly to take advantage of their photonics capabilities and serve as tunable laser source. Quartz crystal has strong piezoelectric effect that has been put into use to build resonant sensors like gyroscope or mass sensors. Biocompatibility will actually force the use of a limited list of already tested and approved material, or suggest the use of durable coating.

Glass is only second to silicon in its use in MEMS fabrication because it can easily form tight bond with silicon and also because it can be used to obtain bio-compatible channels for BioMEMS.

Polymers are also often used for BioMEMS fabrication where they can be tailored to provide biodegradability or bioabsorbability. The versatility of polymers makes them interesting for other MEMS application, and for example the reflow appearing at moderate temperature has been used to obtain arrays of spherical microlenses for optical MEMS. This thermoplastic property also allows molding, making polymer MEMS a cheap alternative to silicon based system, particularly for micro-fluidic application. Recently the availability of photosensitive polymers like SU8 [20] than can be spun to thickness exceeding 100 μm and patterned with vertical sides has further increased the possibility to build polymer structure.

This quick introduction to MEMS materials needs to mention metals. If their conductivity is of course a must when they are used as electrical connection like in IC, metals can also be used to build structures. Actually, their ability to be grown in thin-films of good quality at a moderate temperature is what decided Texas Instrument to base the complete DLP micro-mirror device on a multi-layer aluminum process. In other applications, electroplated nickel will produce excellent micro-molds, whereas gold reflective properties are used in optical MEMS and nitinol (NiTi), presenting a strong shape memory effect, becomes actuator.

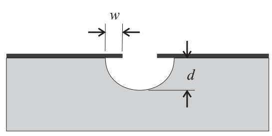
3.3 Bulk micromachining, wet and dry etching

3.3.1 Introduction

Bulk micromachining refers to the formation of micro structures by removal of materials from bulk substrates. The bulk substrate in wafer form can be silicon, glass, quartz, crystalline Ge, SiC, GaAs, GaP or InP. The methods commonly used to remove excess material are wet and dry etching, allowing varying degree of control on the profile of the final structure.

3.3.2 Isotropic and anisotropic wet etching

Wet etching is obtained by immersing the material in a chemical bath that dissolves the surfaces not covered by a protective layer. The main advantages of the technique are that it can be quick, uniform, very selective and cheap. The etching rate and the resulting profile depend on the material, the chemical, the temperature of the bath, the presence of agitation, and the etch stop technique used if any. Wet etching is usually divided between isotropic and anisotropic etching. Isotropic etching happens when the chemical etches the bulk material at the same rate in all directions, while anisotropic etching happens when different etching rate exists along different directions.



However the etching rate never reaches 0, and it is actually impossible to obtain etching in only one direction. This is commonly quantified by estimating the overetch (w/d), that is the lateral etch with respect to the vertical etch, as shown in the figure. This parameter may range between 1 for isotropic etching to about 0.01 for very anisotropic etch, obtained for example by etching Silicon in a KOH bath. For substrates made of homogeneous and amorphous material, like glass, wet etching must be isotropic, although faster surface etching is sometimes observed. However, for crystalline materials, e.g. silicon, the etching is either isotropic or anisotropic, depending on the type of chemical used. In general, isotropic etchants are acids, while anisotropic etchants are alkaline bases.

Figure 3.3 compares isotropic and anisotropic wet etching of silicon. The top-left inset shows isotropic etching of silicon when the bath is agitated ensuring that fresh chemical constantly reaches the bottom of the trench and resulting in a truly isotropic etch. Isotropic wet etching is used for thin layer or when the rounded profile is interesting, to obtain channels for fluids for example. For silicon, the etchant can be HNA, which is a mixture of

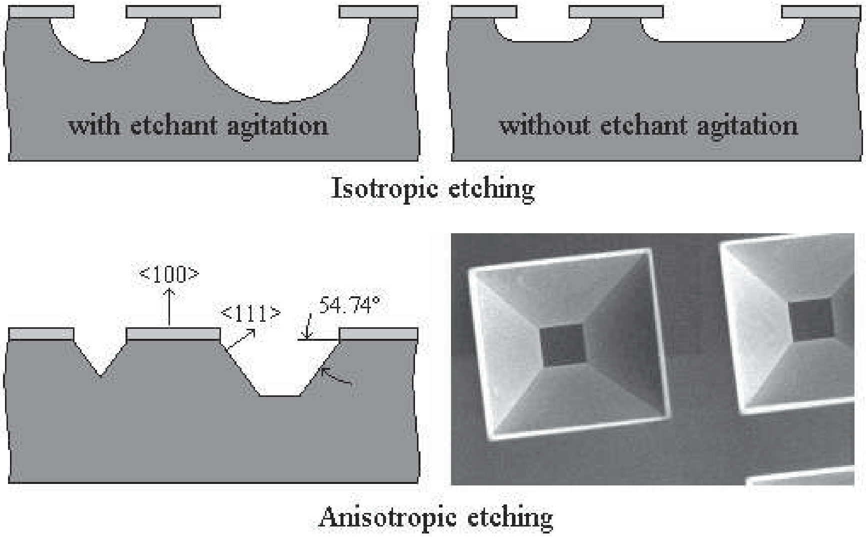


Figure 3.3: Isotropic and Anisotropic wet etching

hydrofluoric acid (HF), nitric acid (HNO_3), and acetic acid (CH_3COOH). In HNA the nitric acid acts as an oxidant and HF dissolves the oxide by forming the water soluble H_2SiF_6. The two steps of the simplified reaction are:

$$\mathrm{Si} + \mathrm{HNO_3} + \mathrm{H_2O} \longrightarrow \mathrm{SiO_2} + \mathrm{HNO_2} + \mathrm{H_2}$$
$$\mathrm{SiO_2} + 6\mathrm{HF} \longrightarrow \mathrm{H_2SiF_6} + 2\mathrm{H_2O}$$

The etching rate for silicon can reach 80 µm/min, and oxide can be used as mask material as his etch rate is only 30 to 80 nm/min. Etching under the mask edge or underetch is unavoidable with isotropic wet etching. Moreover, the etch rate and profile are sensitive to solution agitation and temperature, making it difficult to control the geometries of the deep etch usually needed for MEMS.

Anisotropic etching developed in the late 60s can overcome these problems. The lower part of Figure 3.3 shows features obtained by etching a (100) wafer with a KOH solution. The etched profile is clearly anisotropic, reveling planes without rounded shape and very little underetch. Potassium hydroxide (KOH), tetramethyl ammonium hydroxide (TMAH) and ethylene diamine pyrocatechol (EDP) are common chemicals used for anisotropic etching of silicon. The etching anisotropy has its roots in the different etch rates appearing for different crystal planes because they have different density of electrons. Three important crystal planes, the (100) plane, (110) plane and (111) plane have been illustrated in Figure 3.4. The three orientations

<100>, <110>, and <111> are the respective directions normal to these planes.

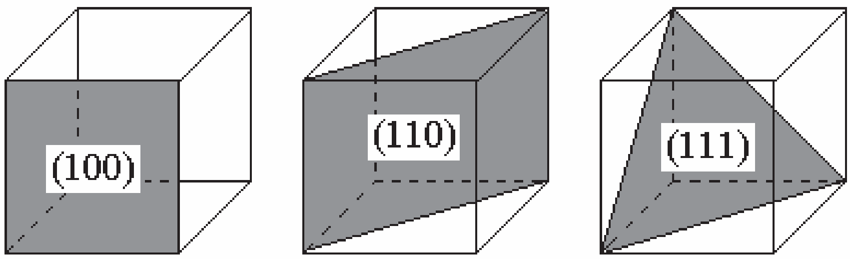


Figure 3.4: Main planes in the cubic lattice of silicon.

The anisotropy can be very large and for example, for silicon and KOH, the etch rate ratio can reach 400 between (100) and (111) planes and even 600 between (110) and (111) planes - meaning that when the etch rate for the (100) plane is about 1 μm/min then the (111) plane will etch at only 2.5 nm/min effectively allowing to consider it as an etch-stop plane. With different combinations of wafer orientations and mask patterns, very sophisticated structures such as cavities, grooves, cantilevers, through holes and bridges can be fabricated. For example, if the (100) wafers in Figure 3.2 shows an angle of 54.7° between the (111) plane and the surface, typically producing V-grooves, (110) oriented wafer will present an angle of 90° between these planes resulting in U-grooves with vertical walls. To obtain these grooves, the mask pattern edges need to be aligned with the edge of the (111) planes. For a (100) wafer it is simple because the groove edge are along the <110> direction, that is parallel to the main wafer flat. Moreover the four (111) planes intersect on the (100) surface at 90° and a rectangular pattern will immediately expose four sloping (111) planes and provide a simple way to obtain precisely defined pits and membrane. (110) wafers are more difficult to handle, and to obtain a U-groove the side should be tilted by an angle of 125.2° with respect to the <110> wafer flat. In addition, to obtain a four-sided pit, the two other sides should make a 55° angle with the flat direction - defining a non-rectangular pit that is seldom used for membranes. If the control of the lateral etching by using the (111) planes is usually excellent, controlling the etching depth is more complicated. The first possibility is to use the self limiting effect appearing when two sloping (111) planes finally contact each other, providing the typical V-grooves of Figure 3.2. Controlling the etching time is another alternative. However producing the

flat membranes of precise thickness needed for pressure sensors required a better approach that what can be achieved by this simple method. MEMS technologist have tackled this problem by developing different etch stop techniques that reduce by one or two order of magnitude the etch speed when the solution reach a particular depth.
The electrochemical etch stop works by first creating a diode junction for example by using epitaxial growth or doping of a n-layer over a p-substrate. Proper polarization of the substrate and the chemical bath allows for the etching to completely stop at the junction. This process yields an excellent control over the final membrane thickness that is only determined by the thickness of the epitaxial layer, and thus can be better than 1% over a whole wafer. Another popular method that does not require epitaxial growth is to heavily dope the surface of silicon with boron by diffusion or implantation, triggering a decrease of the etch rate by at least one order of magnitude. However, if diffusion from the surface is used to obtain the boron layer, the resulting high boron concentration ($> 10^{19}\text{cm}^{-3}$) at the surface will decrease substantially the piezoresistive coefficient value making piezoresistors less sensitive. Ion implantation can overcome this problem by burying the doped layer a few µm under the surface, leaving a thin top layer untouched for the fabrication of the piezoresistors.

Actually, the seemingly simple membrane process requires two tools specially designed for MEMS fabrication. Firstly, to properly align the aperture of the backside mask with the piezoresistor or other features on the front side (Figure 2.5) a double-side mask aligner is required. Different approaches have been used (infrared camera, image storage, folded optical path...) by the various manufacturers (Suss Microtec, OAI, EVGroup...) to tackle this problem, resulting in a very satisfying registration accuracy that can reach 1 µm for the best systems. Secondly, etching the cavity below the membrane needs a special protection tool, that in the case of electrochemical etch stop is also used for insuring the substrate polarization. Actually the presence of the cavity inevitably weakens the wafer and to avoid wafer breakage, the membrane is usually etched in the last step of the process. At that time, the front side will have already received metallization which generally cannot survive the prolonged etch and needs to be protected. This protection can be obtained by using a thick protective wax, but more often a cleaner process is preferred based on a mechanical chuck. The chuck is designed to allow quick loading and unloading operation, using O-ring to seal the frontside of the wafer and often includes spring loaded contacts to provide bias for electrochemical etch-stop.

The chemical used during anisotropic etching are usually strong alkaline bases and requires a hard masking material that can withstand the solution without decomposing or peeling. In general polymer (like photoresist) can not be used to protect the substrate, and if some metals can be used effectively, in general a non-organic thin-film is used. For example, silicon oxide mask is commonly used with TMAH, while silicon nitride is generally used with KOH. Table 3.2 summarizes the characteristics of some anisotropic etching solution.

Solution	**(100) Si etch rate (μm/min)**	**Etch rate ratio**	**Mask etch rate (nm/min)**	**Boron etch stop (cm^{-3})**
KOH / H_2O 44g / 100ml (30 wt.%) @ 85°C [1]	1.4	400 for (100)/(111) 600 for (110)/(111)	3.5 (SiO_2) <0.01 (Si_3N_4)	$> 10^{20}$ rate/20
TMAH / H_2O 28g / 100ml (22 wt.%) @ 90°C [2]	1	30 for (100)/(111) 50 for (110)/(111)	0.2 (SiO_2) <0.01 (Si_3N_4)	$4 \cdot 10^{20}$ rate/40
EDP (Ethylene diamine / pyrocatechol / H_2O) 750ml / 120g / 240ml @ 115°C [3]	1.25	35 for (100)/(111)	0.5 (SiO_2) 0.1 (Si_3N_4) ≈0 (Au, Cr, Ag, Cu, Ta)	$7 \cdot 10^{19}$ rate/50

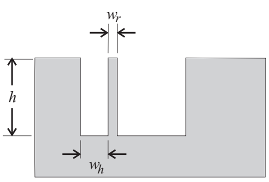
Notes:
1 +largest etch rate ratio; –K ions degrade CMOS; –etch SiO_2 fast
2 +SiO_2 mask; +CMOS compatible ; –large overtech
3 +SiO_2 mask; +no metal etch; +CMOS compatible; –large overtech; –toxic

Table 3.2: Characteristics of some anisotropic etchants for silicon.

Of course anisotropic wet etching has its limitation. The most serious one lies with the need to align the sides of the pattern with the crystal axes to benefit from the (111) plane etch-stop, severely limiting the freedom of layout. A typical example is when we want to design a structure with convex corners - that is instead of designing a pit, we now want an island. The island convex corners will inevitably expose planes which are not the (111) planes and will be etched away slowly, finally resulting in the complete disappearance of the island. Although techniques have been developed to slow down the etch rate of the corner by adding protruding 'prongs', these structures take space on the wafer and they finally cannot give the same patterning freedom as dry etching techniques.

3.3.3 Dry etching

Dry etching is a series of methods where the solid substrate surface is etched by gaseous species. Plasma is usually involved in the process to increase etching rate and supply reacting ions and radicals. The etching can be conducted physically by ion bombardment (ion etching or sputtering and ion-beam milling), chemically through a chemical reaction occurring at the solid surface (plasma etching or radical etching), or by mechanisms combining both physical and chemical effects (reactive ion etching or RIE). These methods have various etching selectivity and achieve different etching profiles and usually the etching is more anisotropic and vertical when the etching is more physical, while it is more selective and isotropic when it is more chemical. Most of these methods are discussed in standard microelectronics process books, but they take a different twist when they are applied to MEMS fabrication as in general MEMS necessitates deep (> 5 µm) etching.



The Figure illustrates an important parameter commonly used to describe dry etching : the aspect ratio. Actually we can define an aspect ratio for features (h/w_r) and for holes (h/w_h) with most technologies giving better results with features than with holes - but generally with only a small difference. Typical values for this parameter would range between 1 (isotropic etch) and 50, for very anisotropic etching like the DRIE process.

To improve the aspect ratio of the etching, several techniques based on RIE have been developed, usually trying to increase the anisotropy by protecting the sidewalls during etching. For example, the SCREAM process developed in Cornell University alternate steps of etching and growth of oxide that remains longer on the sidewall, while for the RIE cryogenic process, very low temperature in a SF_6/O_2 plasma is used to obtain continuous deposition of a fluoro-polymer on the sidewall during the etch. Finally the innovative Bosh process uses alternating cycle of etching and protection in the plasma chamber to achieve the same function. This important process is the corner stone of DRIE micromaching and will be described in more details in a following section.

3.3.4 Wafer bonding

A review of MEMS fabrication technique cannot be complete without mentioning wafer bonding. Wafer bonding is an assembly technique where two or more precisely aligned wafers are bonded together. This method is at the frontier between a fabrication method and a packaging method and belong both to front-end and back-end process, another specificities of MEMS, but at this stage it is not surprising anymore!
Wafer bonding has the potential to simplify fabrication method because structures can be patterned on both wafers and after bonding they will be part of the same device, without the need for complex multi-layer fabrication process. Of course epoxy bonding can be used to bond wafers together but much better MEMS techniques do exist. Intermediate-layer eutectic bonding

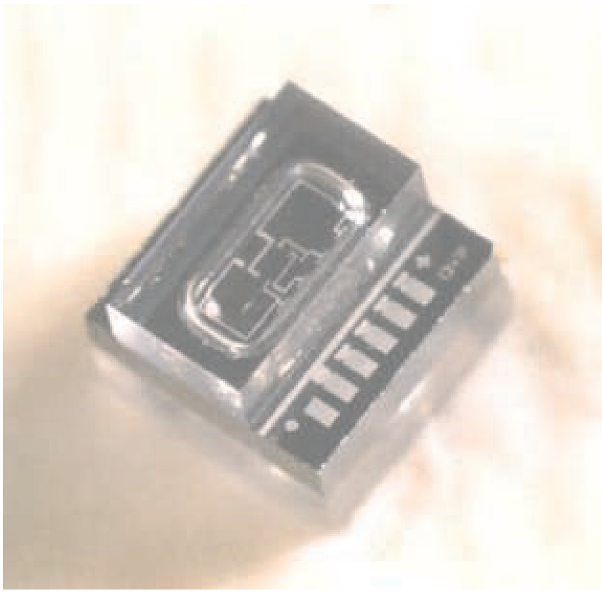


Figure 3.5: Silicon pressure sensor SP15 bonded with glass cover (Courtesy SensoNor AS - An Infineon Technologies Company).

is based on forming a eutectic alloy that will diffuse into the target wafer and form the bond. For silicon-to-silicon bonding the intermediate layer is often gold which form a eutectic alloy with silicon at 363°C. Silicon-to-silicon fusion bonding allows bonding two silicon wafers directly effectively achieving seamless bond possessing an exceptional strength and hermeticity. However the technique requires excellent flatness and high temperature, two hurdles that limit its use.
The most commonly used MEMS bonding methods is probably anodic bond-

ing which is mainly used to bond silicon wafers with glass wafers. The technique work by applying a high voltage to the stacked wafers that induce migration of ion from glass to silicon, allowing a strong field assisted bond to form. This technique is commonly used to fabricate sensors allowing for example to obtain cavities with controlled pressure for pressure sensor as shown in Figure 3.5. At the same time, the glass wafer provides wafer level packaging, protecting sensitive parts before back-end process.
Another important use of wafer bonding is to fabricate MEMS substrates such as SOI and SOG (silicon on glass) wafers.

3.4 Surface micromachining

Unlike bulk micromachining in which microstructures are formed by etching into the bulk substrate, surface micromachining builds up structures by adding materials, layer by layer, on the surface of the substrate. The thin film layers are typically $1\tilde{5}$ μm thick, some acting as structural layer and others as sacrificial layer. Dry etching is usually used to define the shape of the structure layers, and a final wet etching step releases them from the substrate by removing the supporting sacrificial layer.

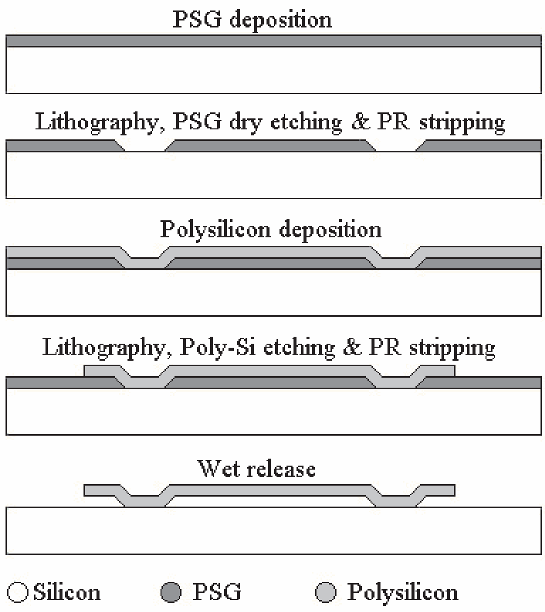


Figure 3.6: Basic process sequence of surface micromachining.

A typical surface micromachining process sequence to build a micro bridge is shown in Figure 3.6. Phosphosilicate glass (PSG) is first deposited by LPCVD to form the sacrificial layer. After the PSG layer has been patterned, a structural layer of low-stress polysilicon is added. Then the polysilicon thin-film is patterned with another mask in $CF_4 + O_2$ plasma. Finally, the PSG sacrificial layer is etched away by an HF solution and the polysilicon bridge is released.

3.4.1 Thin-film fabrication

The choice of the thin-film and its fabrication method is dictated by many different considerations, as the temperature (dictated by the temperature resistance of the material on the substrate and the allowable thermal stress), the magnitude of the residual stress in the thin-film (too much stress cause layer cracking), the conformality of the thin-film (how the thin-film follows the profile of the substrate as shown in Fig. 3.7), the roughness of the thin-film, the existence of pinholes, the uniformity of the thin-film, the speed of fabrication (to obtain thicker thin-film).

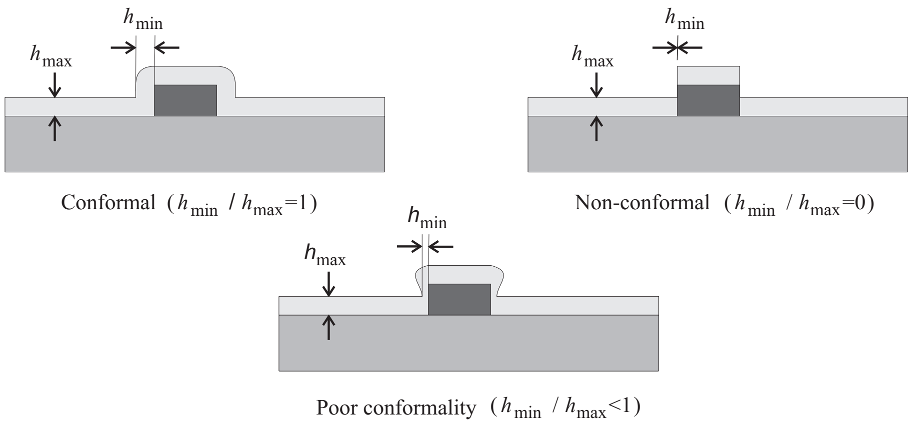


Figure 3.7: Conformality of layer deposited over a ridge.

Common thin-film fabrication techniques are the same as those used in microelectronics fabrication like oxidation (in dry or in wet oxygen), chemical vapor deposition (CVD) at atmospheric (APCVD) or more often at low pressure (LPCVD), sputtering, e-beam or thermal evaporation, spin-coating... They have various characteristics that we compare in Table 3.3. In general the best film quality is obtained at higher temperature, where the highest atom mobility assure good conformality and pin-hole free films with good adhesion.

Technique	**Temperature**	**Conformality**	**Rate**
Oxidation	++	++	0
LPCVD	+	+	+
Sputtering	-	0	+
Evaporation	-	-	0
Spin-coating	- -	- -	++

Table 3.3: Comparison of some thin-film fabrication techniques.

Oxidation is in many aspect excellent as it is a reactive growth technique, where silicon dioxide is obtained from a chemical reaction in the silicon using a gaseous flow of dry or wet dioxygen. Using dry dioxygen results in a slower growth rate than when water vapour are added, but it also results in higher quality films. The rate of growth is given by the well-known Deal and Groove's model as

$$d_o = \frac{A}{2}\sqrt{1 + \frac{t+\tau}{A^2/4B}} - \frac{A}{2},$$

where B is called the parabolic rate constant and B/A the linear rate constant that are obtained for the long and the short growth time limit respectively. Typical value for these constant at 1000°C are $A = 0.165\,\mu\text{m}$, $B = 0.0117\,\mu\text{m}^2$ and $\tau = 0.37\text{h}$ in dry O_2 and $A = 0.226\ \mu\text{m}$, $B = 0.287\ \mu\text{m}^2$ and $\tau = 0$ in wet O_2 . It should be noted that the model breaks down for thin dioxide (<300Å) in dry atmosphere because of an excessive initial growth rate that is modeled through the use of τ. An interesting feature of oxidation is that it results in a net volume change as the density of oxide is lower than silicon. Actually, the growth of a thickness d_o of dioxide results in the consumption of a thickness of silicon $d_{Si} = 0.44 d_o$. This net volume expansion during growth is sometimes used to close holes in silicon or poly-silicon layers.

Besides the characteristics listed above, for surface micromachining we also need to consider an additional condition: the compatibility between sacrificial and structural layers. Actually, the selection of a suitable sacrificial material depends on the structural material and particularly on the availability of an etching method that can selectively etch the sacrificial material without significantly etching the structural materials or the substrate. A few common combinations of structural material and etching method are shown in table 3.4, but the list is endless. As a large variety of materials such as polysilicon, oxide, nitride, PSG, metals, diamond, SiC and GaAs can be de-

Structural material	**Sacrificial material**	**Etchant**
Polysilicon	Oxide(PSG, LTO, etc)	Buffered HF
Si_3N_4	Poly-Si	KOH
SiO_2	Poly-Si	EDP/TMAH
Aluminum	Photoresist	Acetone/O_2 plasma
Polyimide	Cu	Ferric chloride
Ti	Au	Ammonium iodide
SiO_2, Si_3N_4, metal	Poly-Si	XeF_2

Table 3.4: Combination of materials and etchant for surface micromachining.

posited as thin film and many layers can be stacked, surface micromachining can build very complicated micro structures. For example Sandia National Laboratories is proposing a process with four polysilicon structural layers and four oxide sacrificial layers, which has been used for fabricating complex locking mechanism for defense application. Figure 3.8 demonstrates surface micromachined micro-mirrors fabricated using two polysilicon structural layers and an additional final gold layer to increase reflectivity. They have been assembled in 3D like a pop-up structure, using a micromanipulator on a probe-station.

3.4.2 Design limitation

Yet surface micromachining has to face several unique problems that need addressing to obtain working devices. During layer deposition, a strict control of the stress in the structural layer has to be exerted. Compressive stress in a constrained member will cause it to buckle, while a gradient of stress across a cantilevered structure causes it to warp, resulting in both case in probable device failure.
The possibility to stack several layers brings freedom but also adds complexity. Actually there is large chance that the topography created by the pattern on underlying layer will create havoc with the upper layer, as illustrated in Figure 3.9.

A common problem is the formation of strings of structural material, called 'stringers', during the patterning of the upper layer. Actually the high anisotropy of the etching by RIE leaves some material where the layer is

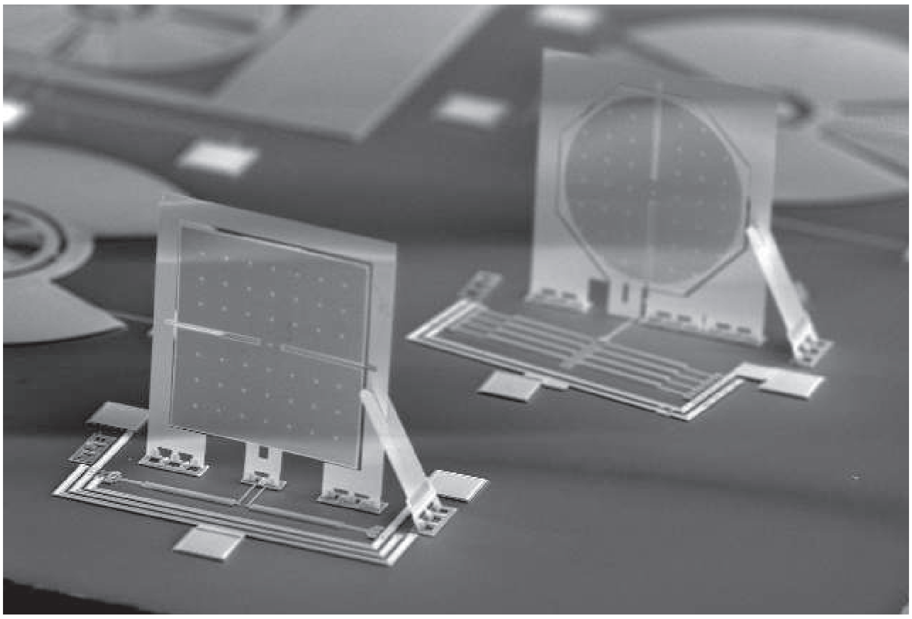


Figure 3.8: A micro optical stage built by surface micromachining.

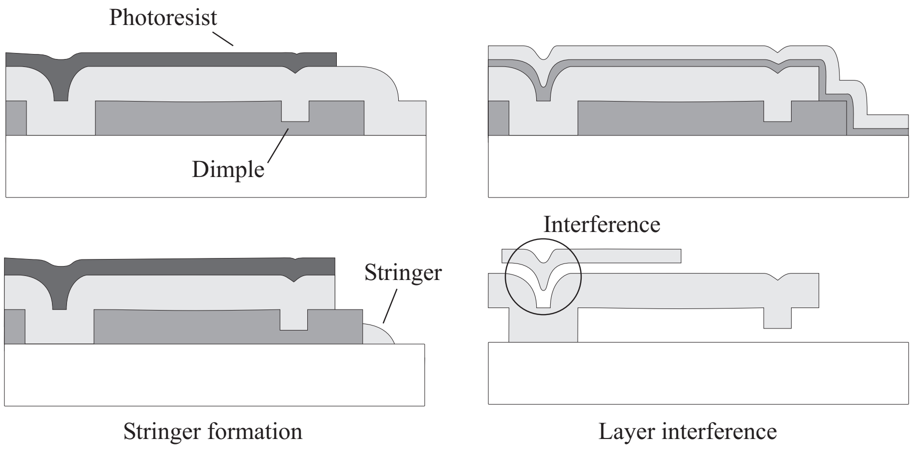


Figure 3.9: Common surface micromachining issues.

thicker because of the conformal deposition of the structural material. To avoid the problem during fabrication, the RIE etching time needs to be substantially increased to fully etch the layer where it is thicker. For example the MUMPS surface micromachining process proposed by the foundry MEMSCAP is using an overteching of 100%, that is, the etching lasts twice the time needed to clear the material in the flat zone. Another common issue is the likelihood of structure interference between the stacked layers. In Fig-

ure 3.9 we see that the topography creates an unintended protrusion below the top structural layer that will forbid it to move freely sideway - probably dooming the whole device. This problem can be tackled during layout, particularly when the layout editor has a cross-section view, like L-Edit from Tanner Research. However even a clever layout won't be able to suppress this problem completely and it will need to be addressed during fabrication. Actually polishing using CMP the intermediate sacrificial layer to make it completely flat, will avoid all interference problems. For example, Sandia National Laboratory uses oxide CMP of the second sacrificial layer for their four layers SUMMiT V process.
However, sometimes the interference may be a desired effect and for example the so called 'scissors' hinge [21] design shown in Figure 3.10 benefits greatly from it. As we see here the protrusion below the upper layer helps to hold the hinge axis tightly. If we had to rely on lithography only, the gap between the axis and the fixed part in the first structural layer would be at best 2 µm, as limited by the design rules, and the axis will have too much play. However the protrusions below the staple reduce the gap to 0.75 µm, the thickness of the second sacrificial layer, and the quality of the hinge is greatly increased.

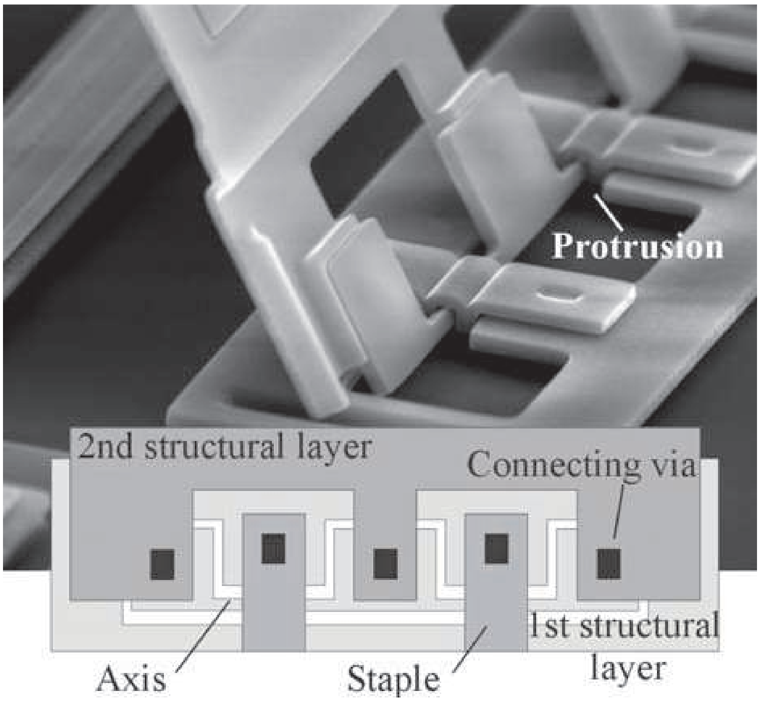


Figure 3.10: Tight clearance obtained by layer interference in a hinge structure.

The final step in surface micromachining process is the release - and this critical step has also a fair amount of issues that need to be considered.

3.4.3 Microstructure release

The release step is the source of much technologist woes. Release is usually a wet process that is used to dissolve the sacrificial material under the structure to be freed. However the removal rate is usually relatively slow because the sacrificial layer is only a few µm thick and the reaction becomes quickly diffusion limited. Then the depth of sacrificial layer dissolved under the structure will increase slowly with the etching time as

$$d_{\text{release}} \propto \sqrt{t_{\text{etch}}}.$$

Simply said, releasing a structure twice as wide will take 4 times more time. However if the etching lasts too long the chemical may start attacking the device structural material too. A first measure to avoid problems is to use compatible material and chemical, where the sacrificial layer is etched quickly but other material not at all. A typical example is given by the DLP (Digital Light Processing) from Texas Instrument, where the structural layer is aluminum and the sacrificial layer is a polymer. The polymer is removed with oxygen plasma, and prolonged release time will only slightly affect the metal. This ideal case is often difficult to reach and for example metals have often a finite etch rate in HF, which is used to remove PSG sacrificial layer. Thus to decrease the release time we have to facilitate etching of the sacrificial layer by providing access hole for the chemical through the structural layer. In the case of Figure 3.8 for example, the mirror metal starts to peel off after about 10 minutes in HF. However in about 5 minutes HF could only reach 40 µm under a plain plate, and the designer introduced 'release holes'. These holes in the structural layer are spaced by roughly 30 µm in the middle of the mirror plate (the white dots in the figure) allowing for the HF to etch all the oxide beneath in less than 5 minutes.

The problems with wet release continue when you need to dry your sample. The meniscus created by the receding liquid/air interface tends to pull the structure against the substrate. This intimate contact give rise to other surface forces like Van der Walls force, which will irremediably pin your structure to the substrate when the drying is complete, effectively destroying your device. This phenomenom is referred as stiction (Figure 3.11). Strategies that have been used to overcome this problem have tackled it at design and fabrication level. In surface micromachining the idea has been to reduce the contact surface by introducing dimples under the structure. From the

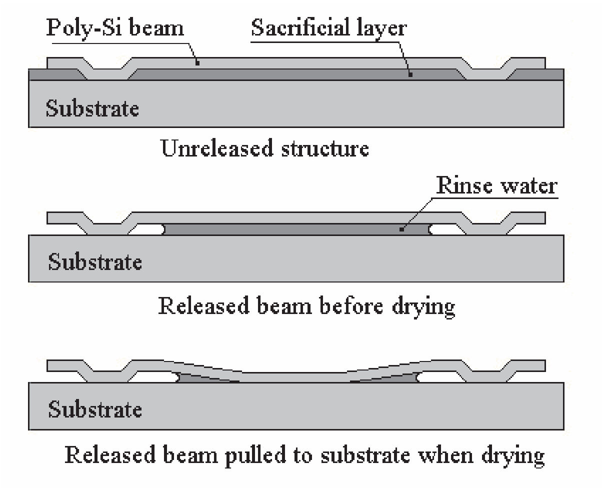


Figure 3.11: Stiction phenomenon during release.

fabrication side, super-critical drying, where the liquid changes to gas without creating a receding meniscus, has also been applied successfully. Coating the structure with non-sticking layer (fluorocarbon, hydrophobic SAM...) has also proved successful and this method, albeit more complex, has the added advantage to provide long lasting protection again sticking that could arise during use.
Finally, a completely different approach is to avoid wet release altogether and instead perform a dry release with a gas suppressing completely the sticking concern. In Table 3.4 we describe two popular methods, dissolving polymer sacrificial layer with O_2 plasma, and using xenon difluoride (XeF_2) to etch sacrificial silicon. The xenon difluoride is a gas showing an excellent selectivity, having etching rate ratio close to 1000 with metal and up to 10000 with oxide. The gas has thus been used successfully to release very compliant or nano-sized oxide structures where silicon was used as the sacrificial material. The process does not use plasma, making the chamber rather simple, and several manufacturers like XactiX (in cooperation with STS), in the USA or PentaVacuum in Singapore are proposing tools to exploit the technology.

3.5 DRIE micromachining

Deep reactive ion etching (DRIE) micromachining shares features both from surface and bulk micromachining. As in bulk micromachining the structure is etch in the bulk of the substrate, but as in surface micromachining a release steps is used to free the microstructure. Figure 3.12 shows a simplified process of bulk micromachining on silicon-on-oxide (SOI) wafer using deep reactive ion etching (DRIE), a special MEMS dry etch technique allowing large etching depth with very vertical side walls. The SOI wafers used in MEMS usually have a device layer thickness between 10 and 200μm used here as the bulk substrate. After photolithography, the wafer is etched with DRIE to form high aspect ratio silicon structures, and the buried silicon dioxide acts as an effective etching stop. Stripping off the protective photoresist by O_2 plasma and then etching the sacrificial layer of the oxide using HF to release the microstructure finish the device. This simple, yet powerful, technique needs only one mask to obtain working devices, and it is understandably used in commercial products. The best known example is the optical switch produced by Sercalo, a company founded by C. Marxer the inventor of this fabrication technique. DRIE has reached a large popularity

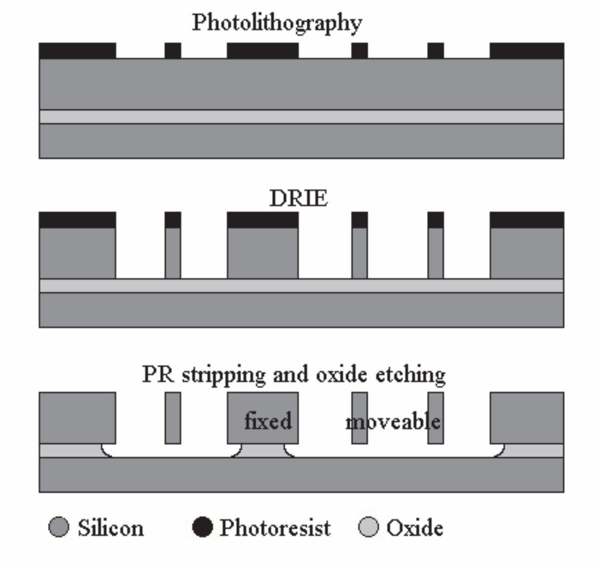


Figure 3.12: Bulk micromachining of SOI wafer by DRIE.

in recent years among MEMS community and the tools produced by Adixen (Alcatel), Surface Technology Systems (STS) and Oxford System produce high aspect ratio structures (>25) with vertical sidewalls (>89°) at a decent etching rate (6μm/min or more).
A standard DRIE setting uses high density inductively coupled plasma (ICP) as the plasma source, and usually adopts the patented "Bosch process". The Bosch process is a repetition of two alternating steps: passivation and etching. In the passivation step, C_4F_8 gas flows into the ICP chamber forming a polymer protective layer (n (-CF2-)) on all the surfaces. In the following

etching step, the SF_6 gas in the plasma chamber is dissociated to F-radicals and ions. The vertical ion bombardment sputters away the polymer at the trench bottom, while keeping the sidewalls untouched and still protected by the polymer. Then the radicals chemically etch the silicon on the bottom making the trench deeper. By carefully controlling the duration of the etching and passivation steps, trenches with aspect ratio as high as 25:1 have been routinely fabricated. Figure 3.13 is a SEM picture of some structures fabricated by DRIE on a SOI wafer.

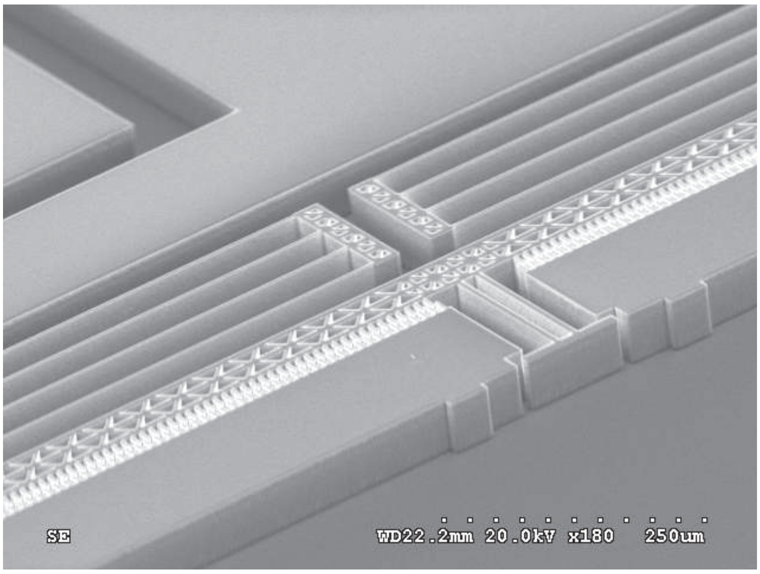


Figure 3.13: 50 μm thick structures fabricated by DRIE on SOI.

The main issues with DRIE are the presence of ripple with an amplitude over 100nm on the vertical edge due to the repetition of etching and passivating steps, and the quick silicon undertech that happens when the etching reach the buried oxide layer of SOI. However, the most recent DRIE tools have managed to tackle these two problems satisfactorily, by tweaking the recipe and usually trading a bit of etching speed for improving another etching parameter.
The SOI wafer used often in DRIE machining is still expensive and it is possible to obtain the thick silicon structural layer by growing it using epitaxy on an oxidized wafer. Even more simply, DRIE has been used is a dry etching version of bulk micromachining (but allowing complete freedom over layout as there is no more crystallographic orientation concerns) without sacrificial layer at all, and using wafer bonding to provide movable part.

3.6 Other microfabrication techniques

3.6.1 Micro-molding and LIGA

Other methods exist where no material is removed but this time molded to achieve the desired pattern. LIGA, a German acronym for lithography (LIthographie), electroforming (Galvanoformung), and molding (Abformung) is the mother of these methods.
LIGA makes very high aspect ratio 3-D microstructures with non-silicon materials such as metal, plastic or ceramics using replication or molding. LIGA process begins with X-ray lithography using a synchrotron source (e.g. energy of 2.4 GeV and wavelength of 2 $\AA$) to expose a thick layer of X-ray photoresist (e.g. PMMA). Because of the incredibly small wavelength, diffraction effects are minimized and thick layer of photoresist can be patterned with sub-micron accuracy. The resist mold is subsequently used for electroforming and metal (e.g. nickel using $NiCl_2$ solution) is electroplated in the resist mold. After the resist is dissolved, the metal structure remains. This structure may be the final product but to lower down the costs, it usually serves as a mold insert for injection molding or hot embossing. The possibility to replicate hundreds of part with the same insert opens the door to cheap mass production. When the sub-micrometer resolution is not much of a concern, pseudo-LIGA processes can be advantageously used. These techniques avoid using the high cost X-ray source for the mold fabrication by replacing it by the thick photoresist SU8 and a standard UV exposure or even by fabricating a silicon mold using DRIE.

3.6.2 Polymer MEMS

Bulk and surface micromachining can be classified as direct etch method, where the device pattern is obtained by removing material from the substrate or from deposited layers. However, etching necessitates the use of lithography, which already includes patterning the photoresist, then why would we want to etch the lower layer when the pattern is already here? Actually lithography for MEMS has seen the emergence of ultra-thick photoresist that can be spun up to several 100 µm and exposed with a standard mask aligner, providing a quick way to the production of micro-parts. SU8, a high-density negative photoresist can be spun in excess of 200 µm and allows the fabrication of mechanical parts [20] of good quality. It is used in many applications ranging from bioMEMS with micro-parts for tissue scaffold or channels, for example to packaging, where it is used as buffer layer. Another application of thick photo-patternable polymer is the fabrication of microlenses using reflow at elevated temperature of thick positive photoresist pillars (e.g. AZ9260).

Next to these major techniques, other microfabrication processes exist and keep emerging. They all have their purpose and advantages and are often used for a specific application. For example, quartz micromachining is based on anisotropic wet etching of quartz wafers to take benefit of its stable piezoelectric properties and build sensors like gyroscopes.

3.7 Problems

1. An optical telecommunication devices manufacturer wants to use microfabrication to produce V-groove for holding optical fiber. the most likely process to use is:

    - silicon substrate, photoresist mask and HF etchant
    - glass substrate, chromium mask and RIE etching with SF_6
    - silicon substrate, silicon nitride (Si_3N_4) mask and KOH etchant
    - silicon substrate, silicon dioxide (SiO_2) mask and HF etchant

2. A mask has the pattern of Figure 3.14(a). Which photoresist and pattern transfer technique could be used to pattern a thin film (in black) as shown in Figure 3.14(b)?

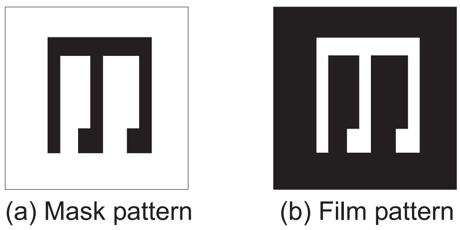


Figure 3.14: Mask and film pattern.

    - positive photoresist and lift-off
    - negative photoresist and wet etching
    - positive photoresist and RIE etching
    - negative photoresist and lift-off

3. A circular hole in silicon is closed by growing oxide. The hole has a diameter of 2 μm.

- Approximate the Deal and Grove's equation when t is much larger than τ and $A^2/4A$.
- How long will it take to close the hole if the long duration oxidation is performed at 1100°C in wet O_2? (Note: we have $B = 0.51\,\mu m^2/h$ at 1100°C)

4. Suggest a complete microfabrication process that can be used to fabricate the channel shown in Figure 3.15.

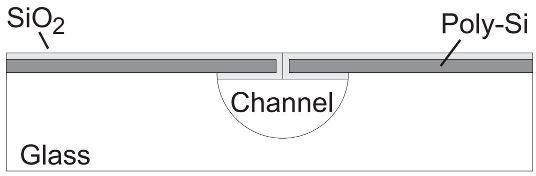


Figure 3.15: Sealed micro-channel in glass.

5. Propose a complete process based on KOH etching that could be used to produce the structure of Figure 3.16. Justify the use of a sandwich of SiO_2 and Si_3N_4. Could the two layers order be inverted?

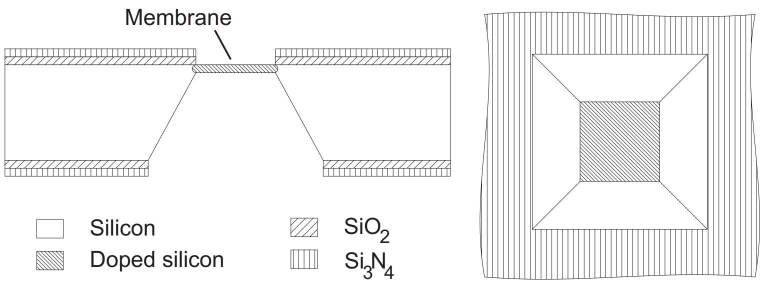


Figure 3.16: Membrane obtained by KOH etching.

Chapter 4

MEMS packaging, assembly and test

MEMS packaging, assembly and test problems are the aspects of the MEMS technology that are the less mature. Actually, although the bookshelves seems to be replete with books discussing all the aspect of MEMS technology, we had to wait until 2004 to finally have a reference book really discussing these three issues with real life examples [22].
The main problem faced by MEMS testing is that we now have to handle signal that are not purely electrical, but optical, fluidic, inertial, chemical... Then, verifying the absence of defect needs the development of specialized system and new strategies. Texas Instruments' DLP chip may have as many a 2 millions mirrors and simple math shows that testing them one by one during 1s would take approximately three weeks at 24h/day - clearly not a manageable solution. TI has thus developed a series of test that allows testing mirrors by group and still detect individual defect, like a sticking mirror. After testing at wafer level the chip are diced, put into packages and then goes through a burn-in procedure. They are then tested again before being finally approved. TI noticed that packaging introduced new problems if the environment wasn't clean enough and they now use a class 10 clean- room for the packaging of their DLP chips.
Actually, unlike the well-established and standardized IC packaging technology, MEMS packaging is still largely an ad-hoc development. The main efforts have been conducted within each MEMS manufacturer companies, and they have jealously kept their secret considered, with reason, as the most difficult step to bring MEMS to market. For inertial sensors, such as accelerometers and gyroscopes, the packaging problem is not so severe because they can be fully sealed and still probe the effects that they measure. In that case, the use of stress relieving submount and a maybe a wafer-level

bonded cap is all what's needed to be able to use modified IC packaging procedure. However the major hurdle will often be that MEMS needs interfacing to the external environment. The diversity of issue encountered has for the moment received no standard solution and the packages are then designed case by case.
Still, some tendencies are starting to emerge and for example sensitive component use first level packaging where a glass or silicon wafer is bonded on the chip, helping to maintain the MEMS integrity during dicing and further mounting in the package. Moreover this may help maintain tight hermeticity by using bonding technologies with limited permeability to gas, like glass to silicon anodic bonding or metal to silicon eutectic bond. The issue of water condensation during use just at the bad place inside the package, as foretold by Murphy 's Law, is what makes hermetic package a must and not only for pressure sensor. Texas Instrument DLP's packaging is complex because the tiny mirror won't survive harsh elevated temperature treatment including glass bonding. Thus a full independent hermetic package in metal with a transparent glass window had to be designed, including a getter for removing the last trace of humidity. The package is sealed under a dry nitrogen atmosphere with some helium to help check leaks.
For chemical and biological sensors, which must be exposed to liquids, the task is even more complex and the package can represent as much as 90% of the final cost.

Chapter 5

Challenges, trends, and conclusions

5.1 MEMS current challenges

Although some products like pressure sensors have been produced for 30 years, MEMS industry in many aspects is still a young industry. The heavily segmented market is probably the main reason why a consortium like SEMI is still to appear for MEMS. However everybody agrees that better cooperation and planning has to happen if the cost of the assembly, test and packaging is to come down. MEMS can currently only look with envy as IC industry seriously considers producing RFID chips for cents - including packaging.
Again the path shown by the IC industry can serve as a model, and standardization to insure packaging compatibility between different MEMS chip manufacturers seems the way to go. Considering the smaller market size of most MEMS component, standard is the only way to bring the numbers where unit packaging price is reduced substantially. This implies of course automating assembly by defining standard chip handling procedure, and probably standard testing procedure.
Of course, the diversity of MEMS market makes it impracticable to develop a one-fit-all packaging solution and the division in a few classes (inertia, gas, fluidic) is to be expected. For example, several proposals for a generic solution to fluidic interfacing have been proposed and could become a recommendation in the future.
In the other hand it is not clear if standardization of MEMS fabrication process à la CMOS will ever happen - and is even possible. But currently most of the cost for MEMS component happens during back-end process, thus it is by standardizing interfaces that most savings can be expected.

The relatively long development cycle for a MEMS component is also a hurdle that needs to be lowered if we want more company to embrace the technology.
One answer lies with the MEMS designing tool providers. The possibility to do software verification up to the component level would certainly be a breakthrough that is now only possible for a limited set of cases.
But it is also true that the answer to proper design is not solely in the hand of better computer software but also in better training of the design engineer. In particular we hope that this short introduction has shown that specific training is needed for MEMS engineers, where knowledge of mechanical and material engineering supplements electronic engineering. Actually, experience has often revealed that an electronic engineer with no understanding of physical aspect of MEMS is a mean MEMS designer.

5.2 Future trend of MEMS

Looking in the crystal ball for MEMS market has shown to be a deceptive work, but current emerging tendencies may help foresee what will happen in the medium term.
From the manufacturer point of view, a quest for lowering manufacturing cost will hopefully result in standardization of the MEMS interfacing as we discussed earlier, but finally will lead to pursue less expensive micro-fabrication method than photolithography. Different flavors of soft-lithography are solid contenders here and micro-fluidic and BioMEMS are already starting to experience this change. Another possibility for reducing cost will be integration with electronics - but, as we already discussed, the system-on-a-chip approach may not be optimal in many cases. Still, one likely good candidate for integration will be the fabrication of a single-chip wireless communication system, using MEMS switch and surface high-Q component.

From the market side, MEMS will undoubtedly invade more and more consumer products. The recent use of accelerometer in cameras, handphone or in the Segway is a clear demonstration of the larger applicability of the MEMS solutions - and as the prices drop, this trend should increase in the future. Of course medical application can be expected to be a major driver too, but here the stringent requirements make the progress slow. In the mid-term, before micromachines can wade in the human body to repair or measure, biomedical sensors to be used by doctors or, more interesting, by patients are expected to become an important market.
A farthest opportunity for MEMS lies probably in nanotechnology. Actually, nanotechnology is bringing a lot of hope - and some hype - but current fab-

rication techniques are definitely not ready for production. MEMS will play a role by interfacing nano-scale with meso-scale systems, and by providing tools to produce nano-patterns at an affordable price.

5.3 Conclusion

The MEMS industry thought it had found the killer application when at the turn of the millennium 10's of startups rushed to join the fiber telecommunication bandwagon. Alas, the burst of the telecommunication bubble has reminded people that in business it is not enough to have a product to be successful - you need customers.
Now the industry has set more modest goals, and if the pace of development is no more exponential it remains solid at 2 digits, with MEMS constantly invading more and more markets. Although the MEMS business with an intrinsically segmented structure will most probably never see the emergence of an Intel we can be sure that the future for MEMS is bright. At least because, as R. Feynman [23] stated boldly in his famous 1959 talk, which inspired some of the MEMS pioneers, because, indeed, "There's plenty of room at the bottom"!

Chapter 6

References and readings

6.1 Online resources and journals

`http://www.smalltimes.com/` the free international press organ of the MEMS–NEMS community.

`http://www.mstnews.de/` free news journal on European microsystem technology

`http://www.dbanks.demon.co.uk/ueng/` D. Banks renowned "Introduction to microengineering" website with plenty of information.

`http://www.aero.org/publications/aeropress/Helvajian/` The first chapter of 'Microengineering Aerospace Systems' co-authored by M. Mehregany and S. Roy and edited by H. Helvajian is online and makes a short, although slightly outdated, introduction to MEMS.

IEEE/ASME Journal of MEMS This journal originally edited by W. Trimmer, is arguably one of the best journal in the field of MEMS (`http://www.ieee.org/organizations/pubs/transactions/jms.htm`).

Sensors and Actuators A That is the most cited journal in the field, with a copious variety of research work (`http://www.elsevier.com/wps/product/cws_home/504103`).

Sensors and Actuators B Catering mostly for Chemical Sensor papers, they also have issue on MicroTAS, where you find numerous microfluidics and Bio-MEMS papers (`http://www.elsevier.com/wps/product/cws_home/504104`).

Journal of Micromechanics and Microengineering A good European journal edited by IOP with all types of MEMS (http://www.iop.org/EJ/S/3/176/journal/0960-1317).

Smart Materials and Structures Another IOP journal, with editor V. Varadan, that has a more material oriented approach than his cousin (http://www.iop.org/EJ/S/3/176/journal/0964-1726).

Microsystem Technologies A Springer journal that favors papers on fabrication technology and particularly on high-aspect ratio (LIGA like) technology (http://link.springer.de/link/service/journals/00542/index.htm).

Journal of Microlithography, Microfabrication, and Microsystems A recent (2002) Journal from the SPIE (http://www.spie.org/app/Publications/index.cfm?fuseaction=journals&type=jm3).

Sensor Letters A new (2003) journal covering all aspects of sensor science and technology (http://www.aspbs.com/sensorlett/).

Biomedical microdevices A Bio-MEMS journal (http://www.wkap.nl/journalhome.htm/1387-2176).

Biosensors and Bioelectronics Another Bio-MEMS journal with more emphasis on sensors (http://www.elsevier.com/wps/product/cws_home/405913).

IEEE Transaction on Biomedical engineering Bio-MEMS and biomedical application can be found here (http://www.ieee.org/organizations/pubs/transactions/tbe.htm).

IEEE Photonics Technology Letters Highly cited photonics journal publishing short papers, including optical MEMS or MOEMS (http://www.ieee.org/organizations/pubs/transactions/ptl.htm).

IEEE/OSA Journal of Lightwave Technology A good quality photonics journal regularly featuring some optical MEMS work (http://www.ieee.org/organizations/pubs/transactions/jlt.htm).

6.2 Other MEMS ressources

http://www.memsnet.org/ the MEMS and nanotechnology clearinghouse.

`http://www.memsindustrygroup.org/` the MEMS industry group aimed at becoming a unifying resource for the MEMS industry. Will hopefully initiate standardization effort and eventually establish a MEMS roadmap.

`http://www.yole.fr/` one of the MEMS industry watch group publishing regular report on the market.

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