CHAPTER 1

Introduction

If you want to view paradise,

Simply look around and view it.

Anything you want to, do it.

You can change the world, There's nothing to it.

Willie Wonka

We are entering a golden age of MEMS. Tremendous progress has been made in the last decade on materials and processes at the micron to millimeter scale. We now have a solid understanding of most of the energy domains and interactions at this scale, and CAD support is emerging which is capable of predictive modeling. In short, if you can dream it up, and it doesn’t violate the laws of physics, we can probably build it!

Physics in the MEMS world is fundamentally just the same as the physics of macroscopic systems, but all of the coefficients are funny. Frictional forces, for example, are tremendously important, and as a result most designs utilize flexures instead of bearings. Electrostatic forces dominate over magnetic forces, so most MEMS motors use electrostatics. Thermal systems can have time constants in the microsecond range, so it is possible to make very fast shape memory actuators. Air starts to look like molasses. Gravity is not important. Mechanical time constants are in the microsecond to millisecond range. Surface effects dominate: surface tension and Van del Wahls forces can destroy structures.

For many years the conventional wisdom in the field was that things were changing too rapidly for a text book to have any longevity or relevance. Over the last five years, however, it has become clear that there are core concepts that any student of the field should know. While things are still changing rapidly, the fundamental principles remain the same.
I’ve been trying to build micro robots since 1990. As a graduate student at UC Berkeley in the late 1980s, I started off with a very process-centric view of MEMS. The field at that time was dominated by people inventing new processes to make new devices, or to make the same devices in a better way. The only players in MEMS were those research labs (mostly academic) fortunate enough to have their own clean rooms for semiconductor fabrication.

Lots of people published papers on processes and devices, very few published papers on applications, and almost no one published anything on systems. I was inspired by the title of the early conferences in the field: the Micro Robots and Micro Tele-operators Workshop. My goal for my PhD was to make a micro robot, but I ended up developing and demonstrating a process that might be useful in making micro robots. The robots themselves elude me to this day.

Leaving Berkeley I went to UCLA, which at the time had a beautiful brand new clean room, with almost no equipment in it. Faced with the choice between pouring my soul into developing a new clean room for a few years or switching research directions, I opted for the new direction, which turned out to be MEMS design. Shortly after I arrived at UCLA as an assistant professor, Karen Markus and her colleagues at MCNC created a new MEMS fabrication service called MUMPS, the Multi-User MEMS Process Service. MUMPS provided low-cost access to MEMS fabrication to those who didn’t have their own clean room.

Given the opportunity to think about the design of MEMS, and without the opportunity to make contributions in the development of new MEMS processes, a new breed of MEMS researcher was born, the designer. From the traditional process-centric MEMS perspective, the new designers had the curse of working in a single process without any control over design parameters. This curse, however, turned out to be a blessing.

In this text I present a design-centric (rather than process-centric) view of this exciting technology. I hope that you enjoy it as much as I do.

A little history

In 1947, Bardeen and Brattain published a paper describing the “semiconductor triode”, which we now call a transistor. In 19xx, Gordon Moore predicted that the number of transistors which could fit on a silicon chip would double every 18 months. This remarkable prediction has held true for decades, and has become
known as Moore’s Law. This law predicts chips with nearly 10 billion transistors in 2010.

The semiconductor industry has perfected the art of miniaturizing construction. Like Bardeen and Brattain’s first transistor, the modern transistor is a three dimensional sculpture combining many different materials in precise alignment. In the late 1980s it became apparent that these were just the characteristics needed to make micro mechanical devices as well. A new field was born: Micro ElectroMechanical Systems.

The first major milestone in the evolution of silicon from electronics to electromechanics was the discovery of piezoresistivity in silicon in 1954. This led fairly quickly to the first silicon strain gauges sold commercially in 1958, and the first silicon pressure sensor in 1961. Pressure sensors continue to be a thriving sector of the MEMS market, with annual sales of billions of dollars. Shortly after the first pressure sensors were sold, silicon accelerometers were demonstrated. Both the pressure sensors and the accelerometers through the late 1980s were made by etching parts of the silicon substrate, in a general family of processes known as bulk micromachining.

The modern age of micromachining was foreshadowed in 1967 by Narvey Nathanson and others at Westinghouse, who developed a transistor with a moving mechanical element. These devices were made only by adding and removing material above the surface of the silicon wafer. In contrast to bulk micromachining, in which structures are made in the silicon wafer itself, this approach to MEMS fabrication is known as surface micromachining.
FIGURE 1. A semiconductor triode (the first transistor). Note that the symbol for the bipolar transistor is based on the shape of this first device, and in fact the name of one of the terminals (the base) is a reference to the mechanical structure of this first device!

The mechanical element in the Westinghouse device was metal, and the semiconductor processing technology of the day was still challenging in its own right, so the technology languished for nearly two decades until Roger Howe, then a student of Richard Muller’s at UC Berkeley, made a similar device using silicon as the structural material in 1984. Between the improved material properties, and the relative sophistication of the basic semiconductor processes available in the mid 1980s, surface micromachining technology took off.

The emergence of surface micromachining as a viable alternative to bulk micromachining had several important implications. The first was that it was much more amenable to integration with electronic circuit fabrication processes. Second was that surface micromachined devices were much more amenable to the structured design methodology of integrated circuits. A third important result was that it allowed the fabrication of a bunch of “gee-whiz” devices that captured the fancy of laymen and experts alike.
A little history

FIGURE 2. The Intel Pentium. 3.3 million transistors, 133 MHz, 0.35 micron lithography, 4 layer metalization, first silicon in May 1995.

A less important result of the emergence of surface micromachining was the creation of an on-going battle between researchers in the two camps over which approach is better. As we will see in the coming chapters, the distinctions between surface and bulk micromachining are growing increasingly fuzzy, and the debate is slowly dying away.

**FIGURE 4. ADXL50 accelerometer. The first surface micromachined product.**

ADXL50

The first surface micromachined product was introduced by Analog Devices in 199x (1?). The product was the ADXL50, an accelerometer with a 50G sensing range designed for the automotive airbag application. The ADXL50 consists of a 2 micron thick silicon mass, much less than a millimeter square, suspended above the surface of a silicon integrated circuit with springs too small for the unaided eye to see. Dozens of silicon fingers sticking off the side of the mass interact with similar fingers bolted onto the surface of the chip, forming an array of capacitors whose capacitance is a function of the position of the mass itself.

Newton tells us that the mass tends to remain where it is when the chip is accelerated, leading to a displacement of the mass relative to the chip, and a corresponding change in capacitance. The change in capacitance is detected with integrated circuitry built alongside the electro-mechanical elements. When a deflection of the mass is detected, a voltage is applied to some of the fingers, resulting in an electrostatic force which pulls the mass back to its rest position.

The entire system, including the mass, springs, variable capacitors, capacitance sensing circuitry, and electrostatic force feedback, fits on a sliver of silicon only 3
mm on a side. The displacements that are sensed are measured in Angstroms, and the entire system, packaged, tested, and calibrated, sells for a few dollars in large quantities.\textsuperscript{1}

Richie Payne at Analog was the driving force behind the ADXL50, shepparding the technology from academic curiousity to large scale manufacturing. While the financial wisdom of the project is subject to debate\textsuperscript{2} the product family has grown dramatically, and the ADXL50 is certainly the poster child of the MEMS revolution.

\textbf{TI DMD}

Texas Instruments has it’s own story of good money thrown after bad, ultimately leading to another truly amazing product, the TI Digital Mirror Device.

\begin{itemize}
\item[1.] As of 2000, Analog Devices sells more than a million accelerometers a month, and the number is continuously growing.
\item[2.] Richie himself likes to claim that “it’s not everyone who can get a company to lose 200 million dollars”
\end{itemize}
Digital Mirror Device. Each chip contains hundreds of thousands of mirror cells. Each cell contains a fifteen micron square moving aluminum mirror suspended above a one bit memory cell.

FIGURE 5. 

FIGURE 6. The Resonant Gate Transistor, the first surface micromachined device.

FIGURE 7. Roger Howe’s resonant vapor sensor.
A little history

FIGURE 8. First Hinge.
Introduction

What are MEMS?

There have been many fights over the definition of MEMS. Whether the definition is based on fabrication technology or feature size, there are always borderline and grey areas that don’t fit. I know MEMS when I see them!

In one on-line fight over who had made the tallest MEMS structure, Greg Kovacs from Stanford made a humorous but insightful comment that he had glued a pencil onto a silicon wafer, and therefore made the tallest MEMS structure!\(^1\)

One of the recurring themes in MEMS is integration. In many cases this is the integration of electro-mechanical devices, e.g. sensors and actuators, with electronics.

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\(^1\) See archives of mems@isi.edu mailing alias at mems.isi.edu
In other cases it is the integration of multiple elements in the same domain, such as different microfluidic channels and cavities.

**What MEMS is not**

MEMS is not precision engineering. Tolerances on our structures are often measured in tenths of microns. Tolerances in an automobile engine can be tighter than that! With care, meter-scale structures can be manufactured with nanometer tolerances, which put most MEMS tolerances to shame. A naive assumption is that because our feature sizes are small, our precision must be correspondingly impressive. Unfortunately, this is not the case.

MEMS is not nanotechnology. While in some cases MEMS devices have features that are measured in nanometers, MEMS and nanotechnology are fundamentally different. MEMS devices operate with dynamics that are determined by modeling matter as a continuum. Nanotech looks at quantum effects. MEMS devices are built using integrated circuit techniques, whereas the philosophy in nanotechnology is that devices are built using chemistry.

MEMS is not miniaturized macro-fabrication techniques. A Japanese automotive components manufacturer built a working model of the first Toyota automobile that was only a few millimeters long. It contained an electromagnetic motor, wheels, a body. It was an amazing testament to engineering, but it wasn’t MEMS.

MEMS is not tiny features. Ghiradelli chocolates once sold a candy bar that had a hologram molded into it. Is that MEMS?

Finally, examples can be found which violate all of the above, so you need to be the judge. MEMS is what you say it is.

**MEMS Design**

MEMS design is the art of taking a concept and turning it into a combination of geometry and process that can be fabricated. Both the geometry and the process require design, and both are very rich and beautiful canvases. Throughout the 1980s and into the early 1990s, the vast majority of the research publications in MEMS were related to process design. The process designers can rightly claim that the geometry designers could not exist without them. Toward the mid 1990s, however, a new breed of MEMS designer appeared. This new MEMS designer did not
have the luxury of a MEMS process development lab, and in fact had to rely on others to do his fabrication for him. As a result, the new MEMS designer focused his efforts on the geometric design problem.

The IC Design Cycle

One of the great innovations in the design of ICs (integrated circuits) was the development of abstractions which let the designer separate the design process from the fabrication process. This enabled IC designers to concentrate on what they were good at, instead of spending their time worrying about how long the wafers were supposed to stay in the furnace. This abstraction opened the doors to legions of new circuit designers. Whereas before circuit design was mainly done by people who did the processing, after the revolution circuits could be designed by anyone.

The IC design revolution traces its roots to two events: the formation of MOSIS, and the publication of a book by Carver Mead and Lynn Conway.

The (traditional) MEMS Design Cycle

Traditionally the MEMS design cycle began with the design of the process. The geometric design was considered to be secondary, and less important, because the process had been designed to get the job done, and the geometry was just “obvious”.

FIGURE 10. Traditional MEMS design cycle.
Foundries and the New MEMS Design Cycle

The new MEMS design cycle looks much more like the IC design cycle than it used to. While it is true that there is still tremendous interest and need for new process design, there is now a solid community of MEMS researchers who do not have their own clean room, and yet still manage to do world class research and development. This is due to a number of commercially available fabrication options for MEMS. The most popular of these is the Cronos Multi-User MEMS Process Service, or MUMPS process.

Cronos/MUMPS is based on an idea that was popularized by MOSIS: if individual users can’t afford the cost of a full wafer run, then collect designs from around the country and combine them together in one run, sharing the cost among all of the participants. MOSIS did this for CMOS, Cronos did it for MEMS. Whereas MOSIS does not actually have any fab capability itself, Cronos has a full MEMS clean room itself.

One interesting byproduct of the MOSIS service was that some of the heaviest users of a given process were often designers from the company providing the service.

Foundries changed the MEMS landscape by opening the doors to the rest of the world. No longer is MEMS restricted to the small club of clean room owners. It is available to the masses.
Introduction

FIGURE 12. The MOSIS foundry model.

FIGURE 13. Sandia micromirror driven by a gear train with a combination lock.
FIGURE 14.

Closeup of Sandia gears and 24 bit locking mechanism.

CAD for MEMS

SUGAR available on the web

layout tools available on the web?

lots of matlab exercises

no FEA

References

Petersen, Silicon as a Mechanical Material, Proc. IEEE 1986


Introduction


IEEE MEMS conference web site?

IEEE/ASME JMEMS web site?

Solid State Sensor and Actuator Conference (Transducers)

Solid State Sensor and Actuator Workshop (Hilton Head)

Problems

1. How many lasers do you have in your home? (CDs, pointers, ...)
2. How many motors do you have in your car?
3. How many sensors do you have in your home? How many have a minimum size necessary for their performance?
4. On the web, find examples of MEMS companies that sell: pressure sensors, accelerometers, mirrors for displays, mirrors for fiber switches, micromanipulators, bioMEMS, MEMS packaging, and CAD for MEMS.
5. 