Microfabrication for MEMS: Part I

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*** With thanks to Steve Senturia, from whose lecture notes some of these materials are adapted.**

Outline

- A way to think about process design
- Surface and bulk micromachining concepts
- Next class: substrates, lithography and patterning, and thin films
- Class #3: etching, wafer bonding (including bulk micromachining), surface micromachining and process integration
- Class #4: in class process design exercise
- Class #5: fabrication for the life sciences and material properties

Learning to “speak” fab

- There are huge lists of things that you can and can’t do in microfab (vocabulary)
- There are limits on how you can combine steps together to form a process (grammar)
- An experienced microfabricator knows most of these capabilities and limits from long experience (fluency)
- A beginning microfabricator must struggle to master details and rules
- Our goal: teach enough vocabulary and grammar to get you started (today starts with grammar)
- Only practice will make you fluent!

The promise and the pain

- Microfabrication can produce a near infinite array of structures
- But making your particular structure can be very difficult!
- You'd think it would be easy…
  - Functional requirements dictate materials and geometry
- … but it's not! Fabrication processes are not ideal.
  - Materials property variability
  - Geometric variability
- Early phase design must seek a self-consistent solution to the question of "what will I make and how will I make it?"
- But for that, we must be familiar with our tools and how they work

Crayon Engineering

> **At the early stages of MEMS design, conceptual process design rather than highly detailed process design is required**

> **It is necessary to obey**
> - **The laws of physics**
> - **Constraints on temperatures**
> - **Constraints on chemical compatibility**
> - **Design rules on geometry**

> **But we can draw our processes with crayons**
> - **Hence the phrase "crayon engineering"**

> **As we approach the final design, we need CAD tools**

Making integrated circuits

Wafers in

↓

1. The Front End (creating transistors, etc.):

Hot processes: growing defect-free oxides, diffusing dopants to create transistors

Clean processes: Junk will diffuse in, too, if you let it

→

2. The Back End (wiring up the system):

Cooler processes: depositing metal inter-connects, separating layers with less perfect insulators

Not-so-clean processes: Dirt is still bad, but you can wash it off

↓

Integrated circuits out

Things to remember about IC fab

> A LOT of effort has gone into designing IC processes so that they achieve the desired result and don't violate the laws of physics

> Why these processes are hard to design and improve:
- What if the circuit would be better if it included feature A, but making feature A requires a back end step followed by a front end step?
- Typical solutions: omit feature A or create a back end version of the front end step
- An unacceptable solution: just go from the back end process into the front end tool. This will contaminate the fab line and may melt your back end features in the process.

> Bottom line: IC processing is always done the same way, with a few variants

Things to remember about MEMS fab

- **You are subject to many of the same restrictions as the IC designers…**
  - **Laws of physics**
  - **Restrictions imposed by vendors: you can't do x because it would contaminate my tools from the point of view of my other customers**
- **… but you have additional challenges and advantages**
  - **Often there is no baseline process to work from (though the literature can often give you a good start)**
  - **There is no guarantee that conventional processes and tools can produce your part**
  - **The MEMS tool kit is significantly broader than the IC tool kit (so there's more available, but it's up to you to figure out how to turn the raw material into a functional process)**

The MEMS tool kit

The Front End (with some front end-compatible MEMS additions)

The Back End (with some back end-compatible MEMS additions)

Everything else:

Soft lithography (polymers, stamping, microcontact printing…)
Electroplating
Electron beam lithography
Spin-cast materials (e.g. spin-on glass)
Piezoelectrics
Magnetic materials
Anodic bonding of glass to silicon

An important caveat

- MEMS processes also basically flow from the front end to the back end
- The lines between front end and back end processes are not set in stone – they depend on your tolerance for risk/contamination.
  - How clean is clean?
  - How hot is hot?
- We will present unit processes according to whether they are roughly front end, back end, or “everything else” processes, but it is up to you, the process designer, to consider the actual temperatures, contamination, and materials compatibilities that are involved. What is clean for my application may not be clean enough for yours.

Implementation of rules is lab-specific (MTL example)

Chart removed due to copyright restrictions.

Complete chart is at http://www-mtl.mit.edu/services/fabrication/ptc_matrix.html

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Fundamentals of Surface Micromachining

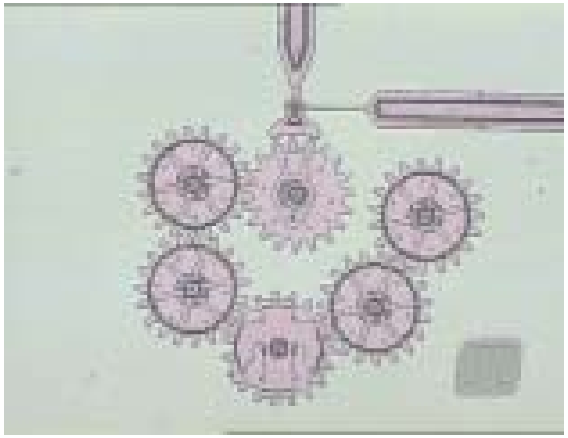
Surface Micromachining

- A technique for fabricating micromechanical devices by selectively depositing and etching thin films on the surface of a substrate
- **Structural layers** are the thin films that form the final structure
- **Sacrificial layers** are thin films that support a MEMS structure during fabrication, until it is released (that is, until the sacrificial layer is etched away)

Important techniques for surface micromachining

- Lithography and patterning
- Wet and dry etching
- Deposit thin films by CVD, PECVD, thermal oxidation, evaporation, etc.

Sandia: surface micromachined gear chain



Courtesy of Sandia National Laboratories, SUMMiT™ Technologies, www.mems.sandia.gov

Texas Instruments Digital Mirror Display

> **One MEMS example: inside the projector**

Images removed due to copyright restrictions.

Figures 48 and 50 in Hornbeck, Larry J. "From Cathode Rays to Digital Micromirrors: A History of Electronic Projection Display Technology." *Texas Instruments Technical Journal* 15, no. 3 (July-September 1998): 7-46.

http://www.dlp.com/

Berkeley: surface micromachined microphotonics

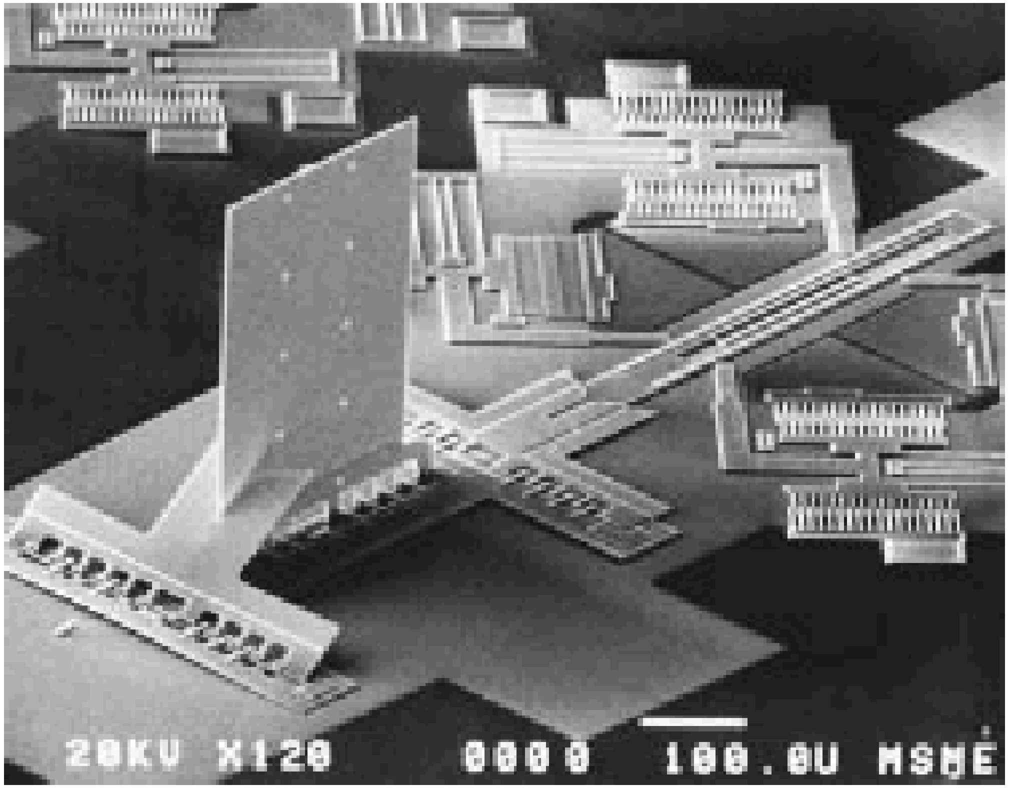


Figure 5 on page 316 in: Friedberger, A., and R. S. Muller. "Improved Surface-micromachined Hinges for Fold-out Structures." *Journal of Microelectromechanical Systems* 7, no. 3 (1998): 315-319. © 1998 IEEE.

Fundamentals of Bulk Micromachining

Bulk Micromachining

- Selectively etch bulk substrate to create microelectronic or micromechanical structures
- Remaining material forms the device structure
- Moving structures, trenches, and membranes possible

Important Techniques for Bulk Micromachining

- Lithography and patterning
- Wet and dry etching
  - Etch rate and profiles are important
  - Selectivity and masking materials, too!
- Wafer bonding
  - A process for permanently attaching two wafers together

MEMS energy harvester

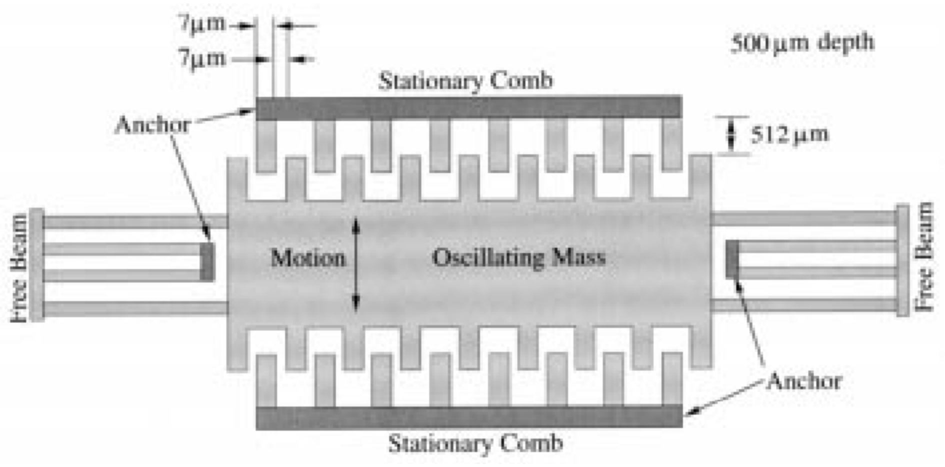


Figure 5 on page 67 in: Meninger, S., J. O. Mur-Miranda, R. Amirtharajah, A. Chandrakasan, and J. H. Lang. "Vibration-to-electric Energy Conversion." *IEEE Transactions on Very Large Scale Integration (VLSI) Systems* 9, no. 1 (2001): 64-76. © 2001 IEEE.

Mur-Miranda, Jose Oscar. "Electrostatic Vibration-to-Electric Energy Conversion." *Doctoral diss., Massachusetts Institute of Technology*, 2004, p. 88.

Designed for microWatts.

MIT: bulk micromachined microengine

Image removed due to copyright restrictions.
3-D cutaway of a micromachined microengine. Photograph by Jonathan Protz.

NIST: bulk micromachined micro-heater

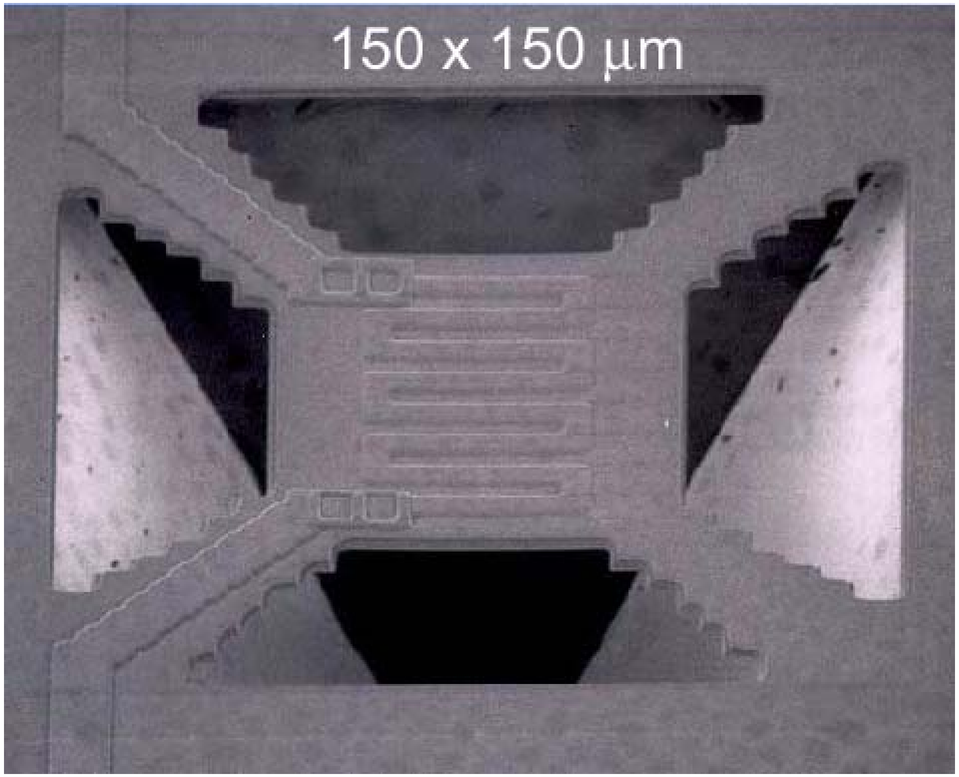


Figure 1 on page 57 in: Parameswaran, M., A. M. Robinson, D. L. Blackburn, M. Gaitan, and J. Geist. "Micromachined Thermal Radiation Emitter from a Commercial CMOS Process." *IEEE Electron Device Letters* 12, no. 2 (Feb. 1991): 57-59. © 1991 IEEE.

Polysilicon micro-heater suspended above silicon substrate

Preview: Unit Processes and Integration

- **Next class we will start to fill in the details of the front end, back end, and everything else with a set of unit process steps out of which processes can be built (vocabulary)**
  - **Oxidation**
  - **Implantation and Diffusion**
  - **Lithography**
  - **Selective Etching**
  - **… etc.**
- **But always remember to consider compatibility of the steps in the overall, integrated process sequence (grammar) – this is critical to the success of the MEMS device**
- **Also remember that theoretical compatibility isn't enough!** ***The process sequence must be available at your facility or your vendor's facility in order for you to use it!***