

# **MEMS Preliminary Exam 2000 Study Notes**

**Prepared by:**

**Joanne Deval**

**Chris Folk**

**Jen-Jr Gau**

**Steve Ho**

**Tza-Huei Wang**

**Based on Courses Taught by:**

**Dr. Chih-Ming Ho**

**Dr. "CJ" Kim**

**Dr. Jack Judy**

**Dr. Ming Wu**

**Additional Material from Texts by:**

**Dr. Jacob Fraden**

**Dr. Gregory Kovacs**

**Dr. Marc Madou**

Note: Several students prepared this material while studying for the 2000 MEMS Preliminary Exam. We apologize for any inaccuracies or errors that may appear. The amount, type, and depth of material varies considerably from class to class. For example, the "EE250A" notes are especially brief, since most of the needed material is contained in the "Kovacs" and "Madou" sections. In general, the notes are brief and are meant to illustrate the important points or concepts of the referenced material. However, some sections, particularly those based on the textbooks, do go into more depth. As a group, we found the most beneficial section to be the individual paper synopses, which are indicated with "Paper" in blue text. Using the Synopses as a guide, we were able to wade through the vast number of papers presented in our MEMS courses. We'd like to pass this on as a study aid for anyone who may need it. Good luck in your studies.

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# EE250A

circa Fall 1998

Professor: Jack Judy

The file for this course consists of three parts;

- 1) detailed outline of the course by subject and lecture
- 2) papers distributed in the course and their subject matter
- 3) individual synopses of the papers presented in the course

## 1) Outline

### Lithography

10/6-10/8

- 1) clean
  - a) solvent
  - b) strong acid
  - c) remove oxide
  - d) dry
- 2) deposit PR -pos/neg  
-methods PR application
- 3) exposure -contact  
-proximity  
-projection
- 4) develop PR
- 5) pattern transfer  
-exotic lithography
  - a) e-beam
  - b) ion beam
  - c) x-ray
- 6) strip PR

### Material & Deposition Techniques

10/13

- crystal structure vs amorphous
- single crystal
- polycrystalline
- thin films
- Si structure
- deposition
  - directional
  - conformal
    - a) diffusion -thermal
    - b) oxidation -thermal
    - c) physical
      - 1) evaporation
        - a) ebeam
        - b) thermal
      - 2) implant
      - 3) sputter

- d) chemical
  - 1) LPCVD
  - 2) PECVD
- e) plating
  - 1) electroplating
  - 2) electroless
- f) bonding

## Diffusion

10/15

- PN junction
- Ficke's law  $1^{\text{st}}/2^{\text{nd}}$ 
  - BC's a) constant source
  - b) constant dose
- gas vs solid/liquid
  - thermal budget
- in poly
- multistep
- bulk resistivity/measurement
- sheet resistance

## Ion Implantation

- advantages/disadvantages
- profile-Gaussian
- diffusion after implant
- annealing
- profile tailoring/measurement
- loss mechanism
  - electronic stopping
  - nuclear stopping
- dose/range/straggle/skewness
- measuring dose
- sheet resistance
- transmission factor of implant mask
- lateral straggle
- 2-D implant profile
- channeling ions through lattice

## Thermal Oxidation

10/20

- $X_{\text{ox}}, B/a, B$ , formulas/modeling
  - long time v short time
- dopant segregation
- wet ox v dry ox
- redistribution of dopants during ox
- oxidation barriers
- crystal orientation/dopant concentration  $\Rightarrow$  oxidation rate

## Chemical Vapor Deposition

- poly Si, SiO<sub>2</sub>, Si<sub>3</sub>N<sub>4</sub>, W
  - A) LPCVD -temp/press
  - B) PECVD -temp/press
- process
  - A) transport
  - B) adsorption
  - C) reaction
  - D) desorption
- mass transport vs reaction rate
  - laminar/turbulent

## Evaporation

10/22

- tilted substrate
- plane source
- planetary substrate
- practical issues/step coverage/shadowing
- kinetics of low pressure gases

## Sputtering

- physics/coverage/uniformity
  - material
  - incident angle
- practical issues
- ion milling
- paschen curve

## Electrochemical

- a) electroplating
  - types of material/electromotive series
  - conductive seed layer
  - fast deposition
  - frame plating
- b) electroless
  - thick/thin plating mold
  - patterned seed layer
  - bus bar
  - example electromagnetic coil fabrication

10/27

## Laser Assisted Deposition

- a) laser ablation
- b) laser assisted CVD

## Wafer Bonding

- Si/Si bonding
- SiO<sub>2</sub>/SiO<sub>2</sub> bonding
- bond strength

- a) anodic bonding
- b) low melting point glass
- c) eutectic bonding
- d) organic bonding
- problems
- paper-Ristic
  - interface integrity
    - voids in SiO<sub>2</sub>/SiO<sub>2</sub>
    - voids in Si/Si
  - shaping bonded wafers
    - a) wafer flatness
    - b) thinning bonded wafers
    - c) polishing bonded wafers
  - microdefects
  - application of direct wafer bonding to sensors and actuators
    - threshold pressure switch
    - pressure sensor

## Etching

11/3-11/5

- wet v dry
- anisotropic/isotropic
- aspect ratio, bias, uniformity, lateral etch ratio, tolerance, undercut
- mask selectivity to films
  - total etch time
- overetch, stringers

## Wet Etches

- a) isotropic wet etches
  - etch rate factors
  - etched materials
    - silicon
    - SiO<sub>2</sub>
    - Si<sub>3</sub>N<sub>4</sub>
    - metals
  - HF
  - buffered HF
- b) silicon crystallography
  - model for behavior
  - miller indices
- c) anisotropic silicon etchants
  - 1) KOH
  - 2) EDP
  - 3) TMAH
    - etch <100>
    - etch <110>
    - etch simulations
    - corner compensation

- street
- grille technique
- two-sided
- pattern alignment
- paper-Etch Rates for Micromachining Processing-Williams
- paper-Principles of Wet Chemical Processing...-Kikyuama
- surface roughness 11/10
- boron doped etch stop
- electrochemical etch stop
- applications
  - fiber alignment
  - membranes

## Dry Etching

11/12

- gas/vapor, plasma, RIE, sputter
- etching process
- a) generation of etchant species
  - gas
  - plasma
  - volatility of etch products
- b) diffuse to substrate
  - other control parameters
  - flow rate effects- gas utilization factor
- c) adsorption
- d) react
- e) desorption
- f) diffusion to bulk gas
- dry etch chemistry
- excitation energy
- control parameters
- temperature dependent selectivity
- anisotropy
  - surface damage
- surface inhibitors
- polymerization
- DRIE
  - a) Etch high F/C ratio
  - b) Polymerize- low F/C ratio
  - c) Ion etch
- Compound Processes Using Bonding-Kovacs
- Multichannel Recording Array
- photo-etch silicon 11/17
- porous si
  - applications/features
- electrochemical etch
- mechanical machining

- electro-thermal machining
- chemical mechanical polishing

### **Mechanical Stress on Thin film-curvature of Substrates**

12/1

- storey's equation
- multiple films
- bonding stresses/curvature/deflection
- biaxial bending of isotropic plate
  - stress/curvature/deflection
- thin film stresses-single thin film on flat substrate

### **Releasing microstructures**

- etches
- capillary forces
- other release methods
  - super critical CO2 drying
  - sublimation
    - p-dichlorobenzene
    - t-butyl
  - evaporation-deionized H2O/methanol
  - sacrificial polymer supports
  - low surface-energy material/SAMS
- Plenty of Room...Feynman
- infinitesimal Machinery...feynman
- Comparative Study of various release methods....Kim
- A Dry Release Method....Mastrangelo
- Elimination of post-bake adhesion...Man
- Self assembled Monolayer...Houston
- Self Assembled Fluorocarbons....Srinivassan
- SCREAM I...Shaw
- Self Adjusting Microstructures..Judy
- Black Silicon Method....Jansen
- Porous Silicon...Lehman
- Permeable Polysilicon...Lebouitz

### **Process Integration**

12/3

- do's/dont's
- hightemp processes
- mems processes
  - single structural layer
    - applications
  - two structure layer
    - in plane motion
    - out of plane motion
- foundry services
  - MCNC
  - IC foundry sources

- adapting IC to MEMS
- integrating MEMS/IC's/solutions
  - a) MEMS fab first
  - b) MEMS fab last
  - c) Mix MEMS/IC together
  - d) MEMS after Al steps
  - e) Don't bother integrating- flip chip

-PR spin on

-non-IC materials

12/8

a) magnetic material

1) soft magnetic

2) hard magnetic

-depositing permanent magnets

3) magnetostrictive materials

b. piezoelectric materials

c) shape memory alloy

-non-IC materials-structural

-SiC

-diamond

-packaging

-chip- level

-Chap 5 CMOS technology...Strojwas

-Atlas of IC technologies-INTRO VLSI...Maly

-Polysil resonant microbeam tech...Guckel

## 2) Papers

EE250A Papers and References

### Papers

Author	Title	Abstract
Petersen, Kurt	Silicon as a Mechanical Material	Overviews mechanical properties of Si, its crystalline planes, etching methods, and potential applications
Williams, Kirt	Etch Rates for Micromachining Processing	A "What etches what" guide to processi Seminal MEMS paper since it was first characterize many different etchants ur identical processing conditions
Kikyuama, Hirohisa, et al	Principles of Wet Chemical Processing in ULSI Microfabrication	Focused on BHF etching, particularly chemistry and processing conditions
Jansen, Henri, et al.	The Black Silicon Method VI: High Aspect Ratio Trench Etching for MEMS applications	Explains problems in RIE etching of hig aspect ratio structures and how to optir design based on several process variat
Shaw, Kevin, et al.	SCREAM I: A Single Mask, Single Crystal	Outlines SCREAM process

	Silicon Process for MEMS Structures	(Note: Was on midterm!)
Judy, Michael, et al.	Self-Adjusting Microstructures (SAMS)	Residual stress in deposited poly flexur resulted in lateral beam bending. Good background on beam bending
Kim, John and Kim, C-J	Comparative Study of Various Release Mechanisms for Polysilicon Surface Micromachining	Addresses stiction problem during relea and explains how to use evaporation, b geometry, and sublimation techniques to reduce the problem
Mastrangelo, C.H. and Saloka, G.S.	A Dry-Release Method Based On Polymer Columns for Microstructure Fabrication	Reduces stiction problem by fabricating sacrificial polymer columns to stiffen the structure during release
Man, P.F., et al.	Elimination of Post-Release Adhesion in Microstructures Using Thin Conformal Fluorocarbon Films	See title
Houston, Michael R., et al	Self-Assembled Monolayers Films as Durable Anti-Stiction Coatings for Polysilicon Microstructures	Another anti-stiction articles; this time SAMS are the coating
Srinivasan, Uthara, et al.	Self-Assembled Fluorocarbon Films for Enhanced Stiction Reduction	See Title
Leboutitz, Kyle, et al.	Permeable Polysilicon Etch-Access Windows for Microshell Fabrication	"Permeable" poly is used as etch holes to create sealed cavities
Lehmann, V.	Porous Silicon - A New Material For MEMS	Theory of porous poly formation
Maly, W., et al	Atlas of IC Technologies: Chapters 1 & 5	Basic processing info and CMOS fab
Gianchandani, Y.B., et al	A MEMS-First Fabrication Process for Integration CMOS Circuits With Polysilicon Microstructures	Make MEMS in a trench then make CMOS nearby. Precursor to SUMMiT without
Cohn, Michael, et al	Wafer-To-Wafer Transfer of Microstructures for Vacuum Packaging	Create a sealed cavity via wafer bonding
Guckel, H., et al	Polysilicon Resonant Microbeam Technology for High Performance Sensor Applications	Explains problems common to sealing cavities and presents an improved process
Li, Wen J. et al.	A MEMS Fabrication Technique for Non-Planar substrates	Wen J. Li's process

### 3) Paper Synopses

#### Stiction

##### A. Release-related stiction

6. Use low surface-tension liquid(Methanol) as final rinser

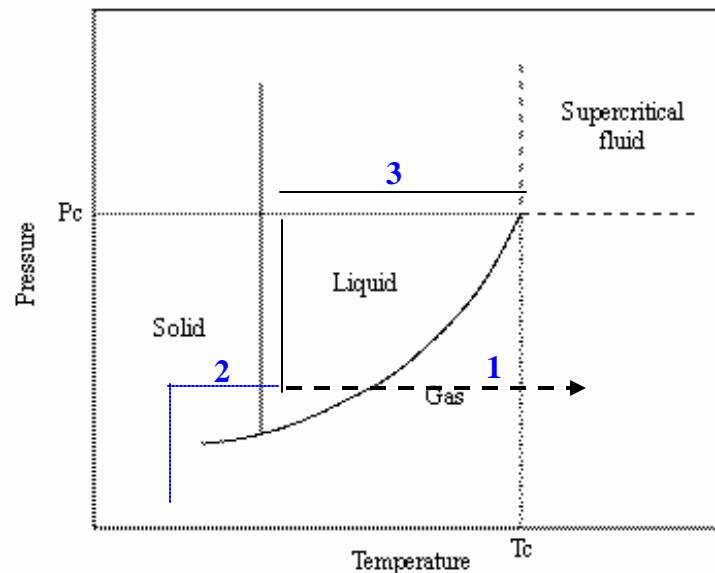
6. Sublimation drying

*Sublimation is the vaporization of a substance from the solid into vapor phase without formation of an intermediate liquid phase*

6. Supercritical drying

Supercritical fluids are able to spread out along a surface more easily than a true liquid because they have lower surface tensions than liquids. At the same time, a supercritical fluid maintains a

Figure 1. Generic pressure-temperature phase diagram.



6. Dry-release w/ polymer columns

6. Add small features to microstructure perimeter

6. SAM(self-assembly monolayer)

6. Thin conformal fluorocarbon film

*1-3: avoid formation of liquid-vapor interface*

*5: reduce capillary force by shaping the liquid meniscus*

##### B. In-use stiction

1. Adding dimple to reduce contact area

2. Surface roughening

3. SAM

4. Thin conformal fluorocarbon film

5. Ammonium fluoride-treated Si, in stead of using HF

**More complete hydrogen termination-> clean, hydrophobic**

**Paper : Comparative Study of Various Release..... John Kim, C.J. Kim**

1. Use MUMP process to fabricate test structure and evaluate 5 different anti-stiction methods. Results are in Fig.6
  - a) Evaporation Drying
  - b) Sublimation
  - c) Supercritical Drying
  - d) HF VPE
  - e) SAM coating

Structure layer : Poly1 (2um), Sacrificial layer : PSG1 (2um). Fig.2

Test structures(Fig.3):

1. Beam
2. Beam w/dimple of constant length (2um)
3. Beam w/antistiction tip
4. Doubly clamped beam (bridge)

for each sample, PSG is etched with 49%HF to release the beam, the chip is rinsed with DI water and then each method

2. Sublimation drying: (t-butyl alcohol and p-dichlorobenzene are used)  
Liquid → Solid → Gas  
Melting temp. for t-butyl alcohol is 26C  
p-dichlorobenzene is 56C  
→ need a refrigerator for t-butyl alcohol and a heater for p-dichlorobenzene  
→ t-butyl alcohol will absorb water from air, so vacuum is needed  
→ the rapid solidification rate of p-dichlorobenzene at RT creates high stress, so temperature control is needed. (Fig.5)  
→ p-dichlorobenzene has smaller vapor pressure than t-butyl alcohol, so the sublimation takes much longer
3. CO2 supercritical drying  
↑ pressure → ↑ temperature above supercritical temp. → ↓ pressure  
carbon dioxide is vented out in vapor state
4. Evaporation drying: increase width → max beam length decreased  
wider beam → bigger droplet underneath at beam end → higher pull down force(proportional to about the square of width) → but the elastic energy is only proportional to width → break easily (Fig.7)  
**BUT**, for the case of beam w/ dimple, the length of dimple is fixed=2um  
→ pull-down force is proportional to width = spring force  
→ max. detachment length is independent of beam width
5. Sublimation drying: increase width → max beam length increased  
*See Fig.8. The final droplet area is independent of beam width*

**So the wider beam has higher elastic energy**

**Paper : A Dry-Release Method Based On Polymer..... Mastrangelo, C.H.**

1. Use polymer to create an array of holder to stiffen the suspended plate
2. Process flow in Fig.3
  - make an array of holes on structure plate
  - BOE etching of sacrificial layer and make undercut
  - deposit polymer (polyimide) and pattern w/ Al mask
  - release structure w/ HF
  - O<sub>2</sub> plasma to remove polymer

**Paper : Elimination of Post-Release Adhesion in ..... Man, P.F., et al.**

1. Plasma polymerized fluorocarbon (FC) films coating. e.g. Teflon (10-20nm)
2. Eliminate post-release adhesion ONLY
3. Robust, durable, withstand high temp. (400C) and very hydrophobic

**Paper : Self-Assembled Monolayers Films as..... Houston, Michael R**

1. Forming a SAM of OTS (Octadecyltrichlorosilane) on oxidized silicon
2. Two conditions for OTS SAM:
  - a. hydrophilic oxide surface (hydroxyl rich)
  - b. below transition temp. of SAM (26C for this case)
3. SAM formation process flow:
  - a. BOE sacrificial layer etching
  - b. Surface oxidation
  - c. Immerse into SAM solution
  - c. Rinse and dry
4. OTS residue after rinse will form polymer on surface
5. Tested on both released and in-use adhesion w/ electrostatically actuated beam

**Paper : Self-Assembled Fluorocarbon Films for ..... Srinivasan, Uthara,**

1. Same as Houston's paper, but use both FDTS and OTS

## **VACUUM PACKING**

**Paper: Permeable Poly Silicon etch-access window .... Kyle S. Leboutz,**

1. Etch PSG with BOE through a permeable Polysilicon etch-access window
2. Supercritical CO<sub>2</sub> process to avoid Poly cracking
3. Seal the shell with LPCVD nitride at 140 m torr (=internal pressure)
4. Sealing by oxidizing the polysilicon will have near zero pressure

**Paper: Polysilicon resonant microbeam technology.....H.Guckel**

1. Focus on electrical property of poly resonant device. For EE geeks only.
2. Procedure and structure are unclear in the paper

**Paper: Wafer-to-wafer transfer vacuum package... Michael B. Cohn**

1. Fabricate the reverse-U shape cover lid on one wafer and deposit Au ring on bonding edge
2. Eutectic bonding to seal the chamber onto wafer with device. 363C for Au/Si
3. 100nm Cr underneath Au(0.7um-1um) for adhesion and prevent excessive diffusion of Au during bonding
4. Heating in a quartz vacuum chamber( $10E-5$  torr) for 60 sec during bonding

## **CMOS-MEMS**

**Paper: A MEMS-first fabrication.....Y.B. Gianchandani**

1. Traditional MEMS-CMOS chips do circuitry first(except metal), and then deposition and patterning for MEMS  
→ it limits the thermal budget of deposition and annealing  
Since MEMS is less affected by thermal budge → MEMS-first
2. MEMS-first process flow in Fig1
3. 1<sup>st</sup> Poly (at the bottom of the trench) should be a non-critical layer
4. Critical dimensions are located  $>100\mu\text{m}$  from recess edges  
*Non-even thickness of photo-resist*
5. If light field mask is used for patterning the 3<sup>rd</sup> Poly  
→ the time needed to expose the PR in the trench will over expose the upper surface  
→ so, needs to deposit thin film, dark field mask for metal, lift-off, Poly3 etching(isotropic dry etching to remove stringer)

**Paper: Porous silicon .....V. Lehmann**

1. Formation of pore array by electrochemical etching of doped silicon in HF.
2. A summary of various porous silicon techniques. Different pore size range(micro/meso/macro) is dominated by different mechanism.
3. System setup is in Fig.3. No general mechanism for different pore size range
4. Design rules are discussed in the paper. Pore size/shape is a function of doping density and current density
5. Alternative for on-chip capacitor

**Paper: A MEMS Fabrication Technique for Non-Planar ..... Wen J. Li**

1. Patterning on a cylinder quartz substrate
2. Making a flexible mask
  - a. Coat non-UV-transparent thinfilm onto flexible film
  - b. Attach flexible film onto a rigid substrate
  - c. Use conventional lithography to pattern the non-UV-transparent thinfilm

- d. remove the rigid substrate
3. Spray PR onto cylinder

**Paper: Silicon as a Mechanical Material (1982)**

**Author:** Kurt Petersen

**Synopsis:** Details the use of single crystal silicon (SCS) in early MEMS applications. Topics covered are mechanical properties of SCS and its advantages thereof, the different types of Si (poly, oxide, nitride), etching solutions and characteristics, and finally a long list of different transducers made from Si. This paper is widely regarded as one of the seminal MEMS papers.

**Specific Notes:**

1. Mechanical properties highly dependent on: crystallographic orientation; orientation; geometry, and number & size of surface, edge, and bulky imperfections; and processing induced stresses.
2. Best mechanical properties achieved by:
  - a. Lowest possible bulk, surface, and edge crystallographic defect density to minimize stress concentration.
  - b. Components subjected to severe friction, abrasion, or stress should be as small as possible to minimize crystallographic defects.
  - c. All mechanical processes (sawing, grinding, scribing, and polishing) should be minimized or eliminated.
  - d. If above mechanical processes are used, then etch afterwards to remove damaged regions.
  - e. Isotropic etching of sharp corners may be desirable to reduce stress concentrations.
  - f. Prefer low temp processing to reduce thermal mismatch.
  - g. Passivate silicon using SiC, Si<sub>3</sub>N<sub>4</sub>, or parylene (very good conformal coating).
3. Wet etching solutions (see p. 43 for Table II and Fig. 4 for illustrations)
  - a. Focused on EDP, KOH, HNA
  - b. HNA is hard to characterize. SiO<sub>2</sub> is OK for short etch times, but use Si<sub>3</sub>N<sub>4</sub> for long etch.
4. Etch process chemistry
  - a. Injection of holes into SCS to raise the Si to higher oxidation state, Si<sup>+</sup>
  - b. Attachment of hydroxyl groups OH<sup>-</sup> to Si<sup>+</sup>
  - c. Reaction of hydrated Si with the complexing agent in the solution
  - d. Dissolution of reacted products into the etchant solution
5. Other etching notes
  - a. Etching is a charge-transfer process, so etch rates dependent on dopant type and concentration.
  - b. Why (111) etches more slowly than (100)?

- (111) has higher surface atom density than (100), leading to more native oxide to screen Si surface
  - (111) bond energy is higher than (100), but difference is only factor of 2.
    - c. Net undercut rate reduced by narrow openings → loading effect.
    - d. p+ etch stop will *increase* undercut rate b/c net flux of reactants remains the same but now cannot etch down.
    - e. See Figs. 6-8, p. 45 for different anisotropic etch profiles (same as in Madou)
6. Electrochemical etching
    - a. Typically use HF/H<sub>2</sub>O solution.
    - b. No etching occurs when current off. Oxidation occurs when positive voltage applied on Si. Reaction is same as for other wet etchants.
    - c. Good way to make a membrane by stopping etch on a lightly doped epi-layer. You have all the advantages of a KOH/EDP etch stop without need for buried p+ layer.
    - d. Porous silicon also can be created using ECE
    - Porosity causes ready gas diffusion → high temp oxidation is very fast
    - Very fast etch rates
  7. Epitaxy
    - a. Same as Madou
    - b. Increased dep. rates seen at bottom of deep, narrow, anisotropically etched grooves.
    - c. See Fig. 10 on p. 47 for example of filling deep grooves using epi.
  8. Thermomigration
    - a. A temp gradient (50 C/cm or 2.0 degree C across typically wafer), a Al/Si alloy zone will migrate across wafer from hot to cold → front to back side connectors
    - b. See Fig 11, p. 48 for example
  9. Bonding – see Madou or Kovacs for better description
  10. Anisotropic etching of grooves and holes
    - a. Uses – high aspect ratio molds, tubes and spheres, and sharp tip creation
    - b. Ink jet nozzle problem: hard to control nozzle size because (see Fig. 16, p. 50)
      - wafer thickness is not easy to control accurately
      - small angular misalignments will cause a larger nozzle than expected due to effectively larger mask size
      - Solution to above is use a circular mask opening → no angular dependence
  11. Many device examples.

**Paper:** Etch Rate for Micromachining Processing (1996)  
**Author:** Kirt Williams and Richard Muller

**Synopsis:** The seminal “What Etches What” guide to processing. First paper to characterize many different etches and masks (317 combinations) under controlled conditions. The really important information is all held in the multitude of etch tables.

### **Specific Notes:**

#### Wet etchants

##### SiO<sub>2</sub>

1. Pure HF reaction
  - a.  $\text{SiO}_2 + 5\text{HF} \rightarrow \text{H}_2\text{SiF}_6(\text{aq}) + 2\text{H}_2\text{O}$
2. BHF reaction
  - a.  $\text{SiO}_2 + 4\text{HF} + 2\text{NH}_4\text{F}$
  - b. As HF and HF<sub>2</sub><sup>-</sup> are consumed, etch rate decreases. Buffering with NH<sub>4</sub>F help keep pH constant, so it stabilizes the etch rate
3. Etch rate increases with temp.
4. For deep undercutting, the etch rate is diffusion controlled and not affected by agitation.
5. Concentrated 49% HF
  - a. Tends to peel off PR but good for sacrificial oxide etching.
  - b. 5:1 BHF is often best choice since it can be masked by PR and has a stable etch rate

##### Nitride

1. Really only 85% Phosphoric acid at 160C. Need a reflux system but the etch is fairly slow. Use a dry etch instead

##### Istropic Silicon wet etchant

1. 126:50:5 solution of HNO<sub>3</sub>:H<sub>2</sub>O:NH<sub>4</sub>F.
  - a. Used mainly for polysilicon wet etch. PR can be mask

##### Anisotropic Si

1. KOH at 80C
  - a. Need a nitride mask. HF dip also needed before nitride deposition to remove native oxide
  - b. Heavily doped p+ etch stop
  - c. Isopropyl alcohol added to KOH will decrease etch rate but improves uniformity → less stirring needed
  - d. Attacks IC circuits
  - e. Reaction:  $\text{Si} + 2\text{OH}^- + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2(\text{OH})_2^{2-} + 2\text{H}_2(\text{gas})$
  - f. Etch rate increases with temp.

##### Aluminum

1. 80% phosphoric:5% nitric :5% acetic :10% water
  - a. Nitric acid oxidizes the Al. The phosphoric acid and water then etch the oxide.

##### Titanium

1. 20:1:1 solution of H<sub>2</sub>O: HF (49%): and H<sub>2</sub>O<sub>2</sub> (30%)

2.  $H_2O_2$  – wet etch Ti/W alloys. Masked by PR

#### PR Stripping

Piranha, acetone, and oxygen plasma (used for really tough PR)

Wet etch rate variations – due to chemistry, temperature, mass transport issues, reactive species depletion. See p. 261 for a full listing.

Dry etches – much information. Specific details etches talked about are:

1.  $O_2$  – used for an organic stripper
2.  $SF_6$ ,  $CF_4$  – nitride etches;  $CHF_3$  – oxide etches;  $Cl_2$ ,  $XeF_2$  – Si etches
3. Rate etch variation in plasma etches – see p. 265

#### Uses of different silicons

- Polysilicon = structural material
- Thermal oxide = thin sacrificial layers and sealing cavities
- LTO = sacrificial layer but much slower etch rate than PSG. Only etched slightly faster than thermal oxides
- PSG (doped LTO) = sacrificial layer
- $Si_3N_4$  = masking and non-freestanding layers
- Low stress nitride = optically transparent membranes and shells
- Al = interconnects and structural materials with organic sacrificial layers (such as polyimide)
- Tungsten = interconnects in high temp processing
- Titanium = adhesion layer for tungsten and gold. Good adhesion to both oxide and nitride

**READ THE SUMMARY AT THE END**

**Paper:** **The Black Silicon Method VI: High Aspect Ratio Trench Etching for MEMS Applications (1996)**

**Author:** Henri Jansen, Mein de Boer, and Miko Elwenspoek

**Synopsis:** An odd paper to read. They're trying to examine the causes and find solutions for some of the problems commonly found in making deep trenches using RIE, namely tilting, bowing, TADTOP, RIE lag, and micrograss. By tweaking a variety of process, plasma, and machine parameters, they present some "solutions" to these problems.

My suggestion here is to simply read the conclusion and look at all the figures. I really didn't understand most of the rest of the paper.

**Paper:** **SCREAM I: A Single Mask, Single-Crystal Process For MEMS Structures (1993)**

**Author:** Kevin Shaw, Lisa Zhang, and Noel MacDonald

**Synopsis:** Make high aspect ratio (10:1) beams using SCS and only one mask. Notable features are self-alignment and low temp (< 300 C). This process was a question on one of the 250A midterms. Before DRIE, SCREAM was an alternative to expensive LIGA for HARMs. Still, it serves as a good example of creatively using the inherent strengths of different deposition and etching techniques to make HARMs.

**More Notes:**

1. The really important figure is Figure 1, the process outline. Make sure you understand the process and why particular depositions/etch techniques were used.
2. Big advantages of SCREAM
  - Automatically defines the metallization areas without need for additional lithography step
  - One mask – oxide mask at the start of the process

**Paper:** **Self-Adjusting Microstructures (SAMS)**

**Author:** Michael Judy, Young-Ho Cho, Roger Howe, and Albert Pisano

**Synopsis:** Clever use of stringers as a sacrificial layer to form beams that laterally bend based on residual stress. The paper's best parts are the presentation of beam bending theory and the process flow presentation. The SAMS are created using 3 extra deposition steps and 2 extra masks. Read the process flow shown in Figure 4.

**More Notes:**

1. The deflection of the beam is calculated from simple statics. Probably a good idea to review your simple statics knowledge because beam bending is likely to be a prelim question.
2. Vertical sidewalls are critical to SAMS, so PSG is used as a mask instead of PR because PSG has a higher selectivity to poly than PR.
3. The sidewalls (PSG, poly, and nitride) are not patterned with an extra lithography step. They are formed as stringers. So only simple conformal deposition followed by anisotropic etching is needed.

**Paper:** **Principles of Wet Chemical Processing in ULSI Microfabrication (1991)**

**Author:** Horihisa Kikyuama, Nobuhiro Miki, Kiyonori Saka, Jun Takano, Ichiro Kawanabe, Masayuki Miyashita, Tadahiro Ohmi

**Synopsis:** A very detailed study of BHF etching of  $\text{SiO}_2$ . They developed a better chemical formulation of BHF based on the determining the exact chemical reactions between BHF and  $\text{SiO}_2$ . Lowering the  $\text{NH}_4\text{F}$  concentration helps etching uniformity while adding surfactants (aliphatic amine and aliphatic alcohol) aids in getting good surface smoothness by improving the wetting characteristics of BHF. If you want, read the introduction, wettability of the wafer surface, and conclusion sections. The others sections are far too detailed.

**More Notes:**

1. The dominant reactive ion species in  $\text{HF}_2^-$ , as etch rate increases linearly with increasing  $\text{HF}_2^-$  concentration while decreases logarithmically with decreasing  $\text{H}^+$  concentration.
2. Reduction of  $\text{NH}_4\text{F}$  concentration to 15% achieves best etch rate uniformity but bad for surface smoothness.

Regular BHF has poor surface smoothness due to its poor wetting characteristics. Adding a surfactant helps smoothness.

# EE 250 B

circa Winter 1999

Professor: Ming Wu

The file for this course consists of;

- 1) class outline
- 2) principles and equations for actuators
- 3) notes on magnetic actuators, taken from the Kovacs text that supplement the material presented by Dr. Wu
- 4) summary/comparison notes on MUMPS and SUMMIT
- 5) synopses of papers presented in this course

## 1) Outline

according to the notes + Kovacs links

1/11	intro- sensor-actuator process steps .....	Chap1		p1-10
	<b>Comb-drive actuator</b> basics mechanics.....	Chap 3.2		p180-186
1/13	spring calculus.....			
	electrostatic force.....	Chap 3.6		p277-281
	static equilibrium – graphic solution .....			p280-281
	<b>Gap closing actuator</b> graphic solution – V pull-in expression.....			
1/18	holiday ??			
1/20	holiday ??			
1/25	Dynamic response of systems - analogy mechanical/electrical.....			p189-191
	<b>Resonant Gate Transistor</b> .....	Chap 3.7		p308-315
	Air damping and consequence on quality factor of a resonator.....			p312 / p316-318
	<b>MUMP</b> standard process.....			
1/27	holiday ??			
2/1	description of design rules.....			
2/3	exceptions in design rules – thicker layers of poly.....			
	Problems.....			
	in-plane joint fabrication.....	Chap 3.4		p202-205
2/8	out of plane joints – <b>scissor hinge</b> , torsion mirrors ( <b>DMD<sup>TM</sup></b> )			p205-207, p467-472
	<b>scanning mirror</b>			
2/10	<b>projection mirror</b> - equations, equilibrium state, MUMP's DMD values	Chap 4.3.2		p473-474
	<b>Grating Light Valve</b>			
2/15	???			
2/17	MIDTERM			
2/22	DRAM – SRAM.....			
	<b>Thermal actuators</b> .....	Chap 6	and	p289-294
	<b>Scratch Drive actuator</b> .....			p287-288
2/24	<b>Scratch Drive actuator</b> .....			p287-288
	<b>linear microvibromotor</b> .....			p286
	Stress -uniform / gradient .....	Chap 3.3		p195-201
	Magnetic actuators magnetization			p624
3/1	type of magnetic materials			
	shape anisotropy			
	magnetostatic energy			
3/3	<b>magnetic flap</b>	Chap7		p624-625
	<b>individual/electrostatic addressing in arrays</b>			p478-480

		magnetic/electrostatic forces with scale Figure Of Merit
3/8	SANDIA process – SUMMIT SUMMIT	technical aspects of fabrication process steps description design rules
3/10		
3/15	?????	
3/17	notions on CMOS, MOSIS	

## 2) Principles and Equations for Actuators

### Ideal actuators

- Use little power
- High mechanical efficiency
- Fast motion
- Linear proportionality between force/torque/speed and a control signal

### Electrostatic Actuation

#### Comb Drive Actuator(p.283)

- Advantages : (compare to gap-closing actuator)
  - Relatively large movement
  - Linear displacement-to-voltage

Spring constant  $k_0 = Ewt^3/4L^3$  where

t: thickness of the beam (line space)

w : width of the beam (etching depth)

L: half the length of a finger

Spring Force :

$$F_{sp} = -k (x - x_0)$$

Electrostatic force:  $F_x = (\epsilon V^2/2) (t/d)$ , where

$\epsilon$  : dielectric constant ( $\epsilon_0 = 8.854 \times 10^{-12}$  for vacuum)

$(\epsilon V^2/2)$  : basic force unit (  $\sim nN$  for  $V=15V$  )

- F is independent of x
- Force remains the same as comb moves
- $F \sim V^2$
- $F \sim (t/d)$  aspect ratio

#### Static Equilibrium

$$F_x = (2n) (\epsilon V^2/2) (t/d) = (n \epsilon V^2/2) (t/d) ; \quad n \text{ is the number of fingers}$$

$$F_x = - F_{sp}$$

$$\rightarrow \Delta x = (n \epsilon V^2/k) (t/d)$$

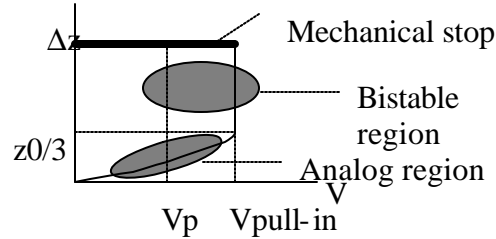
$$\bullet \quad \Delta x \sim V^2$$

#### Gap-Closing Actuator (p.277)

Electrostatic force:  $F_z = (-\epsilon V^2/2) (A/z^2)$ , where

A: area of plate

z: gap  
 $Fz \sim V^2$   
 $Fz \sim (1/z^2)$



Spring Force :

$$F_{sp} = -k(z - z_0)$$

Force Equilibrium:

$$Fz = -F_{sp}$$

$$\rightarrow z^3 - z_0 z^2 + (\epsilon A V^2) / (2k) = 0 \rightarrow f(z)$$

Pull-in voltage  $V_{pull-in}$  : (when  $d f(z) / dz = 0$ )

$$z = 2/3 z_0$$

$$V_{pull-in} = \sqrt{\frac{8k}{27\epsilon A}} z_0^3$$

- Advantages: simple
- Disadvantages:
  - Nonlinear force-to-voltage
  - Less efficiency

**Torsion Beam:**

$$\text{Torque: } T = K_\phi \phi \quad K_\phi = KG/L \quad G = E/(2(1+\nu))$$

K: Geometry-dependent factor

For a circle:  $K = (1/2)(\pi r^4)$

For a square:  $K = 2.25a^4$

For a rectangular ( $b > a$ ):  $K = a^3 b [16/3 - (3.36)(a/b)(1 - a^4/12b^4)]$

**Torque**

$$t_a = \frac{\epsilon_0 V^2}{2} \frac{L}{\tan^2 \theta_M} g(\mathbf{a}, \mathbf{b})$$

$\theta_M$  : max angle =  $h / (w/2)$

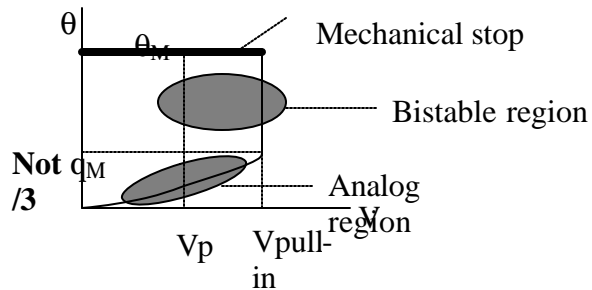
$\alpha$  : normalized angle =  $\tan \theta / \tan \theta_M$ ,  $0 \leq \alpha \leq 1$

$\beta$  : electrode loading factor =  $w_e / (w/2)$ ,  $0 < \beta < 1$

$$g(a, b) = \frac{1}{a} \left[ \ln(1 - ab) + \frac{ab}{1 - ab} \right]$$

$$\Gamma = \tau a \rightarrow$$

$$K_q q = \frac{e_0 V^2}{2} \frac{L}{\tan^2 q_M} g(a, b)$$



### Pull-in Voltage

$$V_s = \sqrt{\frac{2J_M^3 K_q}{eL}} = \sqrt{\frac{2h^3 k_q}{eL \left(\frac{w}{2}\right)^3}}$$

### Electrostatic Rotary Micromotors(p.284,285)

See fig.(p.285)

### Electrostatic Linear Micromotors(p.286,287)- SCRATCH

- Pros:
  - Very precise, step wise linear motion
  - Large movement/ fast
    - $\Delta x \sim 10$ 's nm,  $f \sim 100$  KHz
    - speed =  $2 (\Delta x)(f) \sim$  mm/sec
  - High force
- Cons: wear due to friction

### Electrostatic Microgrippers (p.288)

See figure(p.288)

### Non-Electrostatic Actuation

#### Bimorph Thermal Actuators (p.289,290)

- Advantages:
  - Linear deflection-power
  - Large transverse displacement
- Disadvantages:

- High power consumption,
- low band width and
- complex fabrication
- Thermal actuators in MUMPs (Fujita's group)
  - Displacement up to 16  $\mu\text{m}$ .
  - 4.4 $\mu\text{N}$  @ 8  $\mu\text{m}$  displacement
  - Large force by ganging up actuators in parallel
  - Problems:
- thin beam fatigues at high temp.
- Applied critical current(higher than operating) , the hot beam will permanently defromed, and becomed shorter(back bending)

### Volume-Expansion Actuators (p.294,295,296)

- See figures(p.295)
  - Surface –tension-based actuators (see fig, p.296)
    - Pro: Force is two orders of magnitude than others
    - Con: Must be operated in liquid environment

### Shape Memory Alloy Actuation (p.297)

- Materials: Au/Cu, In/Ti and Ni/Ti
- Low temp (Martensite, memorized shape)  $\rightarrow$  High temp(Austensite)

### Pneumatic/Hydraulic Actuation

See figures in p.298, p.299

### Piezoelectric Actuation

- Pros:
  - Linear strain-electric field
  - High Stress (tens of MPa)
  - High bandwidth, high energy
- Cons:
  - Complex fabrication
  - Much smaller dimensional change
- A very good application for STM (p.300, 301)

## Second-Order Linear System(p191)

### Dynamic Response

$$m \frac{d^2 x}{dt^2} + b \frac{dx}{dt} + kx = F_{\text{external}}$$

### Frequency Response :

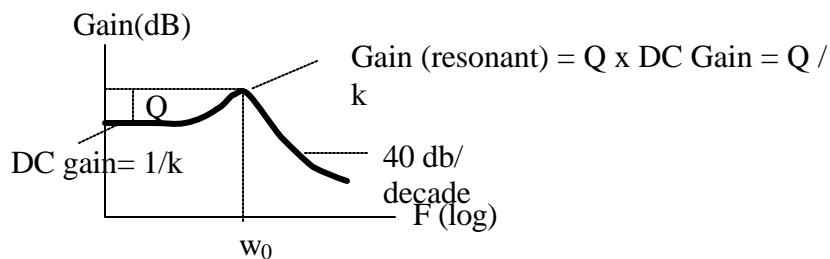
$$\frac{X(s)}{F(s)} = H(s) = \frac{1/m}{s^2 + (b/m)s + (k/m)}$$

$$H(jw) = \frac{-(1/m)}{w^2 - j(b/m)w + (k/m)}$$

Resonant Frequency :  $\omega_0 = (k/m)^{1/2}$

Quality Factor  $Q = \omega_0(m/b) = (km)^{1/2} / b$

- Three important parameters : (1) DC gain, (2) Natural frequency, (3) Quality factor
- **Below the natural frequency**, the system respond with close to the DC gain
- **At the natural frequency**, (1) The response is Q times the DC response and is  $90^\circ$  out of phase with the input force(voltage)
- **At the frequencies above the natural frequency**, the response falls off by 40 dB per decade and phase approaches a phase of  $-180^\circ$ .
- At resonant, sometimes it brings up a potential material failure problem. However, since deflection is Q times as larger as at steady state. Increasing the damping of the system helps to prevent the out of control oscillations.



Equivalent to RLC circuit (Refer to table (P.191))

$$\frac{V_{out}}{V_{in}} = H(s) = \frac{1/LC}{s^2 + (1/RC)s + (1/LC)} = \frac{\omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

## Mechanical Resonators

### Simple Clamped Cantilever ( also holds for double clamped case) (p.309)

$$f_R = \frac{1}{2p} \sqrt{\frac{k}{m}} = \frac{1.03}{2p} \frac{tv}{L^2}$$

- For a given material , the key to increase the resonant frequency  
 $\rightarrow$  maximize the thickness relative the length( short and thick beam)

### Resonant Gate Transistor (RGT)

See figure (p.313)

- With FET structure
- Electrodes: 1.)Bias(Gate), 2.)Source, 3.)Drain and 4.)Deflection electrodes
- Electroplated gold beam  $\rightarrow$  applying polarization voltage, bias ( $V_p$ )
- In put signal is applied to deflection electrode

- Output signal is got from Drain
- Deflection at resonance  
See equation in P.313
- Typical performance  
 $f_R = 1 \sim 50$  KHz  
 $Q \sim 100$

Disadvantages:

- $f_R$  is low ( $< 50$  KHz)
- thermal mismatch between beam(Au) and structure(Si)

### Double Clamped Beam Resonator(p.314)

- $f_R$  can be higher  
U.Michigan  $f_R \sim 300$ MHz  
 $f_R > 1$  GHz for fine features and singal crystal, GaAs
- Some designs eliminate FET structure (which also eliminated its noise controbution)
- Good matching of thermal expansion (Use PolySi beam)
- Tuning approach: (see equation in p.314)

By Changing DC bias to change  $f_R$

### Lateral Resonators (P.316)

- Comb-Drive
- Tuning approach: (see equation in p.314)

### Gravitational Effects (p.310)

- Deflection due to gravity  
 $\delta_g \sim 0.38 / f_R^2$
- Low frequency  $\rightarrow$  high gravitational effects
- It's not important for most of the commercial products because most of them are high frequency.

### Thermal Noise (p.310)

- For micromachined resonators, the noise spectrum is flat(“white noise”) but because of force-to-displacement transfer function, it peaks at  $f_R$ .
- See equations in P.311
- When the resonators are **reduced in size**, the **mass will reduce** and **thermal noise will increase**.  $\rightarrow$  Thermal noise can be a major problem for micromachined resonators.
- Noise/drift can also be generated through the adsorption and deposition of contaminating molecules on the surfaces of the structures. But it can be mitigated by careful process control.

### Viscous Damping: (p.311)

- Viscous damping is inversely related to Q.

- In vacuum, the viscous damping is zero but Q is not infinity due to intrinsic damping due to energy dissipation in the resonator material itself (much less in single-crystal materials than in amorphous or polycrystalline)
- For pressure  $\ll 1$  atm ( $P < 0.04/w$ , in Pa, w is the width )  
Momentum exchange rate is proportional to the velocity difference between the gas molecules and the resonators.  
Damping is proportional to pressure  $\rightarrow$  **Q is inversely proportional to pressure**

$$Q \sim 93 (t/L)^2 (E\rho)^{1/2} / P$$

$$Q \sim 93 (t/L)^2$$

For practical consideration, pressure is rarely much less than 1 atm.

- For pressure  $> 1$  atm ( $P > 0.04/w$ , in Pa, w is the width )  
Most resonators are used in this condition.  
Pressure is no more a key point.  
Gases can be treated as a viscous fluid( molecules interact with each other),  
Q is inversely proportional to viscosity.  
 $Q \sim w(t/L)^2 (E\rho)^{1/2} / 24 \nu$
- Squeeze-film damping effects ( when  $(d/w) < 1/3$  )  
Q is further reduced  
 $Q \sim [ w(t/L)^2 (E\rho)^{1/2} / 24 \nu ] (d/w)^3$

## Stress Measurement(p.196)

### Uniform stresses

- Direct measurement of dimensional change is not easy.
- For **compressive stress** : a set of doubly supported beams of various lengths and determine which of them have buckled at a given stress level.
- For **tensile stress**: Use “ ring –and-beam” (P.197) to convert tension on the ring into compressive stress on the central beam.

### Nonuniform Stress

See P.198

### 3) Magnetic actuators

-From Chap 7 in Kovacs

\*\*\*\*\***Vectors are in bold characters**\*\*\*\*\*

#### TERMS / DEFINITIONS / CALCULUS for magnetic flap

**B** magnetic flux density  $T = \text{tesla} = (\text{N.s}) / (\text{C.m}) = \text{N} / (\text{A.m}) = \text{Wb} / \text{m}^2$   
1 Gauss =  $10^{-4}$  T  
*see table p613 for typical values*

$\mu_0$  free space permeability  $4\pi \times 10^{-7}$  T.m/A  
 $\mu_r$  relative permeability  $\mu = \mu_r \mu_0 = \text{B}/\text{H}$   
*see table p612 for characteristic values*

*coercivity*, in A/m = relative measure of the ease with which a material can be (de)magnetized.

$\phi_c$  Curie Temperature, in °C or K =  $T^0$  at which spontaneous magnetization of material=0

**M** magnetization = characteristic of a magnetic material in A / m  
*Easy axis* is the axis on which **M** aligns itself if no external field

*Magnetostatic energy* is created when magnetic material **M** is in an external field **B**

$$U = -V \mathbf{B} \cdot \mathbf{M} \quad V \text{ is the volume of the magnetic material}$$

*Torque* due to this field:  $\mathbf{T}_{\text{field}} = -\delta U_{\text{ms}} / \delta \theta \mathbf{e}_\theta = V \mathbf{M} \times \mathbf{B}$

Therefore **M** rotate by an angle  $\theta$  from the easy axis, and we have then the *magnetic anisotropy*, which is the tendency to the material to magnetize along the easy axis, while external field has rotated the magnetization axis. (*see p624-625 for explanations*)

Reasons/origins :

- *crystalline anisotropy*: spin-orbit coupling, hence preferred crystal unit axis.
- *processed induced anisotropy* (strong field deposition, annealing)
- *stress anisotropy*: magnetic domain rotation will accommodate induced strain
- *shape anisotropy*: demagnetizing field is produced by north and south poles of the magnets, varies in  $1/r^2$

*magnetic anisotropy energy* :  $U_a = V K \sin^2 \theta$  where K = constant of magnetic anisotropy

$$\text{torque: } \mathbf{T}_a = -\delta U_a / \delta \theta \mathbf{e}_\theta = -V K \sin 2\theta$$

**H** magnetic field strength A / m =  $1.257 \times 10^{-2}$  Oe (Oersted)  
or ----- intensity

or magnetic excitation is defined by  $\mathbf{H} = \mathbf{B}/\mu_0 - \mathbf{M}$

For *diamagnetic* (Au, Ag, Be, Bi) and *paramagnetic* (Al, Mg, Pt, O<sub>2</sub>, Na, FeCl<sub>3</sub>) materials, **no magnetization if no external field**.

They acquire a magnetization that is // to the external field, so that we have:

$$\mathbf{M} = \chi_m \mathbf{B} / \mu_0$$

$\chi_m$  magnetic susceptibility - nondimensional coeff

$$\mu_r = 1 + \chi_m$$

For *diamagnetic* materials,  $\chi_m < 0$  and very small :  $10^{-5}$  for solids,  $10^{-9}$  for gases.

For *paramagnetic* materials,  $\chi_m > 0$ , still very small :  $10^{-3}$ - $10^{-5}$

*Ferromagnetic* materials ( Fe, Co, Ni)

- they can become permanent magnet
- attraction force if placed in a  $\mathbf{B}$  when not previously magnetized is large
- above  $\phi_c$  they behave like paramagnetic material

We define magnetic susceptibility and relative permittivity by

$$\chi_m(\mathbf{H}) = \mathbf{M}/\mathbf{H} \quad \text{and} \quad \mu_r(\mathbf{H}) = 1 + \chi_m(\mathbf{H}) = \mathbf{B} / \mu_0 \mathbf{H}$$

but here, we **DON'T** have linear relations, see B-H loop with **hysteresis**

- *saturated* magnetization
- *remanent* magnetization: they keep a permanent  $\mathbf{M}$  even with no  $\mathbf{H}$
- for  $\mathbf{H}$ = *coercive field* , zero magnetization
- hysteresis loop is symmetric
- wide / shrunk curve for hard / soft materials: means a hard material can hardly be demagnetized.
- diagonal / vertical slope for hard / easy axis : means magnetization can be neglected along hard axis

## Shape anisotropy:

Take a parallelogram,  $a > b > c$ , with *demagnetization coeff*  $N_a, N_b, N_c$ .  $N_a + N_b + N_c = 1$

*Demagnetizing field* :  $\mathbf{H}_d^i = -N_i \mathbf{M}_i / \mu_0$

$$U_{ms} = - \frac{1}{2} \mathbf{H}_d \cdot \mathbf{M} = \frac{1}{2} N_d / \mu_0 M^2 = M^2 / 2\mu_0 (N_a \cos^2 \alpha + N_b \cos^2 \beta + N_c \cos^2 \gamma)$$

Usually  $\mathbf{H}$  is in  $xy$  plane, so that  $\gamma = \pi/2$ . And  $\alpha + \beta = \pi/2$ .

We assume we get the saturation magnetization  $M_s$ , and  $U_{ms} = K_a \sin^2 \alpha$

so *magnetic anisotropy constant*  $K_a = 1/2 \mu_0 (N_b - N_a) M_s^2$

(only due to shape here, could also add  $K_{stress}$ ,  $K_{crystal}$  ...)

example in J.Judy paper, studied also in notes: the **magnetic flap**

remember  $\mathbf{M} = M_s$  is not realistic.

**Fabrication** of the magnetic flap: **electroplating** to deposit the permalloy (80%Ni, 20%Fe) on the top of a poly beam + seed layer, **PR** to pattern the permalloy (as a **sacrificial layer**)

(see description p656-658 of Judy's flap + other fabrication processes p653-656 using permalloy electroplating)

**External field control:**

- **individual addressing** in arrays: integrated inductor coil around the flap: high current (100's mA), **H** not well confined (crosstalk)
- **electrostatic addressing**: potential difference applied between substrate and flap, to exert electrostatic force to oppose to **H** force, which remains the same : no current, **E** field highly confined, low voltage (~10V)

**MAGNETIC & ELECTROSTATIC FORCES SCALING**

Let's take a coil wrapped around a ring (cross section area:  $s$ ), distance between turns :  $g$ , length of wire (???) :  $l$ , then assuming saturated magnetization, **magnetic force**  
 $\propto M^2s$

For a capacitive structure : 2 plates area  $s$ , distance  $g$ , **electrostatic force**  $\propto 1/g^2$

Small gaps : electro  $\gg$  magneto

Large gaps : magneto  $\gg$  electro

Limit:  $1.75\mu\text{m}$  when saturated Fe or Ni are used

**4) MUMPS and SUMMIT**

**MUMPS**

1. All depositions are LPCVD. All etches are RIE
2. The MUMPS manual refers to PSG 1 and PSG 2 as the First Oxide and Second Oxide, respectively. I use the naming convention found in the EE250B class notes.
3. Poly 1 and Poly 2 layers are p+ doped by annealing with PSG at 1050 C for 1 hr. This anneal also relieves stress in the poly layers.

Process Table

Layer	Thickness	Purpose
Nitride	0.6 $\mu\text{m}$	Electrical isolation and passivation
Poly 0	0.5 $\mu\text{m}$	Ground plane
PSG 1	2.0 $\mu\text{m}$	Sacrificial layer; forms dimples and anchors for future Poly layers
Poly 1	2.0 $\mu\text{m}$	1 <sup>st</sup> structural layer
PSG 2	0.75 $\mu\text{m}$	Sacrificial layer; forms POLY1_POLY2_VIA and ANCHOR2
Poly 2	1.5 $\mu\text{m}$	2 <sup>nd</sup> structural layer
Metal	0.5 $\mu\text{m}$	Electrical connections (bond pads, routing, probing) + polished mirror

1. All polysilicon masks are lightfield. All PSG masks are darkfield.
2. Minimum line width/spacing = 2  $\mu\text{m}/2\mu\text{m}$ . Nominal width/spacing = 3  $\mu\text{m}/3\mu\text{m}$ .
  - a. Highly nonplanar topology

- b. Size of die > recticle stepper field of view (1 – 1 projection system)

Mask Table

Layer	Mask	Purpose
Nitride	--	Not purposefully etched.
Poly 0	POLY0	PR mask – used to pattern Poly 0 ground planes
PSG 1	DIMPLE	Create dimples/bushings for Poly 1. Dimples are 0.75 um deep. Anti-stiction mask
PSG 1	ANCHOR1	Open holes to connect Poly 1 to Nitride to Poly 0
Poly 1	POLY1	Thin (0.2 um) PSG layer is used as hard mask to pattern Poly 1. The oxide mask is stripped using RIE.
PSG 2	POLY1_POLY2_VIA	Open holes to mechanically and electrically connect Poly 1 and Poly 2.
PSG 2	ANCHOR2	Open holes to connect Poly 2 to Poly 0 or Nitride. Etches both PSG1 and PSG2 in ONE step = no misalignment of etch holes. Eliminates need to cut PSG 1 for non-Poly 1 structure → prevents damage to Poly 0 or Nitride from overetching.
Poly 2	POLY2	Thin (0.2 um) PSG hard mask. Patterns Poly 2.
Metal	METAL	Patterns metal connects using liftoff.
	Release holes	
Poly 0	HOLE0	Provide holes for POLY0
Poly 1	HOLE1	Provides release holes for POLY1
Poly 2	HOLE2	Release holes for POLY2
Metal	HOLEM	Release holes for METAL

3. Design rule summary on pg. 28 of MUMPS design guide.
4. Purpose of various rules
  - a. Enclosure – prevents unintended etching of underlying layers.
  - b. Cut-in/Cut-out – reduce effect of large topologies by reducing step heights.
  - c. Separation – prevents features from being fused together

#### MUMPS Design guidelines

1. Don't make any unnecessary holes in the PSG layers
  - a. Stringers can form inside the anchor holes
  - b. Underlying layers can be exposed and thinned by overetching.
2. Always make the poly structures larger than the via or anchor holes
  - a. Same effect as making unnecessary holes
3. Improper pad design?
4. Don't use POLY1\_POLY2\_VIA to as an anchor mask. This leaves the substrate exposed.
5. Put metal on top of Poly 2 only to prevent step coverage problem.
6. Breaching the Nitride can be done using a ANCHOR1 + POLY1\_POLY2\_VIA and filling the hole with Poly 2.
7. Stacked Poly1+Poly2 structures
  - a. Large Poly 1 feature → larger POLY1\_POLY2\_VIA → Cover with Poly 2

## SUMMiT

Layer	Thickness	Purpose
Thermal oxide	0.63 um	
Low- $\sigma$ nitride	0.8 um	Mechanical and electrical passivation
MMPOLY0	0.3 um	Ground plane
SACOX1	2.0 um	Anchor
MMPOLY1	1.0 um	Hubs for gears
SACOX2	0.5 um	Hub clearance
MMPOLY2	1.5 um	
SACOX3	1.5-2.0 um	Planarization
MMPOLY3	2.0 um	

See attached handout for mask layers.

### General SUMMiT Notes

- Separate Poly 1 of MUMPS into MMPoly1 and MMPoly2
  - thinner MMPoly1 good for flexures/spring as  $K \sim t^3$
  - more flexibility in electrical interconnects (3-way wiring crossovers possible)
  - maskless metallization using top MMPoly3 as shield
- Designed to make gears, e.g., pin joint undercut
- CMP is critical to SUMMiT. Need to planarize to do MMPoly3, MMPoly4, etc. layers because cannot have high layers on top of highly nonplanar topology.
  - MUMPS overexposes a lot to compensate for topology  $\rightarrow$  loss of resolution
  - CMP remove link/gear interference problem
- All MEMS are done in a trench – 12 um for SUMMiT and 14 um for SUMMiT V.

### Comparison of MUMPS vs. SUMMiT

MUMPS	SUMMiT
“2 + 1” poly layers	“3 + 1” or “4 + 1” poly layers
3 um resolution	> 1 um resolution
1 cm $\times$ 1 cm die (\$2900 for 15)	5 mm $\times$ 5 mm die (\$5K – 10K for 9)
Poly 1	MMPoly 1 + MMPoly 2
p+ doped Poly 2	Undoped Poly 3
No planarization $\rightarrow$ less resolution	CMP before MMPoly3
8 masks	11 masks
Designed for comb drives and rotating gears	More advanced devices – microengine of comb drives, gears, linkage arms possible
	Greater electrostatic forces ( $f \propto t$ ) and spring stiffnesses ( $k \propto t^3$ ).
Cannot monolithically integrate CMOS + MEMS	Monolithic integration possible

## 5) Papers

### **Paper : Surface Micromachined Gear Trains..... J.J. S, E.J. Garcia**

Two comb drives push one gear operating at 300,000 RPM at most  
*Can't find other important things in there. (Sandia)*

### **Paper : Magnetic Microactuation of torsional ..... Jack Judy**

3. Nickel-iron plate attached on a pair of torsion beams. (T-shape, Fig.2)
4. NiFe, soft magnetic material, electroplated onto polysilicon
5. Poly  $\rightarrow$  10nm adhesion Cr  $\rightarrow$  100nm electroplating-seed layer  $\rightarrow$  PR  
 $\rightarrow$  develop  $\rightarrow$  mushroom over the PR edges(Fig.4,5)  $\rightarrow$  remove PR  
 $\rightarrow$  sputter-etching of seed layer  $\rightarrow$  release structure
6. Can be deflected 90 out of the plane by magnetic field 10kA/m
7. Sloping sidewall of the mushroom won't affect the performance in this study

### **Paper : A quantitative analysis of Scratch Drive ..... P.L, H. Fulita**

4. X/Y stage with 40-50um displacement and 25nm minimum motion
5. Put a vertical mirror on it, it could be a optical switch
6. To make a X/Y stage, the yield and performance of SDA are very important
7. Different SDA(Scratch Drive Actuator) shapes and sizes are tested (Fig.4)
8. The attachment length  $L'$ (Fig.2c) is measured vs. time and bias voltage(Fig.5)
  - e. From 0 to T/4, bias from 0 to 200V  $\rightarrow L'$  goes up to  $L'_{max} = 36\mu\text{m}$
  - f. From T/4 to T/2, bias from 200V to 0  $\rightarrow L'$  remains the same

### **Hysteresis of electrostatic actuator and residual charge**

- g. From T/2, when bias 0V to -60V  $\rightarrow L'$  goes to min.  $L'_0 = 10\mu\text{m}$

### **The rear part of the plate shifts forward as bushing remains in contact**

- h. Velocity = total movement ( $\Delta d$ ) / total time ( $\Delta t$ )
- i. Incremental step ( $\Delta x$ ) = (T/2)\*( $\Delta d/\Delta t$ )
- j. Unattached length ( $\Delta l$ ) = beam length  $L''$  – attached length  $L'$
- k. Larger ( $\Delta l$ )  $\rightarrow$  smaller ( $\Delta x$ ) , (Fig.7)

### **Paper : Linear microvibromotor for positioning..... M.J, R.S. Muller**

6. Electrostatically driven with submicron positioning resolution and 100um linear travel range(bi-directional)
7. Impact driven vibromotor. Use impact arm to kick the slider flingstoneily.
8. Four impacters are used (two for each direction of travel) to balance the force components perpendicular to moving direction and increase driving force in the moving direction.
9. Design concept:
  - a. Comb resonators are excited at their resonant frequency to gain an amplification of the electrostatic force by the resonator quality factor (30-100, in air).
  - b. Impact angle :

Is transverse force necessary?  
Yes.

when transverse force onto slider from impact arm -  
longitudinal friction force -  
and when longitudinal friction force exceeds the retarding friction  
force between slider-substrate and slider-flange → move forward

- c. The gap between the impact arm and the slider sidewall determines  
*Slider velocity*  
Required drive voltage

Large gap → lower collision velocity → longer “build-up” time  
Small gap → maximum energy transfer → restrict slider motion  
Gap of 3.6um and 2um were chosen

10. Resonance frequency of comb drive

- a. theoretical prediction in (1), page 56
- b. experimental measurement by applying a 10V(p-p) sin wave on a 40V  
dc voltage and adjust the frequency of sin wave till reach max  
amplitude

11. To control the velocity, a gating signal (control voltage waveform) is  
used(Fig.4) and the velocity and step size are measured

But the standard deviation of step size is too large. Why???

The two flange-to-slider clearances enable the lateral wobble of the slide  
→ needs feedback control for delicate positioning application

**Paper : Integrated microelectromechanical ..in CMOS ..... Gary Fedder**

1. High aspect ratio microstructure with MOSIS CMOS chip(tri-metal process)
2. Use the topmost metal layer as a mask for RIE dielectric layer etching to  
define microstructure with almost vertical sidewall of dielectric structure
3. Dry SF6/O2 plasma etching and then wet etching of Silicon substrate to  
release structure
4. Need large release holes for wet etching. Vertical/lateral etch rate = 2:1
5. Use this for comb drive moving only 2um

**Paper: Laminated high aspect ratio microstructure .... Gary Fedder, Carley**

5. Same guy as above paper
6. Displacement 200um this time

**Paper: CMOS MEMS.....Henry Baltes**

3. Co-integration of MEMS and CMOS technology is reviewed
4. Simulation tool SOLIDIS & ICMAT

**Paper: Simulation toolbox and material ..... H. Baltes**

5. Review of MEMS simulation tool

**Paper: A rotary electrostatic micromotor .....A.A. Yasseen**

6. One input fiber and eight output fiber switched by a mirror on a micromotor
7. They want to fabricate an optical bench on Si but they can only make a motor with mirror. So they mount other optical components (gradient index lenses for minimal divergence) through the use of alignment groove.
8. Design concept:
  - a. Each distinct rotor position → one optical out put channel
  - b. # of stator poles → define # of different rotor position → can't be infinite, because
  - c. scalability is determined by → minimum angular spacing between each fiber channel → to obtain low crosstalk(noise)
  - d. the size(diameter) of rotor → define the number of fiber channel can be packed in a circle
  - e. *Does it work?* Not quite

Mirror surface normal/input channel angle ↑

→ apparent mirror surface ↓

→ mirror will not reflect all the light

→ maximum angle =  $124^\circ$

→ needs 2 input channels for 10 output channels

Mirror surface normal/input channel angel ↑

- f. The stator and rotor patterns were fabricate on separate dices of the same wafer and assembled together manually(Fig.2)
- g. A mirror with four pins was inserted into the holes on the rotor(Fig.3)
- h. Surface coated with Al to reduce crosstalk (in conclusion)

**Paper: Surface micromachined Polysilicon thermal actuator .... John Hi**

4. Use thermal actuator to drive stepper motor, positioner and gripper
5. Electrostatic actuator:
  - a. Low power
  - b. High frequency
  - c. Requires close tolerance
  - d. Requires high voltage for lager force
  - e. Small deflection
6. Thermal actuator:
  - a. Large deflection
  - b. Large force in a current/voltage regime that is compatible with IC
  - c. Fabricated in standard MEMS foundry(MUMP)
  - d. They didn't mention about huge power consumption, accuracy and positioning resolution

7. Design concept:

- a. Thermal expansion is a large force for dual-material structure
- b. For single-material(Poly), “thermo-magnetic” multiplying structure is used. (Fig.1) thermal actuator or “heatuator”.
- c. U shape with narrow hot arm and wide cold arm. Temperature difference between two arms gives the deflection

*Cold arm wider* → decrease current  
→ increase the surface area for cooling  
→ increase temperature difference  
→ increase actuator efficiency

*Trench under hot arm* → better thermal isolation  
→ less heat loss to the substrate  
→ increase the deflection/current ratio

8. Does it work?

*Permanent back-bend* → when driven past the point where they stop deflecting in the forward direction (picture not shown in the paper)  
→ actuator is left permanently back-bend after the current is removed  
→ they claim it can be used in MEMS structure assembly  
→ after back-bend, it's still usable, but starting from “negative” deflection relative to its origin position → they claim it's a beneficial design option

*hot arm bow* → when push a stiff structure, the long thin hot arm will bow rather than push  
→ in back-bend mode, hot arm is in tension, stiffer

*hot arm bow* → when push a stiff structure, the long thin hot arm will bow rather than push

9. They use actuator array to enlarge the force and cancel out the arcing and expanding motion → purely linear motion

Concern over current sharing through so many parallel paths

Polysilicon has build-in current leveling

When current -

- temperature of the arm -
- resistance of the poly -
- current -

→ current self-balance between parallel arms

They demonstrate how to integrate the thermal actuator array into a rotary stepper motor to increase deflection

# EE250C

Circa: Spring 1999

Professor: Jack Judy

The file for this course consists of 4 parts;

- 1) A review of selected topics from Chapter 4 of Fraden
- 2) Review of transduction methods
- 3) Review of magnetic sensors
- 4) Synopses of two additional papers presented in class

## 1) Chapter 4 Fraden

-**Span/dynamic range/input full scale** =range of input stimuli that can be accurately converted by the sensor into output

-1 decibel= $10 \log (P2/P1) = 20 \log (V2/V1)$

-**sensitivty (responsivity Kaiser)** =ratio: electrical signal/physical signal

-**resolution (sensitivity Kaiser)** =minimum detectable signal-smallest electrical signal/responsivity

-**bandwidth** frequency range of measurement

-**noise density** (units:  $\frac{V}{\sqrt{Hz}}$ ) can reduce by decreasing bandwidth or increasing measurement time

### Control System Model

Environment

Sensor

Interface Electronics

Microcontroller, DSP Memory

Mech Actuators/Display

Output Drives

Output Signal Conditioning

### Sensor Model

Sensing Element/Transduction Material

Interconnection/input "gate"

Signal Conditioning/Amplification

ADC

MCU-Bidirectional Bus-Calibration Device

Controller

Memory

## Input Impedence of Interface Circuits

For a generic RC interface circuit

$$Z_{total} = R \parallel Z_C = \frac{R * \frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} = \frac{R}{j\omega RC + 1}$$

if  $f \ll 2\pi RC$ , then  $Z \sim R$

if  $f > 2\pi RC$ , then  $Z \sim \frac{1}{j\omega C}$

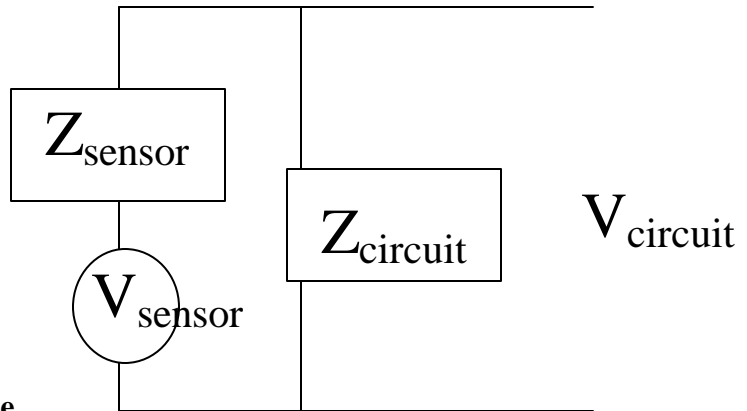
where  $j = \sqrt{-1}$

Sensor with a voltage output:

Must account for sensor's output impedance:

$$V_{in} = V_{sensor} \frac{Z_{in}}{Z_{in} + Z_{out}}$$

-to maximize  $V_{in}$  to circuit  
 want  $Z_{circuit}$  in to be high  
 want  $Z_{sensor}$  out to be low



**Circuit Input Frequency Response**

For a purely resistive sensor connected to input impedance:

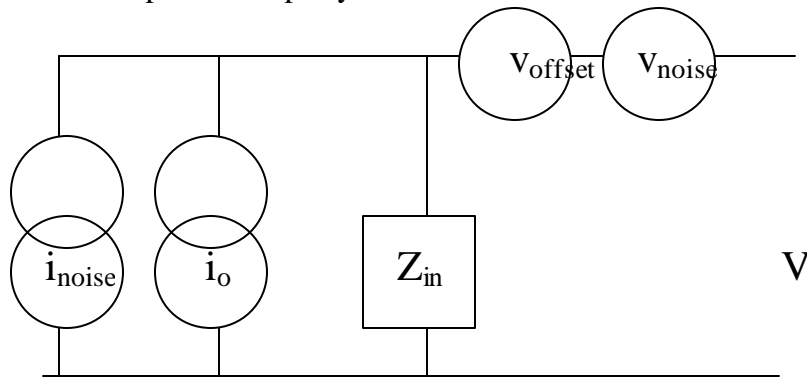
$$V = \frac{V_{sensor}}{\sqrt{1 + \left(\frac{f}{f_c}\right)^2}}$$

if  $f \ll f_{corner}$ , then  $V = V_{sensor}$

if  $f > f_{corner}$ , then  $V = \frac{V_{sensor}}{\left(\frac{f}{f_c}\right)}$

Corner frequency is defined where amplitude drops by a factor of 3 dB:

$$f_c = \frac{1}{2\pi RC}$$



Example: passive electronic circuit

$V_o$ -offset voltage-in series with input and is independent of sensor output impedance  
 $I_o$ -input bias current-generated by the circuit. For:

- Bipolar transistors- high
- JFET's low
- CMOS circuits very low

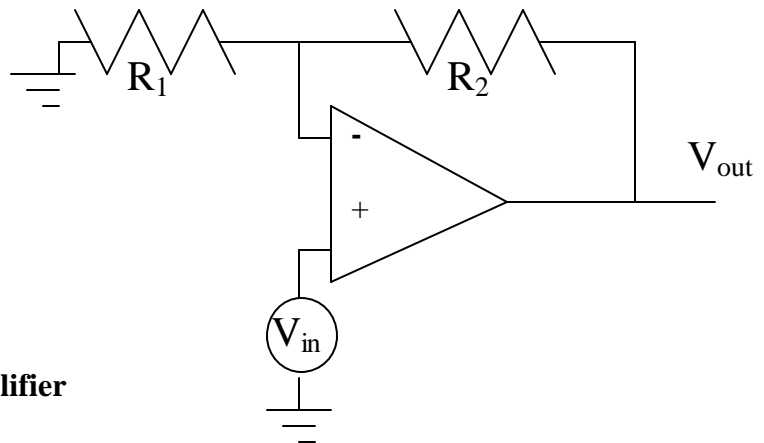
-serious problem for circuit /sensor uses high Z components  
 -leakage current from circuit board may be problem with high Z circuits. Possible if PCB has lower surface resistance. If sensor capacitive, output capacitance will be quickly charged by leakage current.

-to avoid leakage current: careful board layout-co-locate high Z regions  
 OR driven shield-conductive trace that absorbs leakage and delivers to low impedance point

### Operational Amplifier

- typically constructed of 10's-100's of individual components
- two inputs: one inverting -, one noninverting +
- high gain  $A_{open.loop} \sim 10^4 - 10^6$
- high  $Z_{in} \sim (100 \text{ Mohms}-6 \text{ Gohms})$
- small  $Z_{out} \sim 1 \text{ ohm}$
- low bias current=few pA
- low offset voltage=uV-few mV
- broad frequency range of operation
- low sensitivity to  $\Delta T$ ,  $\Delta V$  supply
- high common mode rejection rate (CMRR)-amplifier suppresses signals that are in-phase and equal magnitude

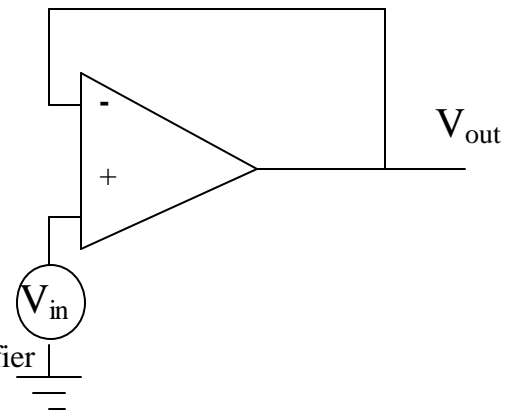
-open loop rarely used, varies as fnx of load, f, and  $\Delta T$ , high gain can cause instability see Figure 4.5B Fraden



### Closed Loop, Non-Inverting Amplifier

$$V_{out} = (1 + R_2/R_1) * V_{in}$$

- ability of OPAM to amplify small magnitude high frequency signals is specified by the GBW- gain bandwidth product =  $A_{open loop} * f_1$ , frequency where amplifier gain=1
- above  $f_1$ , amplifier no longer amplifies
- open loop gain of an OPAM should be 100x closed loop gain at highest desired freq, better to use 1000x



### Voltage Follower-Buffer

- provides impedance conversion from high to low, current amplifier
- has high input Z, low output Z
- gain close to 1, high current gain
- has very little effect on sensor's performance

-for current generating sensors, input bias of follower must be 100x smaller than sensor output

-output offset voltage:

$$V_{out} = A(V_{in} + i_o R_{eqv})$$

$R_{eqv}$  = equivalent resistance at input = sensor output Z + input Z of amp

$i_o$  - input bias current

### Monopolar Amplifiers

-similar to voltage follower, but gain may be higher or lower than unity

$$-A = 1 + R_2/R_1$$

-if amplifier is voltage follower, than minimum gain is 1

-to limit bandwidth, bput capacitor in parallel with  $R_2$

-bandwidth at 3dB may be estimated:

$$f_u = \frac{0.159}{R_2 C}$$

### Instrumentational Amplifier-I didn't draw this one p.158

-two inputs, one output, finite gain

-function is to produce output signal proportional to difference in voltage between two inputs

$$-V_{out} = A(V_+ - V_-)$$

-overall gain is:

$$A = \left(1 + \frac{2R}{R_a}\right) \frac{R_3}{R_2}$$

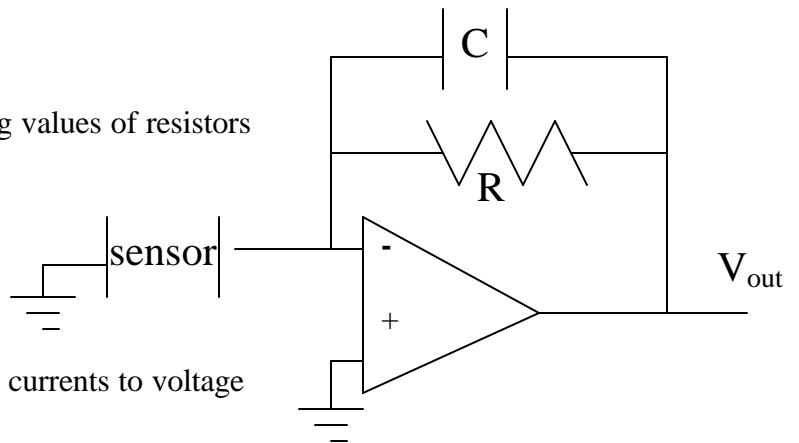
-can construct instrumentational ampifier from 2 identical Op Amps and several resistors.

Fig 4.9 p 15. Gain of amp:

$$A \sim 2(1 + R/R_a)$$

$R_a$  - gain setting resistor

-the CMRR primarily depends in matching values of resistors



### Charge Amplifiers

-very low bias currents

-used to convert from very low charges or currents to voltage signals

-capacitive sensors include capacitive force, pressure, piezoelectric, and pyroelectric detectors

-transfer function of converter is:

$$V_{out} = -\Delta Q/C$$

-a noninverting circuit can convert and amplify a signal. However, its speed response depends on both the sensor's capacitance and converting resistor, Response to step

function is:

$$V_{out} = iR_b \left( 1 + \frac{R_2}{R_1} \right) \left( 1 - e^{-t/\tau} \right)$$

## 2) Transduction Methods

### A. Resistive sensing & Piezoresistivity

- 1) Basic equations:  $R = \rho L/A$        $\rho$ : resistivity  
 $\rho = m/(ne^2\tau)$        $\rho = \rho(T)$
- 2) TCR = Temp. Coefficient of Resistance  $\rightarrow$  determines how  $\rho$  changes as a function of T  
 High TCR  $\rightarrow$  sensor resistance changes a lot with temp, e.g., thermistors.  
 Low TCR  $\rightarrow$  resistance insensitive to temperature, i.e, thermally stable circuits
- 3) Typical circuit: Use a known current source and measure voltage drop across  $R_{sense}$ 
  - Need to account for errors due to other resistances, temp. changes, noise, etc.
- 4) Now take  $R = \rho L/A$  and differentiate to get piezoresistance equation  
 $\rightarrow dR/R = \partial\rho/\rho + \partial L/L - \partial A/A$
- 5) Gauge Factor:  $GF = (\Delta R/R) / (\Delta L/L) = (1 + 2\nu) + (1/\epsilon_{long})(\partial\rho/\rho)$   
 - High GF means high change in resistance for small strains  $\rightarrow$  high amplification
- 6) For silicon, piezoresistance equation is:  $\Delta\rho/\rho = \sigma_s\pi_s + \sigma_t\pi_t$ 
  - Stress field  $\rightarrow$  change in resistivity  $\rightarrow$  measure  $dR/R$
  - In practice: dope a silicon membrane with 4 piezoresistors in a bridge pattern to measure  $dR/R$ . Tweak resistance until  $V_{out} = 0$ .
  - Biasing piezoresistors?
  - High GF possible in Si. SCS  $\sim 200$ , Poly  $\sim 20$ . In comparison, metal  $\sim 2$
  - Causes of mechanical drift
    - thermal stress
    - creeps & cracks
    - change in intrinsic stresses
  - Electrical drift
    - Change  $E$  near piezoresistor  $\rightarrow$  modulate depth of doped region
    - Typical drift  $\sim 2\%$
    - Wheatstone bridge used to reject common mode changes due to this drift

### B. Capacitive Sensing

- 1) For a closing gap actuator,  $\Delta C = (\partial C/\partial g)\Delta g$ 
  - typically  $\Delta C = 100 \times 10^{-18}$  F (closing gap)

- 2) For a comb drive,  $\Delta C = \epsilon_0 t/g = 10^{-21}$  F/finger
- 3) Let's use a differential capacitor sensor.
  - a) First case, a capacitive divider with voltage difference of +V to ground.  
 $\rightarrow V_{\text{sense}} = \frac{1}{2} (1 + \Delta C/C_0)V$ , but  $\Delta C/C_0 \sim 1/1000$ , so lose signal!
  - b) A better way, use the capacitive divider with voltage difference of +V to -V  
 $\rightarrow V_{\text{sense}} = \Delta C/C_0$
- 4) Consider electrostatic forces based on
  - a) Constant voltage,  $F = \frac{1}{2} \epsilon_0 A V^2 / g^2 \rightarrow$  dependent on gap
  - b) Constant charge,  $F = \frac{1}{2} Q^2 / (\epsilon A) \rightarrow$  does not depend on gap!
- 5) What's the current output when you vary the capacitance or voltage?  
 Remember,  $i = C \partial V / \partial t + V \partial C / \partial t$ 
  - a) Vary capacitance  $\rightarrow i = 10^{-15}$  A for 1 Hz,  $i = 10^{-9}$  A for 1 MHz
  - b) Vary voltage  $\rightarrow i = 10^{-12}$  A for 1 Hz,  $i = 1 \mu\text{A}$
  - c) So to get stronger signals, vary the voltage
- 6) Linearity in capacitive sensing
  - a) Single capacitor sensor:  $C(g) = \epsilon_r \epsilon_0 A / (g_0 + \Delta g) = \epsilon_r \epsilon_0 A / g_0 (1 - \Delta g / g_0 + \Delta g^2 / g_0^2 + \dots)$   
 $\rightarrow$  very small  $\Delta g$  needed to get 1% linearity
  - b) Differential capacitor:  $C_2 - C_1 = 2\epsilon_r \epsilon_0 A / g_0 (\Delta g / g_0)$   
 $\rightarrow$  get rid of 2<sup>nd</sup> order nonlinearity
- 7) Noise issues
  - a) Parasitic capacitances (from bond wires, nearby microstructures, packaging, etc) a big problem!
  - b)  $V_{\text{sense}}/V = (C_1 - C_2) / (C_1 + C_2 + C_{\text{parasitic}})$
  - c) Solution  $\rightarrow$  Use a capacitive shield

### C. PIEZOELECTRIC

- 1) Basic idea: An applied stress will generate an measurable electric field OR CONVERSELY an applied field will create a stress and hence a displacement
- 2) Materials with this property: quartz, ceramics (PZT), polymers (PVDF)
- 3) Basic equation:  $\Delta Q = d_{ij} \Delta F_j$
- 4) Measured voltage  $V = Q/C = d_{33} \sigma_3 A_3 / (\epsilon_0 \epsilon_r)$ . Typically  $V/F = 1$  V/N (very high!)
- 5) Displacement (from Hooke's Law)  $\Delta L = FL/(EA)$ ;  $\Delta L \sim 1$  nm for typically values
- 6) Moral of the story: Small displacements generate large voltages! Conversely, large voltages create small displacements.
- 7) Inherent problem: Cannot do static or low frequency measurements

### D. TUNNELING

- 1) Basic equation:  $I_{\text{tunnel}} = I_0 \exp[-\alpha g \sqrt{\Phi}]$ ,  $\alpha = 1.025$  1/(Å√eV)
- 2) Running typical numbers, you get a 3X change in current for 1 angstrom of movement

- 3) Useful for measuring accurately very small (sub angstrom) features. Device is not sensitive to geometry of probe tip until features < 10 nm. Also, oxidation is bad, so use Pt for tip.
- 4) Need high speed, super accurate feedback controller
  - range of motion for tip is only 10 angstroms.
  - highly nonlinear output response

**E. MAGNETIC**

1) Hall Effect Sensor:  $V_H = R_H IB/t$

**Comparison of the 3 Major Transduction Methods**

	Capacitive	Piezoelectric	Piezoresistive
Temperature Range	Very Wide	Wide	Medium
Linearity Error	High	Medium	Low
DC response	Yes	No	Yes
AC Response	Wide	Wide	Medium
Damping Available	Yes	No	Yes
Accuracy (FS)	± 0.2%	± 1%	± 1%
Sensitivity	High	Medium	Medium
Electronics Required	Yes	Yes	No
Noise sensitivity	High	High	Medium
Scaling Issue?	Works well in microscale	Works well in microscale	Limited by membrane thickness
Static Calibration	On chip possible	No	Yes
Resolution ( $\Delta V/\Delta p$ )	$3.1 \times 10^{-5}$	$10^{-8}$	$6 \times 10^{-7}$
Cost	Medium	High	Low

**3) Magnetic Sensors**

**Paper** Review of Magnetic Sensors.....James E. Lenz

Search-coil magnetometer

Change in magnetic flux  $\Rightarrow$  current induced in the coil  $\Rightarrow$  voltage generated between its

leads  $\propto$  flux change rate.  $e = \frac{-d\Phi}{dt}$  (Faraday's law)

Change in magnetic flux due to

- coil is in a time-varying magnetic-field
- coil moves in a non-uniform magnetic field

A rod of ferromagnetic material is placed inside the coil to “gather” the surrounding **B** and increase flux density.

**Sensitivity** depends on

- permeability of the core material
- area of the coil
- number of turns
- rate of change of the magnetic flux

**Frequency response** depends on

- Ratio of coil's inductance to its resistance (dissipation time): Induc  $\uparrow$  current dissipates more slowly. R $\downarrow$  current dissipates more quickly

$\Rightarrow$  Practically, limitations by voltage readout electronics

Sensitivity range:  $10^{-6}$  G up to  $\infty$  ( $10^4$  G = 1 T =  $10^9$   $\gamma$ )

Frequency range: 1 Hz – 1 MHz

Size: 2” – 50”

Power: 1-10mW (readout electronics)

Passive use or active mode.

## Flux-Gate magnetometer

Ferromagnetic material wound with 2 coils. Takes advantage of hysteresis behavior of ferromagnetic materials.

~ signal in coil 1  $\Rightarrow$  Sat. Mag. of the core once every half-cycle  $\Rightarrow$  loop of magnetic flux  $\Rightarrow$  coil 2 senses these changes  $\Rightarrow$  Sat. Mag. for coil 2  $\Rightarrow$  reluctance  $\uparrow$   $\Rightarrow$  field is repelled out of the core  $\Rightarrow$  coil 2 senses this  $\Rightarrow$  current is then reduced in drive coil  $\Rightarrow$  get out of sat. Mag.  $\Rightarrow$  external magnetic field attracted to the core  $\Rightarrow$  coil 2 senses this etc.... Magnetic lines of flux alternatively cut the second coil. Voltage associated with 2<sup>nd</sup> harmonic of the output is proportional to external magnetic field.

Sensitivity depends on shape of hysteresis curve (better with square shape for B-H curve)

Sensitivity range:  $10^{-6}$  – 100 G

Frequency response limited by excitation field and ferromagnetic material response time

Upper limit: 10 kHz

Size: similar to search-coil, but 5 times more power

PRO: precise measurement of DC fields.

Many versions developed, to improve power consumption for example

## Optically pumped magnetometer

Based on Zeeman effect: some of the characteristic spectral lines of atoms are split (with different wavelengths) when placed in an external magnetic field. Especially efficient with Cesium.

Needs cesium vapor optically pumped with circularly polarized light, photodetector, rf source.

Measures total magnetic field, not only components along sensitive axis.

Sensitivity range:  $10^{-8}$ -1 G

LARGE size

HIGH power consumption (several W)

## Nuclear-precession Magnetometer

Protons in a hydrocarbon (benzene) fluid are temporarily aligned in uniform **B** created by a current in a coil. Then current is switched off  $\Rightarrow$  protons spin axis precesses about the ambient magnetic field  $\Rightarrow$  traces a circle at the precession frequency rate, which depends on the strength of the external field  $\Rightarrow$  generate a signal in the coil proportional to magnetic field strength.

Total external field is measured.

Sensitivity range:  $10^{-7}$ -1 G

Frequency range limited by gating frequency of hydrocarbon fluid.

Under development (in 1990) an optically pumped magnetometer relying on nuclear precession for readout: potentially very high sensitivity ( $10^{-8}$ G) with modest operating power (<0.5W)

## SQUID Magnetometer

Superconducting QUantum Interference Device. Materials are cooled below a superconducting transition temperature and show remarkable interactions between electric currents and magnetic fields: an induced current in a ring remains forever, in the absence of further disturbances. The ring can respond to a change in the field corresponding to fractions of a single quantum unit of magnetic flux. Then needs RF circuit coupled with the ring to measure it.

Sensitivity range :  $10^{-10}$ - $10^{-4}$ G

## Hall-effect sensor

Sensitivity range: Si devices:10-1000G

Indium Antimonide sensors:  $10^{-3}$  G

Can measure constant or varying flux

Frequency limit: 1MHz

Size: 0.1 in.<sup>2</sup>

Power: 0.1 – 0.2 W

LARGE range of operating temperatures: -273°C- +200°C

## Magnetoresistive magnetometer

Resistance of a ferromagnetic thin film varies with the direction of magnetization of the film. The more parallel, the higher, and the more perpendicular, the lower.

Sensitivity range:  $10^{-2}$ -50G with open-loop readout electronics.  
 $10^{-6}$ G with closed-loop feedback for limited bandwidths.  
WIDE dynamic range with open-loop readout electronics: DC to 1 GHz.  
Small, light, low power consumption: 0.1-0.5mW  
LARGE range of operating temperatures:  $-55^{\circ}\text{C} - 200^{\circ}\text{C}$

## Magnetodiode

*pn* junction, where *p* region is separated from the *n* region by an area of undoped silicon.  
 $\text{SiO}_2$  on top of the Si, and Sapphire below.

Magnetic field induces deflection for holes and electrons, and eventually resistance is changed.

Response is 10 times higher than Hall-effect device.

CON: requires a silicon-on-insulator substrate, not available for standard silicon technology.

## Magnetotransistor

*npn* transistor, with 2 collectors instead of 1.

Both Hall and Suhl effect, which takes place when Lorentz force is not compensated.

Devices are made in which one of these 2 effects is dominant.

Under evaluation (in '90)

## Fiber-optic magnetometer

2-glass fiber arranged to make a Mach-Zender interferometer. One of the fibers is wrapped around or coated by a magnetostrictive material, whose dimensions depend on the direction and extent of the magnetization, hence changes in interference.

Still problem with noise and packaging

Sensitivity range:  $10^{-7}$ -10 G

Frequency range: constant-60kHz

Size: 4in.x1in.

## Magneto-optical sensor

Exploits the rotation of the plane of polarized light when traveling through a magnetic material.

Largest effects in a few crystals where both crystal axis and applied magnetic field are aligned.

Material: terbium gallium garnet

VERY FAST response time: GHz range already fabricated (in '90)

POOR sensitivity (small effect in relation to earth's magnetic field).

## 4) Paper Synopses

### Paper: Understanding Smart Sensors (Chapter 1 Smart Sensor Basics)

1. The intelligence required from “smart sensors” is available from microcontroller (MCU), digital signal processor (DSP) or application-specific integrated circuit (ASIC) technologies.
2. Sensing Techniques of Mechanical-Electronic Transducers

Technique	Status in Silicon Sensor
Piezoresistive	Pressure,acceleration
Capacitive	Pressure,acceleration
Piezoelectric	Pressure,acceleration
Optoelectronic	Position,velcoity
Magnetic	Position,velcoity,magnetic field

3. Basic elements for a smart sensor
  - Sensing element, amplification and signal conditioning, A/D converter, memory and logic controller.
4. Integration of Micromachining and Microelectronics
  - Integration/Partition is an art, fabrication is a key factor
  - Hybrid(Package level) or monolithic integration ?
  - Advantages:
    - Trade off unnecessary performance characteristics→provide desirable performance advantages
    - Environment or error compensation
    - Increase reliability by reducing internal connections
  - Disadvantages
    - Additional performance improvements is limited the the imagination of designers.
    - Packaging is always a problem, very few commonly accepted packages, instead, each supplier provides a unique package.

### Paper: Sensors for automotive applications

#### Powertrain sensors

A device that costs more than \$1 is considered to be very expensive.

A lot of sensors needed for automotive powertrain, you can refer to Table1 to catch the main ideas of applications.

Sensor types: Pressure sensors, temperature sensors, position sensors

Sensing method:

Piezo-resistive(Pressure), capacitive diaphragm(Pressure), hall effect (Speed)and Potentiometer(Position)

1.Ignition Control

## 2. Fuel Control :

- To measure mass air flow
- Air vanemeter(old type), it measures air velocity rather than mass.
- Hot-wire anemometer, it directly measure mass air flow directly. → Accurate, fast.

## 3. Emission Control:

- To measure the air-fuel ratio, need a feedback control to reduce carbon monoxide(CO), hydrocarbones(HC) and nitrogen oxides (NOx)

## 4. Combustion process measurement

- After the event measurement: (Not good)
  - Direct sensing of combustion chamber pressure, and by timing the pressure peak to use as a measure of work done and efficiency.
  - Detection of position and timing of frame front.
- Before the event measurement: (Good)  
*Measure the parameters like inlet gas velocity combined with a control system.*

## 5. Torque output measurement

- Use fixed inductive sensors to detect the permeability change in the rotating shaft material caused by strain and derive torque from this.

## 6. Transmission Control

- Critical sensors required are those for: engine speed, gearbox output speed, hydraulic control valve position and oil pressure

## **Drive information and diagnostics**

### 1. Fuel quantity

Measurement of the capacitance change between two narrow plates dipping into the fuel.

Measurement of the change in optical transmission between two optical light guides projecting into the fuel.

### 2. Fuel flow

### 3. Oil level

# MAE281

circa Fall 1998

Professor: CJ Kim, Chih-Ming Ho

The file for this course is only a brief outline of the topics covered

## CJ's Part

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- Scaling (isometric scaling)
  - Weight lifting
  - Common nails produced
  - Rowing Shells
- Inertia Force
  - Deformation by inertia force
  - Bending by weight
  - Relative transverse deformation
- Surface Tension Force
  - Laplace-Young Equation
  - Method for measurement
  - Surface tension and gravity
  - Control of surface tension
    - Surfacant
    - Temperature
- Van der Waal
  - dispersion force
  - induced-dipole force
  - casimir force
- Electrostatic force
  - Electrical double layer
  - Strong long range force
    - Coulombic force
    - Ionic bond
    - Hydrogen bond
- Between surfaces
  - In vacuum
  - In non-vacuum
  - In liquid
- Locomotion (Low Reynolds number locomotion)
  - Short stopping
  - Reversibility
  - Ciliary propulsion
  - Flagella propulsion
  - Insect flight
  - Jumping
- Continuous Electrowetting
- Tribology
  - Theory of friction
  - Friction of materials
- Micro material testing
- Thin Film Property Issues in MEMS
  - Summary for stress-strain
  - Engineering Beam Theory
  - Thin-Film property measurement
  - residual stress/strain in thin film

- Fluid Mechanics and heat transfer issues

## Ho's Part

---

- Continuum and Molecular Approaches
- Traditional continuum fluid mechanics
- Flow in microconfiguration
  - Knudsen number
  - Boundary condition for gas
- Gas Flow in channel
  - Pressure distribution
  - Mass flow rate
  - Knudsen number distribution
  - K.E. of molecules
  - Average speed of molecules
  - Mean free path
  - Viscosity of gas
  - Air flow in micro channel
  - Boundary Condition( slip/non-slip)

### Liquid Flows

- Molecular Structure
  - Polar/Non-polar
- Electrical double layer
- Solid surface
- Scaler, Vector, Tensor
- Continuum Approach
  - Governing Equations ( Force, momentum, moment of momentum)
    - Cauchy's laws
  - Constitutive Relation
    - Stress~ strain rate
    - How to reduce 81 viscosity items to 1

### Molecular approach

- Governing Equations
  - Deterministic approach
  - Statistical approach
- Constitutive Relation
  - Potential; function (L-J relation)

### Boundary condition

- Slip length
- Surface to volume ratio
- Short and long range forces
  - Coulomb force
  - Van der waal force
    - Orientation force
    - Induced force
    - Dispersion force
- Electrical double layer

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## **Papers:**

- [1.] Liquid Micromotor Driven by Continuous Electrowetting
- [2.] Microactuation by Continuous Electrowetting Phenomenon and Silicon Deep Rie Process
- [3.] Preliminary Investigation of Micropumping Based on Electrical Control of Interfacial Tension
- [4.] Specimen Size Effect on Tensile Strength of Surface-Micromachined Polycrystalline Silicon Thin Films
- [5.] When Liquids Stay Dry

# MAE287

circa Winter 1999

Professor: CJ Kim

The file for this course consists of two parts;

- 4) Outline of papers presented in class
- 5) Synopses of several papers

## 1) Outline

<b>Author</b>	<b>Title</b>	<b># Pg</b>
Long-Sun Huang & CJ Kim	True Crystal Directions in MEMS	19
M. Shikida, et al	Comparison of Anisotropic Etching Properties Between KOH and TMAH Solution	6
M. Sekimura	Anisotropic Etching of Surfactant-Added TMAH Solution	6
F. Laermer, et al	Bosch Deep Silicon Etching: Improving Uniformity and Etch Rate for Advanced MEMS Applications	6
J. van Suchtelen, et al	Simulation of Anisotropic Wet-Chemical Etching Using a Physical Model	6
H. Suh, et al	Dendritic Materials as a Dry Release Sacrificial Layer	5
J.T. Borenstein, et al	A New Ultra-Hard Etch-Stop Layer for High Precision Micromachining	6
M.M, Maharbiz, et al	Batch Micropackaging by Compression-Bonded Wafer-Wafer Transfer	8
K.S. Leboutz, et al	Vacuum Encapsulation of Resonant Devices Using Permeable Polysilicon	6
N.K. Budraa, et al	Low Pressure and Low Temperature Hermetic Wafer Bonding Using Microwave Heating	3
S. Konishi, et al	Direct Drawing for Microfabrication Without Photolithography	6
S. Tadokoro, et al	Soft Micromanipulation Device with Multiple Degrees of Freedom Consisting of High Polymer Gel Actuators	6
N. Miki & I. Shimoyama	Flight Performance of Microwings Rotating in an Alternating Magnetic Field	6
S. Takeuchi & I. Shimoyama	Three Dimensional SMA Microelectrodes with Clipping Structure for Insect Neural Recording	6

P.E. Kladitis, et al	Prototype Microrobots for Micro Positioning in a Manufacturing Process and Micro Unmanned Vehicles	6
T. Ebefors, et al	A Robust Microconveyer Realized by Arrayed Polyimide Joint Actuators	6
J. Ok, M. Chu, & CJ Kim	Pneumatically Driven Microcage for Micro-objects in Biological Liquid	5

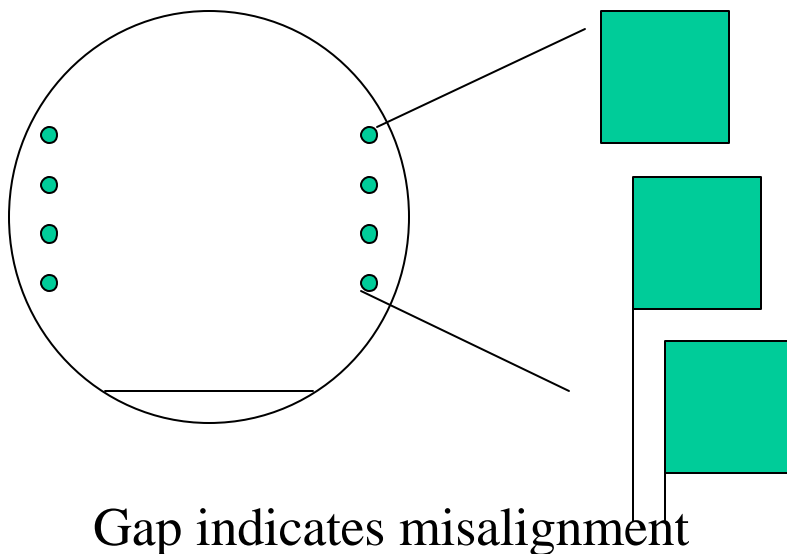
**LECTURES**

- Bonding
- Microchannels in MEMS
- Adhesion & Stiction
- MEMS '94 Video
- Vacuum Chambers & Sharp Tip Formation
- Bulk vs. Thin Film properties & Stress Measurements
- Overview of Different Foundry Services & Standardized Processes
- ADXL50 Accelerometer
- Automotive Micromachined Fuel Injectors
- Development of Microfluid Systems
- Development of Inkjets

**2) Paper Synopses**

**Paper: Reveal True Crystal Direction**

- accuracy of determining crystal direction will determine degree of undercut
- more delicate mechanical structures require precise etching
- misalignment to crystal direction yields “stepping” along 111 faces in anisotropic wet etch
- a bunch of people have worked on this
- for Si (100):
- use “extra” real estate at edges for anisotropic wet etch



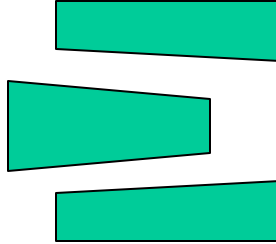
-can either align to square edges or align to center of pyramid-it's your choice!

-find 3 pyramids with smallest d

Si (110):

Can use “fan”-not really sure about this OR

Crate alignment “fork”s to replace “inverted pyramids” along edge:



Contact of fork indicates misalignment

-accuracy: Si (100) 0.05 deg, Si (110) 0.1 deg

Corner Compensation

-convex corners are attacked by undercutting

-generally undesirable-but can accommodate by incorporating sacrificial material into design

-as many different geometries as you can think of

-some additional gibberish about MEMS packaging

### **Paper: Comparison of Anisotropic Etching Properties between KOH and TMAH Solutions**

-to evaluate the etching properties as a function of orientation, hemispherical specimens of SCS were used

-hemisphere radius 22 mm, sphericity > 10 um-different temperatures and conc were examined

-dependence of etching rates on orientation were most noted along 111 and 221 planes

-don't grasp significance of higher order planes

-etch rate of TMAH is half rate of KOH for (100)/(111) ratio. This indicates TMAH is not appropriate for fabricating microstructures where (111) plane must not be attacked significantly by solution

-concentration to maximize etching rate was 25% for KOH and 20% for TMAH

-small hillocks less than 10um in size on (100) plane for TMAH

-activation energy is 0.6 eV for both etchants

-circulation improves TMAH etch but not KOH

**BOTTOM LINE:** check out the charts if you're interested in effects of temp, conc, or orientation

### **Paper: Anisotropic Etching of Surfactant Added TMAH Solution**

-roughness of etched 110 plane improved with surfactant

- in general, TMAH etch rates greatly reduced by presence of detergent surfactant
- it is possible to effectively “switch” (100) and (110) planes with surfactant
- this effect is well-documented for KOH
- to achieve same result with TMAH requires much more detergent but change in etch ratio is much larger
- surfactant helps to eliminate “column” texture commonly seen in pure TMAH
- “wagon wheel” pattern, i.e. an array of trenches arranged like spokes of a wheel are used to detect anisotropy of etchant
- pure TMAH shows clear pattern on wagon wheel, w/ surfactant does not reveal clear pattern
- addition of surfactant also helped address problem of convex corner undercutting
- can use surfactant w/ TMAH to yield 45 deg cut in Si-an important result for optical reflectors

**Paper: Bosch Deep Silicon Etching: Improving Uniformity and Etch Rate for Advanced MEMS Applications**

- bosch deep si etching improves uniformity of plasma etch
- most plasma sources: coil around dielectric vessel, powered by radio frequency
- unlike chlorine, fluorine radicals etch Si without need for ion assistance
- fluorine isotropic by nature, requires passivation to achieve anisotropy
- oxygen used to passivate si sidewalls, enhanced by cryogenic cooling, but difficult to control
- teflon sidewall films are more suitable, but deplete plasma ions before etch
- bosch process relies on very separate deposition and etch steps
- during etch steps, part of sidewall polymer material deposited in previous deposition step is removed by off-vertical ion impact hitting the sidewalls, and redeposited deeper in trench.
- used by plasmatherm and ALCATEL
- etch uniformity improved by factor of 4

**Paper: Dendritic Materials as a Dry Release Sacrificial Layer**

Authors: H. Suh, P. Bharathi, J. Moore, & D.J. Beebe

Synopsis: Nickel cantilevers are dry released in O<sub>2</sub> plasma with dendritic polymers acting as sacrificial layers. This process avoids the stiction normally associated with wet releases, works pretty fast, and is more robust than other dry release methods.

- Notes:
- Dendritic polymers are well-defined polymers generated from a single seed molecule or monomer. They are grown layer by layer and with tunable physical, chemical, mechanical, and electrical properties.
  - Can release a 100 μm × 1000 μm cantilever in 10 minutes

**Paper:**        **A New Ultra-Hard Etch-Stop Layer for High Precision Micromachining**

Authors:        J.T. Borenstein, N.D. Gerrish, M.T. Currie, & E.A. Fitzgerald

Synopsis:        Epitaxially grown SiGe (with over 18% Ge) is tested and shown to be a replacement for p+ etch stops in EDP. Additionally, SiGe etch stops works in KOH and TMAH, a major advantage over p+ etch stops. SiGe exhibits better selectivity than boron doped etch stops.

Notes:         - Mechanism behind p+ etch stops: hole injection from a heavily doped layer accelerates the formation of a passivation oxide. The rate of attack is proportional to  $1/(\text{dopant concentration})^4$ .

                 - Limitations on p+ etch stops:

- upper bound on device thicknesses achievable by diffusion
- defects and curvature induced by heavy boron dopants
- EDP toxicity
- incompatibility of boron doping & electronic integration

                 - Mechanism for SiGe etch stop is *electrical*: band bending at the Si – SiGe interface increases the hole supply.

                 - Large residual stresses due to lattice mismatch exists in released SiGe structures. Solution is to anneal after epitaxial growth.

**Paper:**        **Batch Micropackaging by Compression-Bonded Wafer-Wafer Transfer**

Authors:        M.M. Maharbiz, M.B. Cohn, R.T. Howe, A.P. Pisano

Synopsis:        Packaging of MEMS devices using a transfer wafer with break-away tethers to put a polysilicon lid onto the target substrate. Gold-gold bumps are compressed together to achieve bonding. Hermetic seals have been demonstrated using a modified compression ring technique. Although the lid idea seems to work, a lot of the devices they made with it never worked never well!

Notes:         - Figure 1 is the only really important one, as it shows the entire process flow

                 - Gold bumps act like solder bumps in flip-chip techniques, but no heating is required. The adhesion of gold-gold compressed together is better than at most other interfaces.

                 - This bonding/packaging method is insensitive to particulate or surface imperfections (up to 0.5  $\mu\text{m}$ !).

- Hermetic seals can be accomplished using a compression seal ring. Early sealing attempts using evaporation didn't work and the gap (2.5  $\mu\text{m}$ ) was too large for sputtering. See Fig. 8 for the seal ring idea.
- Other advantages of this idea – precise dimensional control since it's all surface micromachined, not bulk etched. High density, small parasitics, and wafer warp are also less of a concern.

**Paper: Vacuum Encapsulation of Resonant Devices Using Permeable Polysilicon**

Authors: K.S. Leboutz, A. Mazaheri, R.T. Howe, A.P. Pisano

Synopsis: Permeable polysilicon membranes (100 – 200 nm thin poly layers) were deposited and used as etch holes to release underlying structures. They were then sealed with LPCVD nitride and resulted in a hermetic seal. The main advantages of using permeable poly are (1) they allow concentrated HF to quickly release the underlying devices, and (2) it eliminates internal deposition of the sealing film on the devices, which lowers the device quality.

- Notes:
- Problems with previous vacuum packaging approaches
  - Complicated processing (epitaxial layers + electrochemical etching)
    - Long HF etches needed to release structures without etch access holes
    - Sealing film redeposited on devices
  - Permeable poly must be reinforced by 1  $\mu\text{m}$  underlayer of nitride or poly. Etch access holes are patterned onto this underlayer and the permeable poly deposited on top.
  - Key Figures: Figure 2 and 3

**Paper: Low Pressure and Low Temperature Hermetic Wafer Bonding Using Microwave Heating**

- Use microwave to locally bond gold on Si substrate.
1. Microwave radiation selectively heats materials, the is deposited in the metallic portion of the substrate.
  2. Since no pressure is applied to form the bonding, mechanical stressed are minimized.
  3. Short bonding time allows for minimal diffusion of the Si into metallization.

**Paper: Direct Drawing for Microfabrication without Photolithography**

- Use micro pipet or inject printer to draw patterns on the substrate. The possible printing materials are SOG, PR, polyimide and dopatns for directing printing. Metal

is patterned first by printing seed layer and by electroless electroplating.

1. The easiest way to catch the key points in this paper is to see figure 2.  
For metal patterning:
  - 1.) Drawing of the amino silane couple
  - 2.) Activation ( Coating of catalysis on the surface)
  - 3.) Metal plating
2. Possible materials for this patterning method:
  - Direct patterning: SOG, PR, Polyimide and liquid dopants
  - Indirect patterning: Metal
3. Drawing by inject printer  
Easy but not suitable for hard substrate (Useless method?)  
Characterizations(Figure 9):
  - Gap between the injector and the surface :  
Spreading of the satellite droplets could be observed when gap increased
  - Ejection frequency:  
The diameter of the droplet decreases slightly according to the frequency.
  - Scanning speed:  
Interval between two droplets increases as speed increases.

### **Paper: Soft Micromanipulation Devices with Multiple Degrees of Freedom Consisting of High Polymer Gel Actuators**

- Micromanipulator devices which are made by ICPF(Ionic Conducting Polymer gel Film) actuators are used for 3 or 6 DOF soft dextrous motion.
1. The device comprises two parts(Figure 1):
    - A pair of ICPF actuator(EFD)
    - PFS(Perfluorosulfonic acid membrane) membrane and platinum layer
  2. By controlling the voltage applied to the EFD, it can control the motion in X, Y or Z direction
  3. Principle of the ICPF actuators:  
Ionic motion by electric field in the membrane creates nonequilibrium of swelling by water, the the internal stress for the deformation.
  4. 6-DOF motion device can be formed (Fig 11) by using 4 pairs of ICPF (4 EFD) and across membranous.

### **Paper: Flight Performance of Micro-wings Rotating in an Alternating Magnetic Field**

- A flight mechanism that gains thrust by rotating magnetic wings in an alternating magnetic field.

1. Since the Reynolds number is under 1000, flow plane wings have better characteristics than streamline wings.
2. Torque Balance and Scaling Effect( Some calculations in P.154 are good to fresh your magnetic concept we learned from EE250C):
  - (Torque from drag and lift ) = (Torque by alternating magnetic field) = ( Torque by anisotropy)
  - Torque  $\sim R^0$
4. Fabrication
 

Because the torque generated by the magnetic field is proportional to the volume of the magnetic wings, the wings must be a little bit thick. Electroplating is adopted because it involves less residual stress than sputtering.

**Paper: Three Dimensional SMA Microelectrodes with Clipping Structure for Insect Neural Recording ....S. Takeuchi & I. Shimoyama**

- SMA use, fabrication, advantages, performances.
- *Particularity*: 3D shape memorization, room T<sup>0</sup> use.
- *Application*: nerve recording.

**Why SMA:**

- large displacement and large force
- elasticity so no physical damage to the nerve

**Fabrication:**

- SMA= Titanium-Nickel films, deposited by RF sputtering on SiO<sub>2</sub>-isolated Si substrate, and patterned by HF-HNO<sub>3</sub> wet etching
- Ti layer (*mesh*) first by evaporation. [process flow figure 2](#)
- Film properties VERY sensitive to sputtering conditions and annealing final step. Hence many conditions tested. [table 1-2](#)
- Peeling avoided by polyimide film.

**3-D shape memorization:**

- occurs during annealing step.
- they used a bonded wire to force create the 3-D shape and maintain it during annealing step. After annealing, wire is removed, and structure deformed to desired position. Heat will bend it back to the memorized shape.

**Composition of thin films:**

- Ni % depending on sputtering parameters
- DSC measurements. (Differential Scanning Calorimeter). showed annealing temperatures should be lowered to decrease the transformation temperatures further needed to recover memorized shape. Eventually got 600°C annealing for 20 min.

**Mechanical characterization:**

- displacement versus current, force versus current, time response versus current. About 8.1 deg/ms with 51mA current for a 1mm SMA beam.

### Clipping structure:

After annealing, deformation of the horizontal structure to a clip, that will bend back onto the curved structure and clip the nerve, under heating.

### Pros:

Both elastic and tight clipping, hence good signal recording, even if body moves.

### Paper: Prototype Microrobots for Micro Positioning in a Manufacturing Process and Micro Unmanned Vehicles.....P.E. Kladitis, et a

- Polysilicon thermal actuators used as legs.
- Large array of actuators.
- MUMPs fabrication process. (no details in fact)
- Mimics 6-legged insect motion.
- Idea of gold spring wires.
- Supports a large weight.
- 3-hours assembly if manual assembly of legs using micromanipulators.
- [Solder assembly concept](#): use solder at hinge points to pull the plate away from the plate towards vertical position.
- [Self-locking mechanism](#).

### Paper: A Robust Microconveyer Realized by Arrayed Polyimide Joint Actuators.....Ebefors, et al



- [overview of micro-motion systems: read table 1 + introduction](#)
- [self-assembled polyimide joint, including actuator inside the joint.](#)
- [exhaustive testing experiments.](#)

### Principle:

4 V-groove joint filled with cured polyimide, with polysilicon heaters in between, on a silicon plate/leg. Asymmetric thermal expansion results in the rotation of the plate/leg.

### Fabrication:

Shown in [figure 3](#).

### Testing:

- Laser measurement set-up for displacement measurement.
- Dynamic behavior of polyimide joint described by simplified lumped heat capacity model. See dependence with frequency.
- Thermal limit of polyimide (before boiling!).
- Robustness, by shock-test.
- Lifetime measurements.

### Performances:

- 12mm/s with 23V, 250Hz. Velocity is load-independent, for loads <700mg.
- Max. load: 2g

**Paper:: Pneumatically Driven Microcage for Micro-objects in Biological Liquid.....J. Ok, M. Chu, & CJ Kim 😊**

- Mimics the sea anemone.
- Curling due to stress mismatch between Cr and Al.
- Pneumatic actuation for cage opening/closing
- **Knuckles** to prevent widthwise curl, that would prevent lengthwise curl.

**Fabrication**

Process flow **figure 10**.

- Note use of XeF<sub>2</sub> release etching to prevent stiction issue.
- Lift-off patterning for metals.
- Liquid latex is dropped in the pit to form the membrane.

**Test-experiment:**

- microscope visualization, manual syringe pressurization.

**Paper: Monolithic Integration of 3-D Electroplated Microstructures with Unlimited Number of Levels Using Planarization with a Sacrificial Metallic Mold (PSMM)**

Authors: J-B Yoon, et al.

Synopsis: High AR electroplated metal structures can be made using an electroplated sacrificial metal mold (SMM) layer. This SMM layer acts simultaneously as a sacrificial layer, planarization layer, and seed layer.

**More Detailed Notes:**

1. Various processes have tried to make 3D structures, but they either use special equipment of processing steps which are not compatible with monolithic MEMS-CMOS integration.
2. Problems with old method of electroplating multiple layers:
  - Underlying PR molds are thermally stressed during deposition and multiple layer PR baking → poor thermal stability
  - Step coverage and adhesion of upper seed layers can be poor due to planarization
3. The process is redundant in that it first forms electroplates the sacrificial metal (Ni, Cu) layer using standard polymer/PR molds then electroplates the structural layers with the sacrificial layer.
4. Figure 3 is the key process flow
5. Key advantages of using the sacrificial metal layer concept:
  - Good planarization achievable by electroplated sac. metal layer
  - No need for additional seed layer deposition

**Paper:** A Practical Thermopneumatic Valve ...C. Grosjean, X. Yang, Y-C. Tai

- Parylene use, fabrication.
- *Particularity:* composite membrane.

**Membrane Fabrication:** .... *so easy, so fast*

- KOH etching on both side.
- Free standing Nitride membrane after Si etching.
- Top side Parylene C deposition and patterning.
- Molding of rubber silicone. *Note depression due to surface tension, shrinkage ...*
- RIE to remove nitride membrane
- Second Parylene C membrane deposition on the other side.

**Heater Fabrication:**

- Cr/Au evaporation on free standing nitride membrane and patterning.
- Holes etched in membrane

**Valve Seat Fabrication:**

- Previously drilled holes, then Si KOH etched holes, + concentric grooves.

**Optimization:**

- Measurements to optimize the working fluid.
- Heater size tests.
- Leakage problem "solved" with properties of silicone rubber. (???)

**Valve testing:**

- 40mW necessary to close a 33 psi inlet flow of nitrogen.
- 100mW .....water.

**Paper: A Parylene Micro Check Valve.....X-Q. Wang, Q. Lin, Y-C. Tai**

- Parylene use, fabrication.
- Smart idea.
- *Particularly:* adhesion promoter, Si surface roughening by O<sub>2</sub> plasma or BrF<sub>3</sub> gas phase.

**Fabrication: .... so easy, so fast ..... clear process flow description**

- Note use of photoresist as a sacrificial layer.
- Note Si surface roughening using 3-min gas phase BrF<sub>3</sub> etching ( $\pm 2\mu\text{m}$ ).
- Note hard-bake use to smooth PR edges.
- Note brief O<sub>2</sub> plasma etching to roughen Parylene and PR surface.
- Note Al layer used as a mask to Parylene layer etching in O<sub>2</sub> plasma.

**Analysis of orifice flows.**

**Testing.**

- Note twist-up membrane works better than straight-arm membrane.
- Shift with predicted data, but thanks to a scaling factor (!!!) theory matches experimental data .....

**Paper: Re-configurable Fluid Circuits by PDMS Elastomer Micromachining**

- PDMS is used as the material to make channels and inter-connects, the advantages is easy fabrication and easy bonding- soft bonding.
1. Channel fabrication is shown in Fig2 by using Si mold. (Very clear)
  2. PDMS is bio and chemical compatible.
  3. PDMS can be directly bonded with other materials such as glass, SiO<sub>2</sub>, SiN or another PDMS. Oxygen plasma can be used to make the PDMS surface more hydrophilic, which make the bonding easier.
  4. Bonding is done at room temperature.
  5. After the bonding, the two plates can be opened and resealed for the purposes such as liquid priming, cleaning, and waste removal.
  6. The work of adhesion, which is used to determine the strength of bonding, can be got from the test of detachment length . The experiment shows that PDMS-PDMS has a strongest bonding and PDMS-SiO<sub>2</sub> has the weakest bonding.
  7. The maximum flow rate can reach 250  $\mu\text{l}/\text{min}$  in the channel with size of 17mm X 750 $\mu\text{m}$  X 50  $\mu\text{m}$ .

**Paper: Freeform Fabrication of Functional Microsolenoids, Electromagnets and Helical Springs Using High-Pressure Laser Chemical Vapor Deposition**

- Use 3D-LCVD as a micromanufacturing tool for helical microstructures.

1. High pressure needs to be maintain to have a more condensed gas. By controlling both the temperature and precursor concentration over an surface, a solid form of desired shape and composition can be generated under computer-control.
2. Free-standing fibers of diamond-like carbon were grown from ethylene at linear rates of up to 3.5mm/s.
3. Free-standing conductive coils of poly-crystalline tungsten and tungsten carbide were also grown at axial deposition rates of up to 175 $\mu$ m/min using mixtures of WF<sub>6</sub>, H<sub>2</sub>, and C<sub>2</sub>H<sub>4</sub>.
4. The deposition rate is proportional to the pressure.
5. The diameter of fiber formed is controlled by the power. For example, laser power between 150 mW and 1200 mW provided fiber diameters between 5  $\mu$ m and 240  $\mu$ m.

# Kovacs

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## 2) Chapter 2 Notes

-check Size for IC fab technique

### Substrates p22

-crystalline semiconductors (si, ge, gaas) are used:

- 1 well characterized and readily available
- 2 many mature processing techniques
- 3 useful crystal plane anisotropy
- 4 potential of integration with circuits

-others: metals, glasses, quartz, ceramics, plastics, polymers

### Additive films p22

-si, poly, si compounds, metals, metal compounds, ceramics, organics

-W-refractory metal with nearly same  $\alpha$  as Si

-surface-above substrate

-bulk-substrate

### General props p25

-weight, melting, specific heat,  $\alpha$ , electrical-si, ge, gaas p25

Si melt 1415 C,  $\alpha=2.6 \cdot 10^{-6} /K$

-mechanical props-yield, youngs, k, rho p 26

Si yield  $7 \cdot 10^9$  Pa

Mechanical props of si are anisotropic

Cracks propagate along crystal planes

- $\alpha$ , E, k, rho additive films p. 79

-SiO<sub>2</sub>-well masked, thermal stability, very adherent, low defect densities at interface

-GeO<sub>2</sub> is water soluble

-GaAs-10 different oxides-all very different-relative proportion varies with processing

-As oxides soluble in acidic solutions

-Ga oxides soluble in alkaline solutions

-growth occurs at oxide/gas interface=>large electronic defects, poor adhesion

-Si - 4 in or 6 in wafers, ~500 um thick

-IC industry is transitioning from 8 to 12 in wafers

-4 orientations common available

n-type (100) (most common) or (111)

p-type (100) or (111)

flat is (110) plane

### Bulk processes p29

CMOS-complementary metal oxide semi

Wet etchants-HF, Alkali OH, EDP, TMAH chart p30

All but HNA are anisotropic

HNA 1-3 um/min etch rate

1-30 EDP  $\mu\text{m}/\text{min}$  etch rate  
all stopped by  $\text{Si}_3\text{N}_4$   
slow oxide etch 1-80  $\text{nm}/\text{min}$   
only TMAH Al selective  
all Au selective  
all but HF allows  $\text{p}^{++}$  etch stop  
EDP, TMAH CMOS compatible

### **Isotropic wet etching (HF or BOE) p31**

- chemical mass transport issues keep etchants from being perfectly isotropic
- for glass, only isotropic is available
- “BOE”-buffered oxide etch
- “HNA”-HF/ $\text{HNO}_3$ /acetic- most common isotropic etchant
  - $\text{HNO}_3$  drives oxidation of silicon
  - HF form soluble silicon compound
  - Acetic prevents  $\text{HNO}_3$  from dissociating
- drawback: attacks  $\text{SiO}_2$  relatively quickly-30-70  $\text{nm}/\text{min}$
- slowed down heavily by light n- or p- doping

mechanism for wet single crystal silicon etchants

- 1 injection of holes into the Si to form  $\text{Si}^{++}$  or  $\text{Si}^+$
- 2 attachment of  $\text{OH}^-$  groups to  $\text{Si}^{++}$  to form  $\text{SiOH}_2^{++}$
- 3 reaction of hydrated Si with a complexing agent in solution
- 4 dissolution of reaction products

an electrochemical reaction-a charge transfer driven process  
therefore, dopant type/concentration will modulate it

- 3 HNA formulations and properties p 33
- 0.7-7  $\mu\text{m}/\text{min}$ , variable dopant dependence,  $\text{SiO}_2$  or  $\text{Si}_3\text{N}_4$  mask

### **Anisotropic wet etch p33**

- etching on crystal planes thought to be in plane with least “surface density”-not real story
- better,  $\text{H}_2\text{O}$  molecules screen directions from attack
- convex corner undercutting rate very dependent on etchant-EDP fast
- no “master equations” to predict etching performance

theory states that equilibrium form of crystal minimizes the surface energy

### **KOH (alkali hydroxide etchants) p36**

Mechanism for alkali metal hydroxides on Si

- 1 Si atoms react w hydroxyl ions
- 2 Si is oxidized, 4 electrons yield
- 3 electrons reduce water, produces hydrogen
- 4 complexed Si, reacts with hydroxyl ions to form soluble silicon complex

low concentration solutions yield high roughness, typically ~40% is used  
alkali ions destroy MOS circuits  
all alkali hydroxide etchants exhibit high selectivity, 100:111 selectivity~400

all can be dopant modulated-in heavily doped regions, the space charge layer at si surface is decreased, electrons from oxidation reactions are tied up, which in turn, limits reduction of water

(100) orientation si yields pyramidal pits w/ 54.74 deg sidewall angles

KOH can be used to produce a “mirror finish”-low surface roughness, unlike EDP/TMAH

Roughness decreases drastically with stirring

Hillock formation suppressed with oxidizing agent

### **Ammonium hydroxide p40**

-nh<sub>4</sub>oh-a hydroxide-based anisotropic etchant that does not incorporate alkali ions which are harmful to CMOS processes

Problems-slow etch, roughness, noxious, a gas dissolved in water-as heated must be constantly replenished

### **TMAH-tetramethyl ammonium hydroxide p40**

Safer than EDP, low cost, 100:111 selectivity~10-35

Can be modified so it does not etch aluminum

Surface roughness a problem, but new formulas are addressing that issue

1000:111 selectivity ratio not as high as alkali hydroxides

etch rate and roughness decrease as TMAH concentration increased

SiO<sub>2</sub> and Si<sub>3</sub>N<sub>4</sub> are excellent masks

Al protection in TMAH driven by lowered OH

oxidizers are used to prevent local “micromasking”-ie surface roughness-induced by hydrogen bubble formation

### **EDP-ethylene diamine pyrocatechol p43**

-dangerous, 100:111 selectivity~35, but more selective for p-doping  
etch rate 0.75-1.25 um/min

masks: SiO<sub>2</sub>, Si<sub>3</sub>N<sub>4</sub>, Au, Cr, Ag, Cu, Ta

attacks Al quickly-problem for “foundry” CMOS

-CMOS on n-doped Si can be protected from EDP by electrochemical bias

incredibly corrosive-not used in most clean rooms dedicated to “mainstream” IC’s

### **Hydrazine-H<sub>4</sub>N<sub>2</sub> p45**

no doping dependence, masked w SiO<sub>2</sub> or Al

etch Si at 2 um/min, selectivity lower than KOH or EDP

hydrazine is highly corrosive, explosive, carcinogen

### **Amine gallates p45**

high Si etch 140 um/h, stops at high B concentration

EDP/TMAH more popular

### **Ultrasonic agitation p46**

-two common problems:

roughness due to masking by bubbles

geometry dependent etching-etch rates influenced by closely placed features-effected by

local reactant depletion  
ultrasonic agitation eliminates roughness in KOH etching and geometry-dependent etching  
other solutions: surfactants, preemptive chemical elimination of bubbles

-highly p doped regions can be used to etch away wafer, leaving behind doped structures-  
ie micromachined neural needles, or use etch stop to create thin membrane  
max depth of diffusing dopant ~15um  
boron doped p++ epitaxial layer under tensile stress, add germanium to relieve

### **Wet etching gallium arsenide p48**

-111 etch slower than others, however, some 111 planes As, others are Ga  
-Si: 100>110>111  
-GaAs: 111 A(arsenide-reactive face)> 100>110>111B(gallium-passive face)  
-Some hydroxide etchants-KOH-swap etch rates for 100 and 110 for III-V compounds

### **Electrochemical modulation of wet etching p49**

A potential can control injection of holes to permit si to be oxidized to hydroxides  
Silicon is held positive, platinum counterelectrode  
+ voltage source of holes at si face to attract OH-  
causes the si to oxidize-reaction continues  
if potential difference strong, form porous si  
ocp-open circuit potential-condition if no current applied (-1.5V)  
add potential, positive current flow until reach passivation potential where  $\text{SiO}_2$  is  
formed-sharp drop-off for p-type

### **Diode junction etch stop p51**

another approach is to form a p-n junction on surface of a p-wafer and etch until n-layer  
is reached-3 electrode setup-achieve accurate thickness membranes  
junction etch stop technique can be used to postprocess prefab CMOS chips w TMAH-no  
damage to al or ceramics  
another option-photo pump to generate holes to drive etching of si in koh or hf  
result very high anisotropy>70:1

### **Porous silicon- brownish film p55**

formed in high conch hf, or w anodic bias on si  
single crystal, but permeated with voids  
interesting optically, fluorescent and electroluminescent  
higher current density during etching, lower density (more holes)

### **Anisotropic wet etch of porous aluminum/quartz p56**

Aluminum-form a porous anodic oxide on entire substrate and mask regions of oxide  
using patterned Cr, sealing the pores in these regions. Etch unmasked regions with weak  
acid.

Quartz-has hexagonal lattice, with no center or plane of symmetry, and is electrical  
insulator with piezoelectric properties  
Excellent piezo, electrical, optical, mechanical props

Can be anisotropically etched using wet etchants that attack  $\text{SiO}_2$ , such as HF, typically  $\text{NH}_4\text{HF}_2$  is used-etch rates as high as 75  $\mu\text{m}/\text{h}$  along z-axis (slower along x- and y-)  
Etch profiles dependent on type of etchant and etch conditions  
Etch is masked using thin metal patterns  
Devices made to date: torsional differential pressure sensor, magnetically driven accelerometer, tuning fork resonator, optical chopper, microgalvanometers

### **Ion implant assisted wet etching p59**

At sufficiently high doses stoichiometry changed by ion implantation in desired regions, leaving regions susceptible to chemical attack  
Can have anisotropic etch in sapphire-single crystal  $\text{Al}_2\text{O}_3$ - if implant sapphire with silicon, then HF will etch, leaving other material untouched-only  $\sim 0.1 \mu\text{m}$  deep  
Sapphire grown on 100 silicon by CVD-sapphire is chemically inert

### **Ion track damage assisted wet etching p59**

Ionizing radiation from beam sources can be highly collimated-can anisotropically etch materials with bombardment from radiation  
Used to anisotropically etch quartz w/out using z-plane  
1200 deg C anneal heals tracks from ions, although piezo coefficient is reduced by temps above 600 deg C

### **One sided wafer etch p60**

people have tried waxes and epoxies to protect one side from etchant  
better: automatic leveling circuit that keeps etching chamber full as water boils off

### **Vapor Phase Dry Etch p62**

-noble gas fluorides and interhalogens (fluorine based) will etch Si w/ infinite selectivity to masks such as  $\text{SiO}_2$   
-much more controllable than plasma etches via temp and partial pressure; plasma-more variables, tightly coupled  
-result: spontaneous non-plasma reactions are nearly perfectly isotropic

### **Xenon difluoride etching p62**

-non-plasma, isotropic dry etch, high selectivity for Al,  $\text{SiO}_2$ ,  $\text{Si}_3\text{N}_4$ , PR, but high roughness  
useful for post processing CMOS  
-reaction:  $2\text{XeF}_2 + \text{Si} \rightarrow 2\text{Xe} + \text{SiF}_4$  (only Si is solid)  
-rate: 1-3  $\mu\text{m}/\text{min}$ , etched surfaces have granular structure (10  $\mu\text{m}$  and smaller feature size), unsuitable for smooth finish  
-good masks: Al, Cr, TiN, LPCVD  $\text{Si}_3\text{N}_4$ , thermal  $\text{SiO}_2$ , PECVD SiC, and PR  
-generates a lot of heat, reaction rate may be lowered unless etching is pulsed  
- $\text{XeF}_2$  reacts w  $\text{H}_2\text{O}$  (even moisture in air) to form Xe and HF  
-careful dehydration of wafers necessary to prevent formation of a SiF polymer (similar to teflon?) which can stop etching

### **Interhalogen etch chemistries p64**

-interhalogens:  $\text{BrF}_3$  and  $\text{ClF}_3$  with a Xe diluent  
-very dangerous, but roughness went from  $\sim 150 \text{ nm}$  to  $< 40 \text{ nm}$

## **Plasma/ RIE-Reactive Ion Etching p65**

-rf-radio frequency-power drives chemical reactions-applied to a pair of plates accelerates stray electrons, increasing KE so they break chemical bonds on impact, forming ions and electrons

-with continuous input of rf into chamber, electron/molecule collisions continue to yield ions and electrons, while chamber walls absorb or neutralize these species

-after several rf cycles, steady state discharge is reached

-2 regions:

A. central glow/bulk region-semi-neutral, equal numbers of negatively and positively charged particles-electrons more easily depart than ions

B. dark/sheath region-where all the potential drop occurs-retard departure of electrons from bulk-maintain charge neutrality-DC component accelerates + ions in bulk region which bombard the wafers

-DC bias will occur on its own or can be controlled using a DC power supply to reduce damage

-energetic ions supply energy for reactions at low temp in a plasma ~150-250 deg C

-otherwise would require temp upwards of 1000 deg c

-can achieve isotropic or anisotropic etches

-plasma etcher/RIE illustration p66

-fluorine plasma Si etching reactions proceed spontaneously, not requiring ion bombardment

-fluorine free radicals from the dissociation of SF<sub>6</sub> are mainly responsible for Si etching  
-role of C<sub>2</sub>ClF<sub>5</sub> is to introduce a polymeric deposition process in parallel with etch process

-on sidewalls (low ion bombardment) fluorine-rich fluorocarbon layer forms and inhibits lateral etching

-at vertical surfaces, where ion bombardment is highest,, fluorocarbon layer is carbon rich and less than 2nm thick-Si etch rate significant

-deep Si etches require thick deposition of PR

-anisotropy controlled by composition of reactant mixture

-possible to modulate plasma etch anisotropy via local dopant concentrations ex. a Cl-based plasma can be used to anisotropically etch lightly doped p- or n- type, but heavily n-doped Si is etched isotropically

## **DRIE p69**

-relies on a high density plasma source and an alternating process of etching and protective polymer deposition to achieve aspect ratios of up to 30:1, and etch rates on order of 2-3 um/min

-max etch depth capability on order of ~1 mm, precise etch depths can be controlled using buried SiO<sub>2</sub> etch-stop layers

-use a substrate bias of -5 to -30 V so cations are accelerated nearly vertically

-after short etch, polymerization is used with CF<sub>2</sub> to thickness of 50 nm

-commercial equipment tends to use C<sub>4</sub>F<sub>8</sub> combined with SF<sub>6</sub>

-available from Surface Technology Systems Ltd, Redwood City, CA, and Plasma-Therm, St Pete, FL

### **Cryogenic Dry Etching p69**

- enhances anisotropy
- use liquid N to cool wafer to 77 Kelvin during etching
- using pure SF<sub>6</sub>, can yield AR~30:1, and capable of etching through an entire Si wafer

### **Magnetically Controlled Dry Etching p70**

- HARM possible for Oxy RIE with smooth sidewalls using magnetically controlled reactive ion etching (MC-RIE) to obtain high density, low energy plasmas
- set up magnetic field parallel to the cathode surface, forcing the plasma density to vary with the applied magnetic field
- if fluorine gas is added to Oxy RIE, etch rates rise, but masks etched quickly also
  
- can also use thermally assisted ion beam etching to fab HARM in Teflon; rate~1.5um/min
- can use dry etches to alternate between iso/anisotropically-tropic etching (several examples)
- high aspect ratio etching methods have also been demonstrated for GaAs

### **Laser-Driven Bulk Processing p74**

#### Laser drilling

- pulsed lasers used to ablate silicon (localized, rapid, thermal evaporation) rather than melt
- used to drill holes through wafers for electrical feed-throughs
- holes as small as 8um in diameter through wafers 100-200 um thick, used 1.06 um wavelength YAG laser
- tends to cause damage-cracking, ejecta, dislocation defects, vacancies
- laser is slow and inefficient for annealing, compared to thermal processing

### **LACE-laser assisted chemical etching p75**

- much less energy to drive chemical reactions for etching/deposition than to vaporize Si
- in Cl<sub>2</sub> ambient gas, achieve high local etch rates of 100um/s
- direct heating speeds reaction, and free radicals can be formed at proper wavelength
- can make very complex structures, but not undercut, overhanging structures
- not efficient for large volumes: example: 10umx10um cube takes 0.02 sec, a 1 mm x 1mm cube takes ~5.6 hours, this rate is faster than EDM at these scales
- Cl<sub>2</sub> gas is extremely selective for Si over SiO<sub>2</sub>-buried channels can be etched under a SiO<sub>2</sub> layer
- laser driven wet etch has also been achieved
- LACE not a parallel process and not fast enough for most micromachining applications

### **“Surface” Additive Processes p77**

#### **Non-Metallic Thin-Films for Micromachining p77**

- most common dielectric thin films in semiconductor fab are SiO<sub>2</sub> and Si<sub>3</sub>N<sub>4</sub>
- key parameters:
  - A. temp of deposition-avoid destroying underlying devices



- polycrystalline SiC grown from poly base by reaction w/ hydrocarbon fragments at 1360 deg
- single crystal SiC can be grown epitaxially on Si

### **Polycrystalline Diamond p84**

- high hardness, thermally conductive, high temp CVD deposition (900 deg C), and highly stressed films
- or deposit with PR loaded with diamond crystals used to nucleate CVD diamond growth

### **Polysilicon p85**

- uses: gate material for MOSFET, resistors, conductors, structures
- typically deposited w/ LPCVD at 600-650 deg C by pyrolyzing silane-SiH<sub>4</sub>
- PECVD also works, also sputter (w/ or w/out dopant)
- structure strongly function of dopants, temp, and thermal processing
- at 605 deg-amorphous, at 630 deg-columnar
- conductivity is a strong function of temp
- can be doped by implantation or diffusion
- anneal to form fine-grain, low-stress films

### **Organic Compounds p86**

- can be deposited to improve mechanical props or to form hydrophobic regions
- can use a Faraday cage to create a field-free region in a parallel plate plasma system to grow fluorocarbon (CF<sub>2</sub>)<sub>x</sub> films
- fluorocarbon films reduce dynamic coefficient of friction from 1.0 to 0.07, whereas Teflon ~0.04

### **Sacrificial Materials**

- PR, PSG, porous Si etch faster in HF than oxides-good sacrificial layer

### **Sputtered Inorganic Thin Films p87**

- very common for film deposition for optical devices using MgF<sub>2</sub>, CaO, LiF, SiO, and ITO-indium-tin oxide-a transparent, conductive film used in LCD displays
- sputter on PZT with piezoelectric coefficient comparable to bulk materials

- dielectrics-most are glasses (SOG-spin on glass), PR, polyimide can be spun on

### **Wet Etching of Non-Metallic Thin Films p88**

- SiO<sub>2</sub> is typically wet etched with HF and commonly buffered with ammonium fluoride
- alkali hydroxides (KOH, etc) will etch SiO<sub>2</sub> slowly
- possible to etch SiO<sub>2</sub> without etching Al-use very concentrated HF, since etching of Al in HF governed by conch of H<sub>3</sub>O<sup>+</sup> ions, which are low in conch HF
- SiN-etched with phosphoric acid (H<sub>3</sub>PO<sub>4</sub>). More practical to plasma/RIE
- organic films-etched w/ strong oxidizers-sulfuric acid/hydrogen peroxide ("Piranha")
- poly-generally etched same as Si-KOH, EDP, TMAH-but faster etch rates-increased etch rates at grain boundaries

### **Dry Etching of Non-Metallic Thin Films p89**

- allows undercutting Al, eliminate adhesion problems
- SiO<sub>2</sub>, Si<sub>3</sub>N<sub>4</sub>, SiC - Freon variants-CF<sub>4</sub>
- organic films-plasma ashing-O<sub>2</sub> used to “burn” to H<sub>2</sub>O, CO, CO<sub>2</sub>
- poly-freon or fluorine-based etch- modulated by dopants
- SF<sub>6</sub> preferred as a fluorine source since does not damage ozone

### **Metallic Thin-Films for Micromachining p90**

- most common metal available in semiconductor fabs is Al

### **Thermal/Resistive Evaporation p90**

- electrically heated filament of the desired metal or refractory metal “boat” is used to evaporate a film onto the wafers-metal vapor then condenses on surface
- metal atoms stick instantly at surface-no movement creates step coverage/stress problems-substrate temp main factor in ultimate thin film stress-stress generally tensile
- if substrate heated near metal’s melting point, stress will tend to decrease since this is an epitaxial growth situation-atoms move to lowest energy positions
- nearly any material can be evaporated-main limitation is limiting temp of tungsten boat typically used (~1400 deg C)
- suitable for Au, Al, Mg, and Cr is at the limit; adhesion poorer than sputtered films; dep. rate  $\cong$  0.5-5 nm/s

### **E-beam Evaporation p91**

- E-beam-8 to 10 keV, generally 100-200 mA, generate target temps ~2800 deg C
- allows same metals as resistive evap, plus Ti, Pt, Pd, W, Mo, and Ta
- deposition 10x rate of CVD or sputtering
- less substrate heating than resistive evaporation
- ion gun can be used in conjunction with evaporation to drive film to compressive rather than tensile stress-ions impact surface and make arrangement more compact

### **Sputter Deposition p92**

- inert ions (i.e. Ar<sup>+</sup>) accelerated using DC or RF drive through a potential gradient so that they bombard a target, generating ejecting material from incident momentum
  - almost any material can be sputtered if sufficient energy in plasma
  - difficult to compare plasma deposited films-stoichiometry is process dependent
  - methods to obtain plasma:
    - DC glow discharge-only for soft metals, low energy plasma
    - planar RF-2 parallel plates, RF to target, works for dielectrics also
    - planar magnetron-mag field
    - cylindrical magnetron/S-gun-magnetic “racetrack” for electrons, forms high energy plasma near target
  - more energetic atoms than evaporation, allowing surface mobility and resputtering=>better step coverage and stress control, but difficult lift off
  - excellent method to deposit alloys, dielectrics, shape memory alloy (TiNi)
  - drawback: incorporates Argon gas
    - hot substrate from secondary electrons from target
  - stress in metal films tends to be tensile, but compressive at low pressure
- |                      |                               |   |
|----------------------|-------------------------------|---|
| see p. 94            | <b>Evaporation</b>            | <b>Sputtering</b>                                       |
| <b>step coverage</b> | poor, but useful for lift-off | also directional, but from spatially distributed source |

	"directional from the "source" process	molecules maintain directionality for mean free path (~1 cm) planar RF/magnetron: sidewall nearly equal to surface s-gun: substrate is removed from plasma/sidewalls coated less
<b>shadowing</b>	problem avoid by using rotating planetary stage	
<b>composition</b>	compositions of source may change en route to substrate	does not cause changes in composition preferred for compounds and alloys

### Chemical Vapor Deposition of Metals p95

- good step coverage since not directional
- usually thermal energy drives reaction-often 600 to 800 deg C, unless plasma enhanced
- W, Mo, Ta, Ti, and Al (in research applications) have been deposited
- “selective metal deposition” replace Si atoms with Tungsten (typically used)
- often necessary to deposit thin adhesion layer of reactive metal such as Ti, Hf, Cr beneath a relatively non-reactive metal (Au, Pt, other low reactivity metals) that would otherwise not adhere
- typical “trilayer” of Ti/Au/Ti is 30nm/500nm/30nm with top layer included to promote adhesion of next layer
- may also require a diffusion boundary layer of Pt or Pd, otherwise Au can diffuse through Ti and into Si

### Wet Etchants for Metallic Thin Films

Aluminum	strong acids or bases typical: acetic, nitric, phosphoric acid
Gold	aqueous KI3-corrosive vapors
Platinum	Aqua Regia i.e. nitric/HCL acid
Chromium	ammonium nitrate/nitric acid
Copper	nitric acid ferric chloride (typical PCB etchant)
Nickel	nitric acid/ammonium persulfate
NiCr	nitric acid/ammonium nitrate
Palladium	mumbo jumbo
Titanium	dilute HF
TiW	diluted hydrogen peroxide
TaN	nitric acid/HF

### Dry Etching Metallic Thin Films p98

- Al is only metal dry etched in mainstream semi industry
- for Al, must break through Al<sub>2</sub>O<sub>3</sub> (self-passivation) layer-sputtering w/ Ar works
- cross-contamination is problem for all metals

### Lift Off Patterning p98

- allow metal to adhere to substrate only in regions desired
- takes advantage of poor step coverage of most metal deposition methods
- use negative mask and undercut edges of mask, allowing discontinuous metal regions on substrate and mask

- typically, standard PR soaked on chlorobenzene to form overhang “lip”, i.e. AZ1350J
- Pr-spin-on, pre bake, expose/soak in chlorobenzene
- lemon Jello works very well (no joke)

### **Laser Driven Deposition p100**

- laser can drive deposition of W, Mo, Pt, Co, B, single crystal/poly Si, Zn, C
- complicated 3-D structures achievable, growth rate up to 2-5  $\mu\text{m/s}$
- thermal energy applied locally rather than globally, serial process, limited throughput

### **Electroplating p100-113**

- plated object is cathode-negative potential-relative to inert (often Pt) anode counterelectrode
- solution contains reducible form of ion of desired metal-ions are reduced at surface
- Au, Ag, Cu, Ni, Pt, Pd can be plated
- fastest growing crystal planes “grow themselves out of existence”, exposing slow planes
- grain refiners, hardeners, brighteners are added to modify deposition, often proprietary
- conducting salts-increase conductivity of solution, increasing voltage drop at plating surface
- surfactants-increase uniformity of plating surface
- plating formulas p.104
- dangerous: plating solutions often have cyanide containing compounds/mixed with acids result in lethal gas
- possible to electroplate PR
- $J(\text{current density})$ - $V$  characteristic is saturable; current depositing metal plateaus at a certain point-excess current drives unwanted reactions like electrolysis of  $\text{H}_2\text{O}$
- excess voltage, aka overpotential, can result in large, porous, “black” metal
- DC electroplating is standard- voltage adjusted for requisite current density
- or, can regulate current for more constant current density
- agitation (propeller is good) is key for good uniformity, allows increase in maximum possible current

### **Pulsed Electroplating (PEP) p106**

- pulse current (1kHz for Au), need higher peak currents than for DC plating, benefits:

1. PEP favors nucleation of new grains-finer granation
2. Stress control via duty cycle
3. Control of crystal orientation through PEP
4. Better deposition in corners or hard-to-reach areas

Disadvantages:

1. more inclusions such as gases and organic contaminants
2. current distributions may be less uniform-poorer thickness uniformity, but often opposite is true

### **“Black” Metal Films p107**

- at very high current density, dendritic growth may occur
- high field points at tallest crystallites continue plating there
- increased current density, dendritic metal becomes porous and optically black

- “platinum black” used to record bioelectric signals by increasing effective surface area, decreasing impedance and Johnson noise
- good black body absorbers

### **Electroless Plating p108**

- uses chemical reducing agent, rather than electrical reduction
- temperature adjusted below point of precipitation-all solutions nearly unstable
- exposed metal often pre-treated with catalyst like “Pd”, reaction proceeds locally
- can electroless plate on bare Si, accomplished through an initial roughening (HNO<sub>3</sub>/HF), followed by a conventional Pd “seed” layer deposition and plating p.109
- film stress controlled by incorporation of phosphorous
- through implantation of Pd ions into patterned polyimide on Si, electroless Cu plating can be seeded on either Si alone or Si/polyimide-requires “metal vapor vacuum arc”

### **Templates for Plating p110**

- a thin “shorting layer” of metal is deposited over all structures, followed by a template layer that defines regions to be electroplated (often PR)
- shorting layer is removed after electroplate step and removal of template
- for Au plating, Ti/Au or Cr/Au shorting layer often used
- OR, use shorting traces to interconnect plating regions-saw through during dicing-commonly used on PCB (printed circuit boards)
- can create 3-D structures by spacing shorts so outer edge grows slowly, creates conical pyramid
- PR can be distorted by stresses of plating process-causes distorting-polyimide better for high aspect ratio p.114

### **LIGA p115**

- “Lithographie, Galvanoförmung, Abformung”-lithography, electroplating, and molding-yields very high aspect ratios
  - requires well-collimated synchrotron radiation to expose template with nearly perfectly straight sidewalls
1. make special x-ray mask using 1  $\mu\text{m}$  thick poly w/ e-plated Au as x-ray absorber
  2. 5nm Cr and 15 nm Ni deposited as plating mask
  3. several 1-2 $\mu\text{m}$  layers of PMMA spun on, baked, total thickness  $\sim 8\mu\text{m}$
  4. PR spun-on, pre-baked, exposed
  5. PMMA exposed through PR pattern
  6. PMMA developed for vertical sidewalls
  7. ??? don’t understand two set of steps????
  8. 10-1000  $\mu\text{m}$  of PMMA deposited on wafer or metal substrate-serves as template
  9. PMMA dissolved in MMA and cross-linker EGDA
  10. Polymerization initiated w/ DMA and BPO
  11. PMMA applied by casting-cast PMMA mechanically polished
  12. Exposed through x-ray mask material with synchrotron-x-rays break cross-links
  13. PMMA developed
  14. Metal electroplated into PMMA mold
- RIE/plasma can also be used to pattern templates

-can also use a sharp, PtIr wire electrode over a substrate for localized plating-produce highly 3-D structures (springs, columns)-very serial process

### **Selective Epitaxial Growth p118**

-of SCS is possible via  $2H_2+SiCl_4 \rightarrow Si(s)+4HCl$

-used extensively for fab of SOI(silicon on insulator) devices for high voltage apps

-Si-on-sapphire ( $Al_2O_3$ ) wafers used for apps requiring radiation resistance

-SiC can also be grown epitaxially

### **Bonding Processes p119**

-variety of processes, form covalent bonds between substrates to using intermediate adhesive layers like glues

-hermetic sealing becoming more important for MEMS that would be compromised by plastic injection molded packaging (common w/ low cost IC's)

-metal/glass interface can form metal oxides that create excellent bonds-used for hard vacuum seals in vacuum tubes-requires temps  $\sim 1000$  deg C

### **Anodic Bonding p119**

-electric fields can permit bonds at only 400 deg C with a glass;  $\sim 1.2$ kV

-positive ions in glass drift towards neg electrode, producing large electric field at interface, pulling surfaces together

-minimize thermal stress by using glass with alpha close to Si i.e. Pyrex et al.

-does not require vacuum

-problem: danger of electrostatic discharge damage-requires  $\sim 1$  kV-shielding helps

Can be done in atmosphere.

Similar process with lower voltages ( $\sim 30$ - $60$  V) used for **Si-Si bonding using intermediate glass layer**(sputtered, evaporated, spinned-on) or other layer (Al, ITO).

### **Anodic Bonding with Deposited Glass p121**

-Si-Si bonding possible with intermediate glass layer-sputtered, evaporated, or spun-on

-possible at bonding voltage of only 30-60 V, possible at only 15 V, 300 deg C

-evaporation glass deposition rate as much as 1000x deposition by sputter

-generates large compressive stress in films-annealing at 500 deg C helps, also allows out-gassing

-pre-clean in organic solvents is critical to bond quality

-bond strength comparable to Si-to-glass; up to 40Mpa

### **Fusion Bonding p122**

-direct Si-Si (or can use  $SiO_2$ ) bonding, broadly used for high-V circuits where SOI required

-no thermal stress, bonds have same mechanical strength as Si

-requires plenty of hydroxyl groups at surface-supply by boiling in nitric acid

-bonding occurs between 300-800 C, sometimes 800-1100 C

-anneals in  $O_2$  or  $N_2$  used to strengthen bonds

-particulates trapped can form voids

### **Other Bonding Techniques p123**

- PR can be used as adhesive
- PMMA used to glue sheets of polyimide to substrates
- waxes available as temporary adhesives or protective layers
- oxygen plasma etch good for removal, but leaves behind inorganics
- flip-chip - use solderable bumps on metal pads; matched to pads on substrate, thermally bonded

### **Compound Processes Using Bonding p123**

- advantage over poly mechanical structures is uniformity of properties and easily integrate circuits
- disadvantage: typically wet bulk processing, bonding step

### **Sticking Problems During Wet Release p127**

- attractive capillary forces cause drying fluids to pull structures into contact w/ substrate
- Van der Waals (dipole-dipole) forces create stiction of hydrophobic surfaces
- hydrogen bonding-adhesion for hydrophilic surfaces
- less polar solvents reduces effect of hydrogen bonding
- can avoid surface tension by solid/gas sublimation or remove liquid/gas interface (critical point)
- ex. T-butyl alcohol used to replace H<sub>2</sub>O, froze, sublimated
- biological specimens are prepared for electron microscopy using critical point-liquid and gas no longer exist as separate states
- used to free 850 um long Si cantilever beam without sticking, only 80 um w/ air dry
- less-general methods include adding tip protrusion to long cantilever, or magnetic levitation of plated NiFe alloy structures, or use polyimide bilayer to curl out of substrate plane and provide mechanical force

### **Sacrificial Processes p126**

- sacrificial layers (polyimide, SiO<sub>2</sub>, poly) combined with LIGA to form HARM structures
- SIMOX-separation by ion implantation of oxygen-made by implanting conventional wafers with oxygen to form SiO<sub>2</sub>
- can form thin 300-400 nm layer of SiO<sub>2</sub> buried beneath 200-300 nm of Si
- additional SCS can be grown epitaxially on top if desired
- vapor-phase etch of sacrificial layer using HF and methanol gas
- Texas Instruments DMD's are released by plasma etch of PR

### **Template Replication p133**

- the substrate is not part of finished device and is used as a mold
- mold can be used many times-can invest more \$ into
- molten plastics can be injection molded into metal molds, cooled and removed
- to fabricate metal or ceramic parts, uses plastics mixed w/ 50% metal or ceramic powder
- plastic is removed via fire in reducing atmosphere (H<sub>2</sub>)
- feature sizes on order of microns possible using LIGA-can form HARM templates for plating

### **Electroforming p134**

- templates are formed in metal and plating is used to replicate them
- template may be peeled away, or simply dissolved
- used to make HP ink jet print heads-3-D thin film Ni nozzle

### **CVD Based Template Replication p136**

-HARM structures grown by etching deep trenches in Si, grow SiO<sub>2</sub> release layer, fill trenches w/ poly, etch release layer. Process:

1. plasma etch Si using a CVD SiO<sub>2</sub> mask
2. sidewall residue removed with Si isotropic wet etch
3. etch repeated to smooth sidewalls after plasma finished
4. PSG deposited
5. CVD poly or Si<sub>3</sub>N<sub>4</sub>, or electroless Ni as structure at 580 C for fine granation, for optimal geometry
6. Anneal poly in N<sub>2</sub> at 1000 deg C 1 hour
7. Lap and polish
8. Poly 2 deposited/patterned
9. SiO<sub>2</sub> removed

-ceramic materials can be formed by casting slurries and then firing to desired shape

### **Sealed Cavity Formation p138**

- form a structure with sac layer that can be removed through narrow access holes, which are then covered over
- simple, in atmospheric pressure, use epoxy or PR
- thin film sealing layer using CVD, sputtered, or evaporated layers
- “reactive” sealing requires reacting cavity structural material to form a seal-oxidize poly, etc
- in the fab of vacuum tubes, use a getter material (highly reactive, like Barium) that can be activated after tube is sealed to remove residual gases that could react with microstructures over time
- important for hot-filament devices or inertial sensors

### **Surface Modification p.142**

- covalent bonding of monolayers (SAMs) to a surface to change surface properties
- two commonly used: siloxane for Si substrates, thiol for Au
- used for biotech apps, wet etch release, mechanical property enhancement
- most common in clean rooms is HMDS-enhance adhesion of PR by coating it with methyl
- HMDS removes ligands/moisture on surface, leaving surface methylated
- this type of chemistry can be used to attach proteins and DNA to Si
- silane based SAM's (OTS) used to improve wear of poly micromotors or adhesion
- typically used for antistiction, thermal stability, selectivity of chemical sensor, molecular recognition with dendrimers

### **Printing and Stereolithography p142**

- simple printing can be adapted to fab of microstructures with micron features

- cannot be used for complicated structures, or integrate w/ IC's
- good for non-planar surfaces or very large areas, low cost
- several layers can form 3-D structures-this is stereolithography

### **Screen Printing p143**

- use a mask to allow transfer of ink in desired patterns to substrate
- usually template ink applied through regions of a silk screen
- alignment may be much worse than conventional optical lithography
- can pattern large features (!00 um or larger) on wafers, such as active polymer layers
- material must be in liquid form
- for PCB's, modern screen printing has resolution ~500um, capability of 50um

### **Transfer Printing p143**

- wet a plate with raised regions, transfer pattern via an unpatterned carrier to object to be inked
- used to transfer SAMs of long chain alkanethiolates to act as nano-scale resists
- can "load" polymer/liquid matrix with powders to obtain composite materials
- 3-D "Stereolithography" with polymers, ex laser used to harden photopolymer, built up on several layers-"spatial forming"
- can also use "negative" ink to form template

### **Sharp Tip Formation p146**

- required for tunneling transducers, field emission devices, STM
- self-occluding masks-continuous metal deposition perpendicular to substrate (i.e. evaporation) onto template layer to gradually close off holes in which metal is being deposited
- when tip complete, lift off template, leaving sharp tip on substrate p.147
- plasma/RIE often leave needle-like structures "grass" from micromasking by particulates from the etcher-often Al sputtered from etch chamber walls
- can use to deliberately form sharp tips
- wet etch-undercut SiO<sub>2</sub> squares with KOH (110 Si)-radius of curvature<100nm

### **Chemical-Mechanical Polishing and Planarization p148**

- common in Mainstream IC fab between repeated interconnect/dielectric layers polished to roughness of <2nm
- requires alkaline, silica slurry with mechanical polishing
- CMP used to reduce poly average surface roughness from 42 nm to 1.7nm

### **Electric Discharge Machining (EDM) p149**

- draw an electric arc from a negatively-biased, sharp, robust tip to the workpiece, a conductive material submerged in a dielectric fluid
- workpiece is eroded by discharge, much faster than erosion at the tip
- features as small as 2-5um, but serial and slow
- used to create micro-car seen in photos from Al

### **Other Machining p150**

- abrasive powder machining- “sandblasting” to machine-some resists can withstand
- precision mechanical-diamond turning machine with accuracies to 25 nm RMS
- scanning probe microscopy can manipulate on atomic level
- droplets of metals that alloy with Si can be migrated in straight line paths from cold side of wafer to hot side
- molten “alloy zone” migrates toward the hot side, dissolving Si atoms at the hot side and deposits them on the cold side
- used to make conductive wires that reach through the wafer-problem is very high temps ~1000deg C and induces high stress on wafers
- photosensitive glass can be lithographed-good for optical lenses
- focused ion beam of reactive ions, ex. Fluorine, can achieve very high resolution, can even etch CVD and single crystal diamond, but very serial process

# Madou Notes

## I. Lithography

### 1. Masks

-nearly optical flat glass/quartz plate w/ 800Å-thick Cr absorber

- a) mask: feature resolution of 1:1 for hard contact and proximity masks
- b) hard contact- pattern placed in direct contact with PR and exposed to UV-  
problems:
  - i) limited mask lifetime due to contact
  - ii) creates defects on mask and substrate → not suitable for VLSI
- c) hard masks good for R&D, mask printing, and prototyping
- d) proximity masks~10-20 μm above wafer
- e) “shadow printing” =both hard and soft contact masks
- f) projection printing-mask imaged by high-res lens system-lifetime limited by operator handling

### 2. Lithography process

#### a) Apply PR

-common to grow oxide for subsequent wet etch or boron implant before PR applied

-PR dispensed onto wafer on resist spinner-spun 1500-800rpm

$$-T=K \cdot C^B \cdot \eta^\gamma / \omega^\alpha$$

K- calibration constant

C- polymer concentration

$\eta$ - viscosity

$\omega$ - rpm

B,  $\gamma$ ,  $\alpha$ - correlation coefficients

-after baking, for IC's, PR thickness =0.5-2μm, but up to 1 μm is used

- 1) *PR uniformity must be  $\pm 5$  nm (for 1.5 μm PR) for reproducible line widths and development times*
  - 2) *Too much resist @ edge covering or run out, hillocks, ridges, and reduced yield*
- b) Soft bake (75-100 C for 10 minutes)
    - 1) Remove solvents/stress and promote adhesion
  - c) Expose
    - 1) Alignment usually to 5 μm or better
    - 2) Wavelengths run from deep UV (150-300 nm) to near UV (350-500 nm)
    - 3) Typically, use g-line (436 nm) or I-line (365 nm)
    - 4) Shorter wavelength = reduced brightness = higher PR sensitivity required
    - 5) dose ( $J/cm^2$ ) = light intensity ( $W/cm^2$ )  $\times$  exposure time (sec)
    - 6) smaller the dose for a given resolution, the better
  - d) Post-exposure bake (not usually needed?)
    - 1) Might be desired to complete chemical reaction caused by exposure
    - 2) Useful in image reversal and dry development systems
    - 3) Precise control needed → typically a few seconds at 100 C
  - e) Development

- 1) Based on 3 different exposure induced changes
    - cross-linked polymers
    - reactivity change
    - polarity change
  - 2) Types of wet developers
    - Immersion (cassette-loaded wafers)
    - Spray developers
  - f) Descum and Post bake
    - 1) Oxygen plasma descum removes unwanted PR after development
    - 2) Residual PR problem severest for small ( $< 1 \mu\text{m}$ ) high aspect ratio structures
  - g) Post bake
    - 1) removes residual developing solvents and anneals PR to promote interfacial adhesion
    - 2) improves film hardness  $\rightarrow$  increases PR resistance to etchants
    - 3) higher temp (120 C) and longer time (20 min) than softbake
    - 4) major limitation: excessive heat could reflow PR  $\rightarrow$  degrade wall profiles and makes PR removal difficult
  - h) Etch
  - i) Strip PR
3. PR essentials
- a) Requirements for PR
    - 1) high sensitivity, high contrast, good etching resistance, good resolution, easy processing, high purity, long shelf life, minimal solvent use, low cost, and high glass transition temp ( $T_g$ ) (see p.5 for explanation of  $T_g$ ).
  - b) Principal PR components
    - 1) Polymers – changes structure when exposed
    - 2) Sensitizers – control chemical reactions in the polymeric phase
    - 3) Solvents – allows spin application and formation of thin layers
  - c) Positive PR – areas exposed will dissolve
    - 1) PMMA (polymethylmethacrylate) -- used in e-beam, ion, and X-ray lithography
    - 2) DQN + phenolic novolak resin
    - 3) Soluble in strong alkaline solutions and developed in mildly alkaline solutions
    - 4) Resolution of better than  $0.5 \mu\text{m}$
    - 5) Development is time dependent  $\rightarrow$  profile can be tailored
  - d) Negative PR – areas exposed will remain
    - 1) Always need to overexpose to ensure polymerization occurs in bottom of PR layer
    - 2) Overexposure means more scattered radiation, leading to less resolution
    - 3) Resolution of  $2 - 3 \mu\text{m}$
    - 4) Need thin layers for good resolution, but pinholes becomes an issue
    - 5) Good adhesion to substrate
    - 6) Highly resistant to acid and alkaline solutions, lasts longer in wet etch than positive PR

7) Profile is independent of development but subject to swelling

See Figure 1.1 (p.6) and Table 1.1 (p.9) for Positive/Negative PR comparisons

- e) Humidity control and adhesion promoters (i.e., HMDS) are critical to PR adhesion
4. Wafer Cleaning and contaminants
- a) See clean room classification table, Figure 1.2 (p.10)
  - b) See listing of possible contaminants, Table 1.3 (p.10)
  - c) Variety of wet/dry wafer cleaning procedures
    - 1) RCA1 and RCA2
    - 2) vapor cleaning
    - 3) thermal treatment
    - 4) ultrasonic
    - 5) plasma/glow discharge
    - 6) high temp (1000 C) bake
5. Critical dimensions, etc.
- a) Minimum reproducible feature size = critical dimension
  - b) Limited by hardware, material, and processing considerations
  - c) see figure on p.12
6. Lithographic sensitivity and PR sensitivity
- a) Lithographic sensitivity = measurement of the overall efficiency in the lithographic process
  - b) PR sensitivity = PR response to radiation
7. PR profiles and lift-off
- a) See Figure 1.3 (p. 14) for positive and negative PR profiles
  - b) See Figure 1.4 (p. 14) for lift-off process
  - c) Lift off advantages
    - 1) Can pattern many hard to etch metals and polymers
  - d) Lift off disadvantages
    - 1) Rounded profile of deposited features
    - 2) temperature limited by PR (200 – 300 C)
8. Photolithography resolution
- a) Contact and proximity lithography resolution limited by
    - 1) diffraction of light through the mask
    - 2) alignment of mask and wafer
    - 3) nonuniformities in wafer flatness
    - 4) debris between mask and wafer
  - b) see “self-aligned” mask example, Figure. 1.8, p. 17
  - c) Projection systems
    - 1) Scanning projection – multiple scans of whole wafer
    - 2) Stepper – reticle exposes small part of wafer then steps to the next position

9. Alignment issues
  - a) Front-to-back alignment on the same wafer
    - 1) Etch holes through the wafer
    - 2) Infrared aligner
    - 3) Double-sided mask aligner (see Figure 1.13, p. 23)
  
10. Image reversal
  - a) see Figure 1.17 (p. 27)
  
11. Thin film interference effects
  - a) see Figure 1.20 (p. 29)
  - b) Problems
    - 1) standing wave profile -- coherent interference of monochromatic light
    - 2) line-width variations
    - 3) reflective notching -- light reflected from reflective features (Al, gold, etc) buried in the PR
    - 4) scumming (underexposed resist leaving organics after development)
    - 5) alignment inaccuracies
  - c) Solutions
    - 1) Broadband light and thinner resists help with standing wave problem
    - 2) Anti-reflective coatings help with interference effects
    - 3) increase the PR absorption
    - 4) multi-layer PR
  
12. Polyimide
  - a) Uses – passivation and interlayer dielectrics, planarizing compounds, reactive ion masks, alpha particle barriers, structural elements, humidity sensitive materials, LCDs, color filters, and waveguides.
  - b) Properties – excellent thermal stability (up to ~450 C), good dielectric properties, chemical resistance, toughness, wear resistance, flame retardance, and flexibility
  
13. PR stripping
  - a) Wet stripping
    - 1) strong acids like  $H_2SO_4$
    - 2) organic solvents and alkaline strippers
    - 3) acetone (if postbake was at low temp or short duration)
  - b) Dry stripping (oxygen plasma)
    - 1) Advantages – constant over time, even PR removal, less corrosive to metal features, leaves a cleaner surface, no undercutting and broadening of PR, fewer environmental disposal problems
    - 2) Plasma stripping – use a plasma to split  $O_2$  in O molecules, which then attack PR in an isotropic manner
    - 3) Ozone strippers use ozone to do same thing
    - 4) UV/ozone stripping – UV breaks bonds in PR and allows for faster ozone attack

14. Alternative Lithography techniques (see Figure 1.27, p. 38 for comparison)
  - a) X-Ray lithography (basic building block of LIGA)
    - 1) Advantages – no vacuum needed, flood exposure possible, large depth of focus, high reproducibility (independent of substrate type, surface reflections, and wafer topology), dust contamination not a problem, negligible diffraction effects.
    - 2) Dominant PR material: PMMA, i.e., plexiglass.
    - 3) Expensive mask. see Table 1.5, p. 39 for optical vs. X-ray mask comparison
  - b) e-beam lithography
    - 1) see Table 1.6, p. 42 for applications
    - 2) Advantages – very good resolution (0.1  $\mu\text{m}$ ), precise energy and directional control, lower defect densities, large depth of focus
    - 3) Disadvantages – resolution limited to 10 nm or greater due to electron scattering, vacuum chamber needed, slow scan speed, high system cost.
    - 4) E-beam lithography resist – PMMA
  - c) Ion-beam lithography
    - 1) Advantages – Surface modification, i.e., patterned doping, possible, better resolution than e-beam due to less back-scatter, smallest spot size.
    - 2) Disadvantages – same as e-beam, namely serial scanning and expensive vacuum equipment
  - d) Other methods
    - 1) STM tips to move atoms or pattern surfaces
    - 2) Holographic lithography
    - 3) Stereolithography/Micro-photoforming

## II. Deposition

1. General
  - a) two main types of techniques
    - 1) physical vapor deposition (PVD) -- direct line of sight impingement
      - evaporation, sputtering, molecular beam epitaxy (MBE), laser ablation deposition, ion-plating, cluster deposition
    - 2) chemical vapor deposition (CVD) -- diffusive-convective mass transfer
    - 3) see Table 3.1 (p.89) and Table 3.2 for deposition methods and applications. Table 3.2 is especially important...
  - b) better quality thin-film from low pressure processes, e.g., sputtering and LPCVD, than aqueous solutions, e.g., electroplating
  - c) Silicon wafer specs, see p.92
2. Wet and Dry Silicon Oxidation
  - a) Temp. range = 600 - 1250 C  $\rightarrow$  high temp aids diffusion of oxidant through surface oxide to silicon interface to form thick oxides quickly
  - b) Room temp native oxide is 20 Å thick
  - c) Oxidation reactions, p.92
    - $\text{Si} + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2 + \text{H}_2$  (wet)
    - $\text{Si} + \text{O}_2 \rightarrow \text{SiO}_2$  (dry)

- d) Ratio of silicon converted to oxide  $\rightarrow X_s = 0.46 \cdot X_{ox}$
- e) Grown oxide is compressive, but wet oxidation helps relieve it
- f) Oxide growth rate  $\rightarrow dX_{ox}/dt = C_i \cdot K_s/N$
- g) Oxide thickness as function of time, Eq. 3.4, p. 93
  - 1) 
$$X_{ox}(t) = \frac{A}{2} \left\{ \left[ 1 + \frac{(t+t)}{A^2} 4B \right]^{1/2} - 1 \right\}$$
  - 2) case for short times (reaction rate limited)  $\rightarrow$  linear growth, B/A depends on surface orientation
  - 3) case for long times (diffusion limited)  $\rightarrow$  parabolically decreasing growth
- h) see Figure 3.2 (p. 93) and Figure 3.3 (p.94)
- i) Uses of oxide: insulating layer, mask, sacrificial layer, structural element, dielectric in passive device
- j) Good diffusion mask against common dopants, e.g., boron and phosphorous
- k) Poor diffusion mask for alkali ions (sodium and potassium), especially when hydrated (wet) since it's an ion sponge
- l) dry oxidation (900 - 1150 C) makes better oxides (stoichiometric, high density, pinhole free) but wet oxidation is faster
- m) Typical oxidation thickness = tenths of micron, max thickness = 1-2 micron
- n) Surface orientation of oxidation
  - 1) in reaction-rate limit,  $B/A(111) / B/A(100) = 1.7$
  - 2) oxidation rate for Si:  $(110) > (111) > (311) > (511) > (100)$

### 3. Thermal Evaporation

- a) Based on boiling off (or sublimating) a heated material onto a substrate in vacuum, the higher the vacuum, the better
- b) Number of molecules leaving a unit area/sec  $\rightarrow$  Eq. 3.8 (p.97)

$$N = N_o \exp\left(-\frac{\Phi_e}{kT}\right)$$

- c) Oxygen partial pressure  $< 10^{-8}$  Torr to avoid reactions at source, e.g., oxide impurities
- d) Way to thermally evaporate (see Figure 3.6 and Table 3.6, p. 97)
  - 1) Resistive heating -- high current passed through a highly refractory metal containment structure, e.g., a tungsten boat or filament.
  - 2) e-beam -- magnetically directed 3-20 KeV e-beam focused on a target that's placed in a water-cooled copper hearth.
    - local melting of target creates its own crucible  $\rightarrow$  reduces source contamination problems
    - disadvantage: possible X-ray damage and ion damage on the substrate
  - 3) RF induction -- water-cooled RF coil surrounds crucible holding the target.
- e) Target suitability: elements or simple compounds with  $1 - 10^{-2}$  Torr vapor pressure in temp range 600-1200 C
  - 1) Refractory metals (platinum, molybdenum, tantalum, tungsten) have too high a temp to reach needed vapor pressure
  - 2) Target vapor pressure must be  $\geq 10^{-2}$  Torr

- 3) Target at  $10^{-1}$  Torr vapor pressure deposits 1000 atomic layers/sec
  - f) Fraction of particles scattered by collisions is, eqn. 3.10, p.98
    - $1 - \exp(-d/\lambda)$
  - g) Arrival rate at a function of angle given by eqn 3.13, p. 99, see FIGURE 3.5 (P.98)
    - $A \sim \cos\beta \cos\theta/d^2$
  - 1) max deposition occurs when target is perpendicular to substrate
  - h) Shadowing
    - 1) ratio of film thickness  $t_1/t_2 = \cos(b_1)/\cos(b_2)$
    - 2) two solutions
  - i) heat substrate to 300-400 C during deposition to increase surface mobility of metal atoms
  - j) rotate wafers on a planetary wafer holders
  - k) Advantages
    - 1) fast (0.5 micron/min for Al) and simple
    - 2) low energy impact on substrate ( $\sim 0.1$  eV)  $\rightarrow$  no surface damage except for e-beam evaporation
    - 3) film of known structure and extreme purity possible
  - l) Disadvantages
    - 1) shadowing, especially with metal deposition on very small structures
    - 2) can be nonhomogeneous over large areas
    - 3) Alloy sources can decompose at high evaporation temperatures
  - m) can use multiple sources to deposit complex metals
  - n) Evaporation in low pressure oxygen ambient create oxides on deposited metals, process known as reactive evaporation
4. Sputtering (see Table 3.7, p.100, for comparison of evaporation and sputtering)
- a) Basic idea -- hold the target at a high negative potential while bombarding it with positive argon ions created from a plasma. The target is sputtered away by momentum transfer from the impinging ions and the sputtered material condenses on the substrate at the anode
  - b) Sputter Yield (S) = number of atoms removed/incident ion. see Figure 3.6, p.100
    - 1) Typical ion energy range = 0.5-3 kV as nuclear collisions dominate here. Sputter yields are 0.1-20 atoms/ion, with metal sputter yield = 1 atom/ion
    - 2) ion energy of 10 KeV - 1 MeV  $\rightarrow$  max sputter yield but gradual decline due to deep ion implantation
    - 3) Due to high ionic energy, sputtered film adhesion is better than other PVD deposition methods
    - 4) 100-1000 times the evaporation activation energy needed to sputter 1 atom  $\rightarrow$  lots of excess heating of target
  - c) High working pressure ( $> 10^{-2}$  Torr) needed to produce ionizing collisions between secondary electrons released from the cathode and ambient gas
    - 1) max practical pressure  $\sim 10^{-1}$  Torr  $\rightarrow$  mean free path  $\sim 1$  mm.
  - d) Advantages
    - 1) Good step coverage due to low mean free path
    - 2) Broad source means no shadow effect

- 3) Good film adhesion and less contamination (from trapped gas atoms) at low pressure sputtering
  - e) Conductors -- DC sputtering. Insulators → may need RF sputtering
  - f) In situ substrate cleaning possible via a pre-sputter etch using ions from the plasma
  - g) Magnetron sputtering (cross electric and magnetic fields trap electrons in the plasma) has higher ion densities → deposition rate increases to several hundred angstroms/min.
  - h) Heating the substrate promotes film adhesion
  - i) Good to have ions hit the substrate during deposition
    - 1) ions add energy and mobility to the surface atoms → fills voids
  - j) Ways to deposit a composite film
    - 1) Reactive sputtering -- sputtering with a reactive gas → can control or modify the deposited film properties
    - 2) Co-sputtering multiple targets
    - 3) Sputter a composite target
  - o) Self-correcting mechanism if one element is preferentially sputtered. Composition of that element decreases and other elements increase in sputter rate until new balance reached.
  - k) Disadvantages
    - 1) complex process vs. evaporation
    - 2) excessive substrate heating due to secondary electron bombardment
    - 3) slow deposition rate
5. Molecular Beam Epitaxy (MBE)
- a) Basic idea -- put atoms in a single-crystal fashion on a substrate (seed crystal), hence making the film lattice identical to the substrate lattice
  - b) Can make films of exact thickness and dopant level
  - c) Growth rate dependent on substrate crystal orientation
    - 1) Si (111) planes grow fastest
  - d) Homoepitaxy, AKA epi -- film type is same as substrate. Important examples, Si on Si, GaAs on GaAs.
  - e) Heteroepitaxy -- Si on SiO<sub>2</sub>, i.e., silicon on insulator (SOI) and Si on sapphire (Al<sub>2</sub>O<sub>3</sub>).
  - f) MBE process
    - 1) heat single crystal sample (400 - 800 C) in ultra high vacuum (10<sup>-11</sup> Torr) and place in path of atoms from heated targets
    - 2) Atoms impinge on substrate, ala evaporation
    - 3) Precise shutters control deposition and deposition rate is very slow (1 monolayer/sec, 1 micron/hr)
    - 4) Able to in situ monitor
  - g) low growth temps reduce diffusion and autodoping effects
  - h) Atomic control of layer thickness and doping profile possible
6. Laser Sputtering/Ablation see Figure 3.8, p.103 for schematic
- a) Basic idea -- very short wavelength radiation is adsorbed in the target's upper surface and evaporates a tiny bit of material. The partially ionized material (in

the laser-induced plasma) is deposited onto the substrate with very little decomposition.

- b) Very good for complex compounds, e.g., superconducting films
  - c) Deposited films are amorphous → need anneal at 700-900 C to crystallize
  - d) Not good for large-scale coatings due to small active source size
7. Chemical Vapor Deposition (CVD) see TABLE 3.9, p. 109 for comparison.....
- a) Basic idea -- chemicals in a vapor phase (often diluted with an inert carrier gas) react at a hot surface to form a film.
  - b) Homogeneous reactions (those occurring off the substrate in the gas) are bad because they cause poor adhesion, low density, and high defect films
  - c) Slowest step determines deposition rate while the substrate chemistry, temperature, and thermodynamics determines the deposited compounds.
  - d) Many types of films possible -- amorphous, polycrystalline, epitaxial, and uniaxially-oriented polycrystalline layers.
  - e) Reaction mechanism (see Figure 3.13, p. 106)
    - 1) Mass transport of reactants from reactor inlet to deposition zone
    - 2) Homogeneous gas phase reactions forming film precursors and byproducts
    - 3) Mass transport and adsorption of film precursors and reactants to substrate
    - 4) Heterogeneous surface reactions
    - 5) Surface diffusion of film formers to growth sites
    - 6) Nucleation and island growth
    - 7) Redesorption of film precursors
    - 8) Mass transport of byproducts from substrate to reactor exit
  - f) Thermally driven CVD requires temperature gradient in reactor. Gas-phase reactants form in hot region and desired film forms in slighter colder region.
  - g) FICK'S FIRST LAW (governs diffusion of gas phase reactants to substrate), eqn 3.16, p.106
    - 1)  $F = D \, dc/dx$
  - h) Film growth dependence on limiting regime
    - 1) Film growth rate in mass transport limited regime depends on square root of gas velocity, eqn. 3.21, p.106
    - 2)  $F = D \frac{\Delta c}{2L} 3\sqrt{\text{Re}_L}$
    - 3) High flow rate → surface reaction limited regime.
      - $R = R_0 \exp(-E_a/kT)$ , eqn. 3.22, p.106
    - 4) see Figure 3.15.
    - 5) practical application → in LPCVD wafers are stacked vertically (surface reaction limited) while APCVD wafers are stacked horizontally (mass transport limited)
  - i) Film uniformity dependent on flow stability, i.e., fully developed or not.
    - 1) importance of Knudsen number.
  - j) Step coverage see Figure 3.16, p. 108
    - 1) mean free path of a molecule  $l = \frac{kT}{2^{1/2} P_T p a^2}$ , eqn. 3.25, p. 108

- 2) where reactants have enough energy for surface migration → uniform film (Figure 3.16a), e.g., CVD poly & nitride
  - 3) mean free path is larger enough to hit trench bottom, but little leftover energy for migration → Figure 3.16b, e.g., evaporated and sputter metal films
  - 4) mean free path is too short and no surface migration → Figure 3.16c
  - 5) eqn 3.27, p.108 yields pressure minimum for uniformity.
- k) PECVD see Figure 3.17, p. 110
- 1) RF plasma transfers energy to reactant gases → lower temp substrate than APCVD or LPCVD
  - 2) Surface reaction limited. Substrate temp control ensures uniformity.
  - 3) Wafers on grounded electrode get less energetic bombardment than those on powered electrode.
  - 4) Less radiation damage than sputtering due to
    - lower power densities
    - high pressures
    - high substrate temp
  - 5) Films are not stoichiometric because deposition reactions vary widely and particle bombardment changes film composition according to ratio of sputtering yields of the component materials
  - 6) More bombardment = better film equality
  - 7) Advantages of PECVD
    - good adhesion
    - low pinhole density
    - good step coverage
    - adequate electrical properties
    - compatible with VLSI
    - most used application -- deposition of oxide or nitride over metal lines
  - 8) Parameters in CVD
    - Total reactor pressure. lower pressure = better quality films w/low compressive stress
    - Note: film stress goes from tensile to compressive as pressure decreases
    - RF frequency. Lower frequency imparts high energy to ions → better films w/compressive stress. Also improves sidewall film quality
    - RF power. Higher ion current -> higher film deposition rate. Max ion bombardment (power density / dep. rate) leads to best film.
    - Substrate temp. Low temp = high growth rate but little surface diffusion and amorphous film formation. High temp = low growth rate but high surface diffusion, so adsorbed species can get to step growth sites to form single crystalline film.
    - Best combo: low RF frequency, low pressure, high substrate temp.
- l) APCVD
- 1) Primarily for epitaxial Si and compound semiconductors (GaAs, InP, HgCdTe). Also low temp oxide (LTO) at 300-450C
  - 2) Susceptible to gas phase reaction and poor step coverage
  - 3) Mass transport limited → wafer access important but temp is not

- m) LPCVD (below 10 Pa)
  - 1) Surface reaction limited → large wafer batches possible without compromising film uniformity
  - 2) Reactants used without dilution, so growth rates only 10X slower than APCVD
  - 3) LPCVD poly = good for structural layers. Oxide and PSG good for sacrificial layers
  - 4) Disadvantages → low deposition rate and high temperatures
  - 5) Hot wall reactors require lots of maintenance since they get coated
- n) MOCVD (metallorganic CVD)
  - 1) Thickness control to 1 atomic layer → preferred epitaxial process.

### III. Dry Etching

The preference of dry etching over wet etching:

1. Fewer disposal problem
2. Less corrosion problem for metal features in the structure
3. Less undercut ( economic chip area utilization)
4. A variety of PR
5. No surface tension issue

Very sharp sidewall /Anistropic etching is not always good:

1. Conformal deposition is not easy
2. Need more undercut to remove all mask materials.(P.56, Fig.2.4)

The preference of RF Plasmas over DC plasmas:

1. Sustaining the plasma at lower pressure( long mean free path)
2. RF allows etching of dielectrics as well as metals.

Etch Performance (p.62)

- Radiation damage can be minimized by keeping energy low and can also be remedied by annealing.
- Higher etch rate → higher throughput  
→poor selectivity, poor uniformity and poor profile control

#### Physical Etching:

Sputtering or Ion-Etching (**Diode set up**): (p.63)

Pros:

1. **etching material is nonselective**
2. directional anistropy
3. etch rates for different materials are almost the same
4. volatility of the etch product is not critical

Cons:

1. **Electrical damage from ion bombardment**

2. Etch rate is very slow
3. Unwanted heating in substrate. (most electrons do not cause ionization events with Argon, end up being collected in the anode, the substrate)  
→ can be remedied by applying magnetic field
4. Need high gas pressure to increase ion current, which results in shorter mean free path. → redeposition of sputtered atoms
5. Nonselective etching → masking problem

Ion-Beam Etching or Ion-Beam Milling: (p.63)

- **A triode setup**: control of the energy and flux of the ions to the substrate are independently.(p.63, Fig 2.10)
- The sample can be rendered and this makes the equipment usable for **sputtering insulators as well as conductors**.
- The argon pressure in the upper portion of the chamber is low → **low mean free path**

Limitations of Physical Etching (p.64,65)

1. Faceting (on PR mask) due to Angle-dependent sputter rate(P.64, Fig2.11)
2. Trenching, which happened only when:
  - A sizable fraction of off-vertical ions: ( due to sheath scattering or field nonuniformity)
  - Sidewall must have a slight taper (due to faceting, redeposition)
3. Redeposition on the sidewalls of the mask and trench( for aspect ratio > 1)  
It can be remedied by tilting and rotating wafer during etching

### Dry Chemical Etching(p.66)

Preference over physical etching:

Low voltage, low surface damage, **neutral species** formed in plasma (species can be insulation or conductive materials)

Disadvantages: volatile gas treatment

Reaction mechanisms:

1. Generation of etchant species
  2. Diffusion to surface
  3. Adsorption
  4. Reaction
  5. Desorption
  6. Diffusion into bulk gas
- Radicals and molecules serve as the primary etching species for all chemical etching; however, ions are primary etching species for physical etching.

Why Dry Chemical Etching requires less voltage than Physical etching:(p.68)

Radicals and other neutrals reach the surface by **diffusion**; whereas for physical etching, ions are accelerated toward the surface by the negative potential on the substrate electrode.

It can have a very good selectivity by choosing right gas:

- PR stripping: Oxygen plasma
- Silicon etching: Fluorine compounds, Chlorine (which can enhance selectivity)
  - Anisotropic etching:  $\text{CF}_4 + \text{O}_2$  plasma
  - Isotropic etching:  $\text{SF}_6$
- Aluminum: Chlorine but not fluorine compounds (aluminum fluoride is involatile)
- Nitride, Oxide :  $\text{CF}_4 + \text{O}_2$

Factors for uniformity(p.68)

1>Loading Effect and wafer loading:

It occurs as a result of gas phase etchant being depleted by reaction with the substrate materials.

- The more purely chemical the etching the bigger loading effect; With lower pressures the loading effect becomes smaller.
- If the supply of gas limits the etch rate, small variation in gas flow may lead to nonuniformity.

2.Gas flow rate and symmetry of gas flow

- Utilization factor  $U$  (rate of formation of products to rate of gas flow) , It's suggested  $U > 0.1$  to get a good uniformity .

3.**Bull's Eye Effect**(fig 2.13):

Etching uniformity also impacted by the relative reactivity(etch rate) of wafer surface with the **cathode material used**.

4.Position of wafer in the chamber:

Wafer should be placed in the middle.

5.Good thermal conduction between wafer and cathode.

Local temp. variation results in nonuniformity

6.'**Grass' Structure Effect**: Contamination of  **$\text{Al}_2\text{O}_3$**

Ion Energy vs. Pressure Relationship in a Plasma(p.69, Fig2.14)

- Two factors control the etching rate:
  1. **Gas Pressure**
    - The neutral atoms,
    - Free radical concentration
    - Ion concentration(gas pressure, control the reaction rate)
  2. **Ion energy**(control the anisotropy)
- Low Gas Pressure
  - (+)More anisotropic/Good critical dimension control
  - (+)Less contamination
  - (+)Reduce the loading effect
  - (-)Low etch rate
- High Power
  - (+) High etch rate
  - (-) More device damage
- High pressure & low voltage  $\rightarrow$  isotropic chemical etching

- Low pressure & high voltage → anisotropic etching
- 

Gas Phase Etching without Plasma (XeF<sub>2</sub>)

- Isotropic Si etching
- Good for mask selection

Dry Etching Spectrum(p.70): good summary

Anisotropy:

- Low temperature (wafer cooling) can improve anisotropy and CD
- $V_x/V_z = X/Z$  (p.72, Fig. 2.17)
  - $V_x$ : Lateral etching rate for zero bias → equivalent to anisotropic etching status
  - $V_z$ : Normal etch rate
- Inhibition-Driven Anisotropy(p.73)
  - Si etching: Adds H<sub>2</sub> (10%) to CF<sub>4</sub> (Fig. 2.18)
  - Al etching: Adds Cl<sub>2</sub> to CCl<sub>4</sub>
  - Phosphorous-doped Si etching: Adds C<sub>2</sub>F<sub>6</sub> to Cl<sub>2</sub> plasma

Some rules(p.76)

1. F/C ratio: Higher H<sub>2</sub>(more **polymerization**) → Better Anisotropy; Higher O<sub>2</sub> → Higher etch rate
2. Selective vs. unselective etching:

The closer to the polymerization, the better selectivity

- Decrease temp
  - High H<sub>2</sub> concentration
  - High pressure
  - High monomer concentration
  - Small addition of **halogens** significantly increase the selectivity of fluorine base etch
3. Substrate: Higher negative bias on substrate, more etching than polymerization
  4. Metal etching :
    - Use Chlorocarbons or Fluorocarbons
    - Oxygen and water vapor must be rigorously excluded (prevent metal-oxide forming)
    - Ion bombardment is essential (because bond is too stable)
    - For Al, use Chlorine compounds, cannot use Fluorine.
  5. Organic films: CF<sub>4</sub>-C<sub>2</sub>H<sub>2</sub> but cannot use oxygen

**Comparing Wet and Dry Etching (p.79, p80. Table2.10)**

Pros for Dry etching:

- Higher aspect ratio/High Anisotropy
- Good CD control

- It can etch more types of materials
- Good for etch rate control

Cons for dry etching:

- Low etch rate
- Poor etch selectivity
- High sensitivity to operating parameters

There four very good examples for Dry etching (p.79 ~p.87)

## IV. Wet Etching

Silicon Crystallography

- The flat for {100} wafer is <110>
- Normally, the flat for {110} wafer is <111>
- To fabricate a membrane, [100] wafer is prepared:
  - Easy to control the membrane thickness
  - Shape and orientation of membrane is easy to control
- [110] has a more densely packed structures because it can have a vertical wet etching, while [100] cause a lot loss of real estate
- To have a higher aspect ratio, [11] is preferred.

Silicon as a substrate:

Pros:

- Existing mature technology for etching and deposition
- Existing equipment
- Silicon is cheap

Cons:

- Not good for chemical or biological applications, not disposable/electrical problem
- An overwhelming determining factor for substrate choice is the final package of the device

**Isotropic etching** : (p.166)

mixture of nitric acid (HNO<sub>3</sub>)and hydrofluoric acid (HF),

( HNA: R ~ 50 μm/min)

1.) HNO<sub>3</sub> → oxide the surface

2.) HF → reduce the oxide

3.) CH<sub>3</sub>COOH→ buffer for HNO<sub>3</sub>

Advantages:

- Higher etch rate
- Removal of work-damage surface
- Rounding of sharp anisotropically etched corners
- Removal of roughness after dry or anisotropical etching
- Creating structures or planar surface in single-crystal slices

- Mask materials: Nitride, thick oxide and Au
- Agitation is very important
- Etch rate is very sensitive to agitation as well as temp.
- Etch stop
  - By reducing the dopant concentration to below  $10^{17}$ , the etch rate of Si in HNA is reduced by ~150 folds
  - Apply bias to supply holes to silicon surface without illumination

Problems with Anisotropy etching:

- Difficult to have a precise masking
- Etch rate is very sensitive to agitation
- Difficult to control lateral as well as vertical geometry

Anisotropic Etching (p.168)

Advantages:

- Better lateral and vertical control
- Many etch stop techniques available

Disadvantages:

- Slow etch rate
- Etch rate is also temp. sensitive

Etchants: (p.171, Table 4.9)

1. KOH

- IC incompatible
- Faster etch rate
- Cannot use Al, Oxide as mask material

2. EDP

- Toxic
- Al, Oxide can use as mask
- Easier to control etch rate
- Etch stop (requires less concentrated boron)

3. TMAH

- IC compatible
- Slower etch rate

**Surface Roughness(Microscopic roughness)**

**Notching(Macroscopic roughness)**

Centers of exposed areas etch with a seeming lower average speed compared with the borders of the areas

**Backside Protection**

- LPCVD Nitride, Teflon coating, waxes and two wafer glued together

Photoelectrochemical etching( PEC-etching) (Kovacs, P55)

- (Electropolishing) / (Micro porous etching/Macroporous etching)
- Porous: 20 Å - 10 μm, aspect ratio: ~250

- Illumination results in holes(+) in wafer which gather at the prefabricated pittings.
- Biased: Positive to Wwafer and negative to HF solution.
- Use HF to etch. Etch rate is very high at the highly carrier concentrated pittings. This is because there is a high electrical field in the interface between the pitting and HF .  

$$\text{Si} + 2 \text{F}^- + 2\text{h}^+ \rightarrow \text{SiF}_2$$

$$\text{SiF}_2 + 2 \text{HF} \rightarrow \text{SiF}_4 + \text{H}_2$$
- If the current is below " a critical current density", porous silicon is formed. If the current is higher the critical density, electropolishing is formed.
  - Charge-supply-limited: Porous Silicon Etching (Low current, High HF Concentration)
  - Mass-transport-limit: Electropolishing (High current, Low HF Concentration)
- Pore Size : Smaller Current  $\rightarrow$  small size  
 With illumination (higher energy/high p+ concentration)  $\rightarrow$  smaller size  
 p+ substrate(more p+, holes)  $\rightarrow$  smaller size
- Macroporous Etching:
  - High voltage, Low Current, with illumination and in the dark
  - By using a pore initiation pattern, the macropores can be localized(p192, fig.4.46)

#### Etch Stop(p.193)

- 1.) Boron etch stop : Doping Boron to  $\sim 7 \times 10^{19}$  resulted in etch rate of Si dropping sharply for EDP and KOH. Etch rate for EDP drops even more.
- 2.) Electrochemical etch stop: (P.195, Fig. 4.51)
  - A lightly doped P-N junction is used as an etch stop by applying bias between wafer and a counter electrode in the etchant.
  - $\text{N}^+$  Phosphorous Doped,  $10^{15}$  on a p-type substrate
  - Reverse biased :Apply reverse biased on pn junction to make positive on n+ and negative on p+.
  - Positive bias relative to open-circuit potential (OHP) eliminates built in electric field repelling hydroxyl ions and thus, enables oxidation of surface.
  - Advantages: It doesn't heavy boron doping. Heavy boron doping results in slip planes and tensile stress, and also some piezoresistive coefficient drops dramatically while highly doping.
- 3.) Photo-Assisted Electrochemical Etch Stop (for n-type)
  - Use HF etchant
  - Use illumination
  - Positive on n+
- 4.) Photo-Induced Preferential Anodization (for p-type)

- Use HF etchant
- Use illumination
- Positive on p+

Problems with Wet Etching:

- Not applicable for submicron technology
- Extensive real estate consumption
- Undercutting
- Corner compensation(p.201, Fig 4.60,4.61)