MicroElectroMechanical Systems:

MEMS Technology

Overview and Limitations

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1 Introduction to MEMS

Micro-Electro-Mechanical-Systems (MEMS) technologies can be used to produce structures, devices and systems on the scale of micrometers. Our goal is to closely look at MEMS and outline the main benefits and limitations of this cutting edge technology. In the process, we will investigate MEMS applications, fabrication processes, and the future of MEMS, namely Nano-Electro-Mechanical-Systems (NEMS).

Although there are many technologies available to miniaturize devices, the acronym MEMS is used almost universally to refer to all devices that are produced by microfabrication or micromachining except Integrated Circuit (IC) or other conventional semiconductor devices; micromachining is any process that deposits, etches or defines materials with minimum features measured in micrometers or less. The general field of miniaturization is known as other names as well, namely MicroSystems Technology (MST) which is popular in Europe, and MicroMachines which is popular in Asia.

MEMS represent the combination of semiconductor processing and mechanical engineering, however at a very small scale. It is interesting to note that the first MEMS device was a gold resonating MOS gate structure in 1967. [17] MEMS became firmly established in the mid-1980s; the technology has now matured to a level where many real-world applications can be implemented and utilized. As a general rule of thumb, MEMS typically have dimensions ranging from nanometers to centimeters; however, very little has been done with MEMS below one micrometer. On the contrary, recent developments in IC technologies can now mass produce chips with features as small as 0.13 microns; the new Intel Pentium 4 processor running at 2.2 to 2.4 GHz is one such example [12]. SEMATECH, a think-tank of semiconductor companies in the US, predicts that the minimum feature size will shrink to 0.07 microns (70 nanometers) by the year 2010. [13]

MEMS are the integration of mechanical elements such as sensors and actuators with electronics on a common silicon substrate through utilization of microfabrication technology. ICs can be thought as the "brains" of the system while the MEMS augments this decision making capability with "eyes" and "arms" to allow the microsystem to sense and control the environment. In the most basic form, the sensors gather information from the environment through measuring mechanical, thermal, biological, chemical, optical, and magnetic phenomena; the electronics process the information derived from the sensors and hence direct the actuators to respond by moving, positioning, regulating, pumping, and filtering, in order to control the environment for some desired outcome or purpose. [20]

2 MEMS Applications

MEMS devices can be classified into two categories, mainly sensors and actuators. Sensors are non-intrusive while actuators modify the environment. Micro sensors are useful because of their small physical size which allows them to be less invasive. Micro actuators are useful because the amount of work they perform on the environment is also very small, and therefore it can be very precise. Some typical examples of MEMS technology are polysilicon resonator transducers, high aspect ration electrostatic resonator, magnetic micro motors, precision engineered gears, etc.

MEMS are already in wide use in the automotive industry, and are beginning to penetrate other industries as well, such as Nation Defense, etc. For example, MEMS are utilized for engine oil pressure, vacuum pressure, fuel injection pressure, transmission fluid pressure, ABS line pressure, tire pressure, stored airbag pressure, various temperature throughout an automobile, active suspension systems, etc. MEMS accelerometers can also be used to trigger airbags or lock seat belts in the event of an accident; it has been shown that the cost per sensor and the failure rate is dramatically reduced when it is built on the microscale rather than on the macroscale. For example, the conventional approach uses several bulky accelerometers made of discrete components which are separate from the electronics near the airbag and costs over $50 for each set; MEMS has made it possible to integrate onto a single silicon chip the accelerometer and needed electronics that is only a small fraction of the size for under $5. [2]

One application of MEMS is “Smart Dust”, a project being undertaken at UC Berkeley. The goal is to explore the limits on size and the power consumption in autonomous sensor nodes. The size reduction will be a major challenge since the functionality of

Smart Dust will require that the nodes have requisite sensing, communication, computing hardware, and power supply all in a volume no more than a few cubic millimeters without sacrificing the performance of the node. With a cubic millimeter volume, using the best available battery technology, the total stored energy is limited to the order of 1 Joule. [10] With energy as the most precious resource, and time not as likely to be as likely to be critical, elementary operations and algorithms are likely to be judged in terms of their energy cost. Energy-optimized microprocessors use roughly 1 nano-Joule per sample. For comparison purposes, Bluetooth radio frequency (RF) communication chips will burn about 100 nano-Joules per bit transmitted; picoradios will be targeting 1 nano-Joules per bit. [9]

Another application is to make micro-robots using the Smart Dust technology; if we add legs and wings to the already existing Smart Dust, we get micro-robots that can sense, think, communicate, move, and interact with their environment. Micromachining is used to build microactuators and micromechanisms, forming the legs and wings. A crawling micro-robot consumes only tens of microwatts of power generated by solar cells while it can lift over 130 times its own weight. The flying micro-robot has 10 to 25 mm wingspan and can maintain autonomous flight. Developers folded 50 micron thick stainless steel into the desired shape the wings and the exoskeleton. Piezoelectric motors attached to the exoskeleton actuate the wings. The power consumption will be less than 10 milliwatts which will be provided by an onboard solar cell. [6]

Another application coming from the same group at UC Berkeley in [7] is an electrostatic linear inchworm motor. This family of motors is fabricated on Silicon-on-Insulator wafers using only a single mask. The authors demonstrated the fabrication of the inchworm motor measuring 3000 μm by 1000 μm by 50 μm that can lift 130 times its own weight. The motor can achieve a travel of 80 μm and a calculated force of 260 μN at 33V. The force density of the motor was 87 $\mu N/mm^2$ at 33V and the energy efficiency was estimated at 8%. The motor was cycled 23.6 million times for over 13.5 hours without stiction. [7]

Although microactuators are less mature than that of microsensors due to the initial lack of appropriate applications and the difficulty to reliably couple the microactuators to the macroscopic world, there quite a few techniques that have evolved. To name a few, there are electrostatic microactuators [32], thermal microactuators [33], magnetic microactuators [34], piezoelectric microactuators [35], etc. Since most microactuators are custom developed for specific applications, no microactuator standards yet exist.

MEMS promises to revolutionize nearly every product category by brining together silicon-based microelectronics with micromachining technologies, and therefore bring the system-on-a-chip or microsystems to reality. MEMS technologies is enabling new discoveries in science and engineering such as Polymerase Chain Reaction (PCR) microsystems for DNA amplification and identification, the micromachined Scanning Tunneling Microscopes (STMs), biochips for detection of hazardous chemical and biological agents, microsystems for high-throughput drug screening and selection, optical switches, valves, RF switches, microrelays, electronic noses, etc. Although the existing market for microsystems is dominated by pressure sensors, strain gauges, inertial sensors, chemical sensors, in vitro diagnostics, infrared imagers and magnetometers, capacitive position detection, thermal sensors, biosensors, there is also a relatively large market segment specializing in recording magnetic heads and inkjet printer heads. [21]

The fabrication of microsystems is one of the greater achievements of microfabrication; microsystems consist of microsensors (input), circuits (processing), and microactuators (output). The power supply would ideally be miniaturized to the same scale; however, this still presents a great challenge. Communication with the microsystems would be done via a direct connection or a wireless communication link. [36] The micro total analysis system (μTAS) [37] allows very complex chemical analysis due to the ability of electronically controlling fluid flow in micromachined channels. As we stated earlier, much work has been done in genetic analysis by polymerase chain reaction (PCR) [38]; because of the much lower thermal mass of the reaction chamber, the cyclic process is much faster, and therefore the analysis is also faster. Microsystem can also be utilized for gene detection; because of the miniaturization and improved methods, a single 1 cm^2 chip with a 50 μm probe area can test over 40000 different compounds at the same time.

3 MEMS Fabrication Processes

Typically, a MEMS device is first designed with a Computer Aided Design (CAD) tool. There are many tools currently available from companies such as MEMSCAP Inc. [4] which allow the user to design a MEMS device, optimize it, simulate it, verify its functionality, and generate its layout. Existing CAD tools compute the equilibrium solutions in a lengthy iterative process. Ideally, the MEMS CAD tool would be capable of rapid solving, mechanical, thermal, electrostatic, magnetic, fluidic, RF, and optical solutions in a coupled fashion. This layout is then sent to a foundry, where the chip is fabricated, a mask-less post-processing release step is performed where sacrificial layers are etched away, allowing the structural layers to move and rotate. Following the release, the devices are assembled and tested. [16]

Unfortunately, the cost of a microfabrication facility capable of producing MEMS is prohibitively expensive for most companies and universities. In order to maximize the utility of the foundries, some microfabrication facilities make their processes publicly available for modest fees. The most prominent MEMS foundries include MUMPS process by Cronos [28], the SUMMiT process by Sandia National Laboratories [29], the iMEMS process by Analog Devices [30], and the IC foundry broker MOSIS [31].

There are two main fabrication classes for manufacturing MEMS devices, namely surface micromachining [18] and bulk micromachining [19]. Some other micromachining processes are: deep reactive ion etching (DRIE) [26], substrate bonding [21], LIGA [22], SU-8 [23], plastic molding with PDMS [24], micromolding (HEXSIL) [27], etc. The permutations of materials and processes for depositing and etching make it impossible to discuss them in sufficient detail. For a thorough understanding of deposition and etching processes, the reader is directed to the book by Madou [25].

Surface micromachining is an additive fabrication technique which involves the building of the device on top the surface of the supporting substrate. This technique is relatively independent of the substrate utilized, and therefore can be easily mixed with other fabrication techniques which modify the substrate first. An example is the fabrication of MEMS on a substrate with embedded control circuitry, in which MEMS technology is integrated with IC technology. Surface micromachining has been used to produce a wide variety of MEMS devices for many different applications; some of the commercially available MEMS devices were fabricated in large volumes of over 2 million parts per month. [18]

On the other hand, bulk micromachining is a subtractive fabrication technique which converts the substrate, typically a single-crystal silicon, into the mechanical parts of the MEMS device. Packaging of the device tends to be more difficult, but structures with increased heights are easier to fabricate when compared to surface micromachining. This is because of the substrates can be thicker resulting in relatively thick unsupported devices. [19] Exploiting the predictable anisotropic etching characteristic of single-crystal silicon, many high precision complex three-dimensional shapes, such as V-grooves, channels, pyramidal pits, membranes, vias, and nozzles can be achieved. [21]

4 Future of MEMS: NEMS

NEMS stands for Nano-Electro-Mechanical-Systems is the technology that is similar to MEMS, however it involves fabrication on the nanometer scale rather than the micrometer scale. According to Michael Roukes in [13], NEMS can be built with masses approaching a few attograms (10^{-18} grams) and with a cross-section of about 10 nanometers.

Processes such as electron-beam lithography and nanomachining now enable semiconductor nanostructures to be fabricated below 10 nm. Although the technology exists to create NEMS, there are three principal challenges that must be addressed before the full potential of NEMS can be realized. First of all, communicating signals from the nanoscale to the macroscopic world can pose a great challenge. Understanding and controlling mesoscopic mechanisms is still at the very early stages. Thermal conductance in this regime is quantized, which implies that quantum mechanics places an upper limit on the rate at which energy can be dissipated in small devices by vibrations. Lastly, we do not have the methods for reproducible and routing mass nanofabrication; device reproducibility is currently very hard and almost unachievable. It is clear that if NEMS are ever to become a reality, cleaner environments and higher precision of nanofabrication techniques are needed. [13, 14]

As we shrink MEMS towards the domain of NEMS, the device physics becomes increasingly dominated by the surfaces. We would expect that extremely small mechanical devices made from single crystals and ultrahigh-purity heterostructures would contain very few defects; therefore, the energy loses are suppressed and higher quality factors should be attainable. [15]

In the 1820s, Charles Babbage designed the first mechanical computer. In the 1960s, the idea of a mechanical computer was abandoned as the modern electronic logic gates and IC were discovered and could operate at nanosecond granularity. However, with the possibility of NEMS which can move on timescales of a nanosecond or less, the era of the digital electronic age needs to be carefully re-examined.

5 Scaling Issues with MEMS Technology

When miniaturizing any device or system, it is critical to have a good understanding of the scaling properties of the transduction mechanism, the overall design, and the material and the fabrication processes involved. The scaling properties of any one of these components could present a great challenge. Since MEMS devices can be thousands of times smaller than their macroscale counterparts, we cannot expect that the macroscale phenomena and designs will transfer directly to the microscale.

According to K.S.J. Pister from UC Berkeley and other researchers, MEMS performance is inversely related to size. The raw sensitivity of most sensors decrease, however the frequency response should improve. The fundamental limit of most MEMS sensor system is thermal noise. Temperature, the vibration of molecules, causes all mechanical and electrical devices to jitter around with an average kinetic energy of a few thousands of a billionth of a billionth of a Joule. While objects on the macroscale are virtually unaffected by this small amount of energy, MEMS devices that are built on the microscale and are very sensitive to this small amounts of energy. [1]

The proof mass of a particular accelerometer MEMS device is about the size of a pollen grain which Robert Brown saw through his microscope in 1827. The real problem is that the accelerometer's usefulness is questioned if random collisions with air molecules cause it to bounce around in Brownian motion. One partial solution to the accelerometer's size limit is to run the sensor in a vacuum; this can lead to dramatic improvements in thermal noise performance for most sensors. Without loss of generality, we can assume all MEMS devices will have a lower limit on the size to which we can miniaturize them; they must be either massive or stiff enough so they are not greatly influenced by the particular phenomena they are sensing or interacting with. [1]

In the next few paragraphs, we will attempt to cover the limitations or barriers that MEMS technology will face with various systems, materials used, or technologies employed. We will cover the scaling of material properties [39], mechanical systems [39], electrical and magnetic systems [46], thermal systems [25], optical systems [22], fluidic systems [40], chemical and biological systems [41], microbearing surfaces [43], electrostatic microactuators [44], microvalves [21], and finally micropumps [45].

It should be no surprise that the material properties will be different when scaled down to the microscale. The homogeneity we commonly associate with macroscale devices is virtually non-existent, and therefore becomes unreliable when used to model devices that have dimensions on the scale as individual grains; it should be clear MEMS produced either together or from different batches can have varying material characteristics. One the other hand, one of the advantages of scaling MEMS to densities approaching the defect density of material is that devices can be produced with a very low defect count. [39]

When scaling mechanical systems, it is interesting to note that relationship between the mass, volume, and mechanical strength of objects. When the linear dimensions of an object are reduced by x, the volume and hence the mass is reduced by a factor of x^3. On the other hand, the mechanical force is reduced by x while the inertial force it can generate is reduced by x^3. A major benefit of this phenomenon is that MEMS can withstand tremendous accelerations (more than 100,000 g force acceleration) without braking. A negative consequence is that devices requiring proof masses must have much higher sensitivity. [39]

Scaling of electrical systems has shown much success, especially as the IC industry has proved that 0.13 micron feature sizes are possible in mass production. On the other hand, magnetic systems pose a challenge since the maximum energy density of magnetic actuators is on the order of 10,000 times larger for macroscopic devices when compared to their microscopic counterparts. Therefore, the macroscopic assumption that material has enough domains (regions of material with uniform magnetization typically on the scale of micrometers) to ignore them individually and therefore consider only the average will not be valid; we need new more complex models for accurate and reliable prediction of experimental results. If magnetic MEMS are reduced to dimensions smaller than typical the typical domain, then the behavior will be dominated by single-domain phenomena. [46]

When scaling thermal systems, it is important to realize that as the linear dimensions of an object are scaled down by x, the thermal capacitance times the volume is reduced by x^3 and the rate of heat transfer is reduced by x^2. Since it is easy to microfabricate delicate structures and only allows heat conduction along paths of very high thermal resistance, it is also simple to achieve very good thermal isolation. On the other hand, submicron structures properties change since the dimension of the elements are on the same scale as quantum mechanics lattice vibrations responsible for carrying heat waves. [25]

Scaling optical systems has been quite successful with the production of LEDs, lasers, mirrors, etc. Due to the wavelength of visible light (475 nm for blue and 650 nm for red), the dimensions of these optical systems cannot be any smaller than these values. The behavior of scaled optical components is well predicted by existing equations. [22]

Although we commonly observe turbulent and chaotic fluid flow in most macroscopic systems, fluid flow in microscopic systems is almost entirely dominated by laminar flow conditions; as the dimensions of the fluidic system is reduced by *x*, the measure of flow turbulence is also reduced by *x*, and therefore fluid becomes more laminar the more it is reduced. Because of this behavior, it is very challenging to achieve thorough mixing in microfluidic systems. [40]

The scaling of chemical and biological systems is limited by a fundamental tradeoff between sample size and detection limit. As the sample size is reduced, the total molecules which need to be detected are also decreased, and therefore an increasing sensitive detector will be needed, but there is an obvious cut-off at detecting a single molecule. The miniaturizing of systems interfacing with biology also have limitations based on their applications; for example, for a device to be able to manipulate cells, the device must be on the scale of 5 to 20 μm, while devices that must interface with DNA can be arbitrarily smaller. [41]

To enable fully free structures capable of unlimited rotation or translation, microbearing surfaces are needed; bearing hubs and sliders respectively. In-plane rotary hubs enable the development of micromotors and complex gear trains. A serious issue with microbearing surfaces is that the amount of mechanical slop is a large percentage of the size of the bearing elements; the relative tolerances in MEMS are typically much worse than that easily achieved with conventional machining techniques – approximately 10 and 0.1% respectively. [25] Due to poor relative tolerances, the lack of sufficient lubrication and poor bearing surface materials, MEMS with bearing surfaces experience considerable wear and fail after prolonged testing [43]. Also, although electrostatic forces are proportional to the square of the applied voltage, typically tens of hundreds of volts are needed to generate enough force (a few μN) to achieve actuation on the order of a few micrometers. [44]

The performance of microvalves compares favorably with those of the macroscopic solenoid valves. Actually, microvalves have longer operational lifetimes and typically operate faster. However, since microvalves are typically driven by thermal transduction mechanisms, their power consumption is relatively high, on the order of 0.1 to 2 W; because of this, valve temperatures might easily exceed the tolerated fluid or gas media being controlled. [21] As for micropumps, they work rather well, however they require high voltages on the order of 100 V for significant pumping to occur. Some fluids cannot tolerate aggressive mechanical pumping without degradation, and therefore careful designing must be made that is application specific. [45]

Just as there are many obstacles to overcome technically, there are also major barriers in standardization. IEEE is working on eliminating some of these obstacles by creating standards for smart sensors (IEEE 1451), however standardization is far from being complete. In specific, CAD tools are inadequate at the level they are currently at in order to achieve smooth design from the drawing board, to simulations, to implementations.

6 Concluding Remarks

The potential exists for MEMS to establish a second technological revolution of miniaturization that may create an industry that exceeds the IC industry in both size and impact on society. Micromachining and MEMS technologies are powerful tools for enabling the miniaturization of sensors, actuators and systems. In particular, batch fabrication techniques promise to reduce the cost of MEMS, particularly those produced in high volumes. Reductions in cost and increases in performance of microsensors, microactuators and microsystems will enable an unprecedented level of quantification and control of our physical world.

Although the development of commercially successful microsensors is generally far ahead of the development of microactuators and microsystems, there is an increasing demand for sophisticated and robust microactuators and microsystems. The miniaturization of a complete microsystem represents one of the greatest challenges to the field of MEMS. Reducing the cost and size of high-performance sensors and actuators can improve the cost performance of macroscopic systems, but the miniaturization of entire high-performance systems can result in radically new possibilities and benefits to society.

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