Electrostatic Sensors and Actuators

Chang Liu
Outline

• Basic Principles
  – capacitance formula
  – capacitance configuration

• Applications examples
  – sensors
  – actuators

• Analysis of electrostatic actuator
  – second order effect - “pull in” effect

• Application examples and detailed analysis
Basic Principles

- **Sensing**
  - capacitance between moving and fixed plates change as
    - distance and position is changed
    - media is replaced

- **Actuation**
  - electrostatic force (attraction) between moving and fixed plates as
    - a voltage is applied between them.

- **Two major configurations**
  - parallel plate capacitor (out of plane)
  - interdigitated fingers - IDT (in plane)
Examples

- Parallel Plate Capacitor
- Comb Drive Capacitor
Parallel Plate Capacitor

Fringe electric field (ignored in first order analysis)

\[ C = \frac{Q}{V} \]
\[ E = \frac{Q}{\varepsilon A} \]
\[ C = \frac{\frac{Q}{A}}{\varepsilon A} = \frac{\varepsilon A}{d} \]

- Equations without considering fringe electric field.
- A note on fringe electric field: The fringe field is frequently ignored in first-order analysis. It is nonetheless important. Its effect can be captured accurately in finite element simulation tools.
Forces of Capacitor Actuators

- Stored energy \( E = \frac{1}{2} CV^2 = \frac{1}{2} \frac{Q^2}{C} \)

- Force is derivative of energy with respect to pertinent dimensional variable
  \( F = \frac{\partial E}{\partial d} = \frac{1}{2} \frac{\partial C}{\partial d} V^2 \)

- Plug in the expression for capacitor
  \( C = \frac{Q}{\varepsilon A} = \frac{\varepsilon A}{d} \)

- We arrive at the expression for force
  \( F = \frac{\partial E}{\partial d} = -\frac{1}{2} \frac{\varepsilon A}{d^2} V^2 = -\frac{1}{2} \frac{CV^2}{d} \)
Relative Merits of Capacitor Actuators

Pros
• Nearly universal sensing and actuation; no need for special materials.
• Low power. Actuation driven by voltage, not current.
• High speed. Use charging and discharging, therefore realizing full mechanical response speed.

Cons
• Force and distance inversely scaled - to obtain larger force, the distance must be small.
• In some applications, vulnerable to particles as the spacing is small - needs packaging.
• Vulnerable to sticking phenomenon due to molecular forces.
• Occasionally, sacrificial release. Efficient and clean removal of sacrificial materials.
Optical Micro Switches

- Texas Instrument DLP
- Torsional parallel plate capacitor support
- Two stable positions (+/-10 degrees with respect to rest)
- All aluminum structure
- No process steps entails temperature above 300-350 °C.

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“Digital Light” Mirror Pixels

- Mirrors are on 17 μm center-to-center spacing
- Gaps are 1.0 μm nominal
- Mirror transit time is <20 μs from state to state
- Tilt Angles are minute at ±10 degrees
- Four mirrors equal the width of a human hair
Digital Micromirror Device (DMD)
DMD™ Pixel Exploded View

- **Mirror**
- **Landing Tip**
- **Mirror Address Electrode**
- **Yoke Address Electrode**
- **Bias/Reset Bus**
- **Torsion Hinge**
- **Yoke**
- **Via 2 Contact to CMOS**
- **Landing Site**

**Layers:**
- **Mirror Layer**
- **Yoke and Hinge Layer**
- **Metal-3 Layer**
- **Memory Cell (CMOS SRAM)**
Perspective View of Lateral Comb Drive
Transverse Comb Drive Devices

- Direction of finger movement is orthogonal to the direction of fingers.
- Pros: Frequently used for sensing for the sensitivity and ease of fabrication
- Cons: not used as actuator because of the physical limit of distance.

\[ C_{sl} = N\left(\frac{\varepsilon_0 lt}{x_0 + x} + C_f\right) \]

\[ C_{sr} = N\left(\frac{\varepsilon_0 lt}{x_0 - x} + C_f\right) \]
Lateral Comb Drive Actuators

- Total capacitance is proportional to the overlap length and depth of the fingers, and inversely proportional to the distance.

- **Pros:**
  - Frequently used in actuators for its relatively long achievable driving distance.

- **Cons**
  - Force output is a function of finger thickness. The thicker the fingers, the larger force it will be.
  - Relatively large footprint.

\[
C_{tot} = N \left[ \frac{2 \varepsilon_0 t (x + x_0)}{d} + c_p \right]
\]

\[
F|_{x=0} = \frac{N \varepsilon_0 t V^2}{d}
\]

N=4 in above diagram.

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Basic Sacrificial Layer Processing

• Step 1: Deposition of sacrificial layer
• Step 2: patterning of the sacrificial layer
• Step 3: deposit structural layer (conformal deposition)
• Step 4: liquid phase removal of sacrificial layer
• Step 5: removal of liquid - drying.

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Process and Chemical Compatibility

• For a two layer process

• The deposition of the structural layer must not damage the sacrificial layer
  – Thermal stability

• The patterning of the structural layer must not damage the sacrificial layer
  – Chemical and thermal stability

• The removal of the sacrificial layer must not damage the structural layer
  – Chemical and thermal stability
Let's Analyze

- Structural layer: polycrystal silicon
- Sacrificial layer: LPCVD oxide

### TABLE II
**Etch Rates of Si, Ge, SiGe, and C (nm/min)**

<table>
<thead>
<tr>
<th>Etch</th>
<th>Si (100)</th>
<th>Float-Zone Si</th>
<th>Poly Si LPCVD Undoped</th>
<th>Poly Si LPCVD In-situ n⁺</th>
<th>Poly Ge LPCVD Undoped</th>
<th>Poly SiGe LPCVD P-type</th>
<th>Graphite Ion-Milled</th>
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<tr>
<td>Si Iso Etch</td>
<td>150</td>
<td>W</td>
<td>100</td>
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<td>890</td>
<td>550</td>
<td>60</td>
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<tr>
<td>KOH</td>
<td>1100</td>
<td>F</td>
<td>670</td>
<td>&gt;1000</td>
<td>-</td>
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<td>10:1 HF</td>
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<td>R 1.8</td>
<td>0.45</td>
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<td>Pad Etch 4</td>
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<td>Phosphoric</td>
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<td>0.7</td>
<td>0.13</td>
<td>0.40</td>
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## TABLE II

<table>
<thead>
<tr>
<th>ETCHANT</th>
<th>EQUIPMENT CONDITIONS</th>
<th>TARGET MATERIAL</th>
<th>SC Si Poly n</th>
<th>Poly undop</th>
<th>Wet Ox</th>
<th>Dry Ox</th>
<th>LTO undop</th>
<th>PSG unusual</th>
<th>PSG anneal</th>
<th>Steic Nitrid</th>
<th>Low-α Nitrid</th>
<th>Al/Ti</th>
<th>Spat Ti/A</th>
<th>Spat Ti/W</th>
<th>OCG</th>
<th>OCM</th>
<th>OCM 1%N2O PR</th>
<th>OCM 1%N2O PR</th>
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<tbody>
<tr>
<td>CF&lt;sub&gt;4&lt;/sub&gt;·He (90:30:120 sccm)</td>
<td>Lam 90 Plasma</td>
<td>Silicon oxides</td>
<td>1900 1900</td>
<td>2100 2100</td>
<td>4700 4700</td>
<td>4500 4500</td>
<td>7300 7300</td>
<td>6200 6200</td>
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<tr>
<td></td>
<td>Lam 90 Plasma</td>
<td>450W, 2.8T, gap=0.3mm, 13.5 MHz</td>
<td>1400 1900</td>
<td>1500 2100</td>
<td>2400 4800</td>
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<td>CF&lt;sub&gt;4&lt;/sub&gt;·He (90:30:120 sccm)</td>
<td>Lam 90 Plasma</td>
<td>Silicon oxides</td>
<td>2200 1900</td>
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<td>3800 3800</td>
<td>- W W W 2900 2700</td>
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<td>850W, 2.8T, gap=0.3mm, 13.5 MHz</td>
<td>2200 2200</td>
<td>1700 2500</td>
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<td>6000 5500</td>
<td>5000 4000</td>
<td>4000 4000</td>
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<tr>
<td>SF&lt;sub&gt;6&lt;/sub&gt;·He (13:2:1 sccm)</td>
<td>Technics FE II-A Plasma</td>
<td>Silicon nitrides</td>
<td>300 300</td>
<td>730 300</td>
<td>670 730</td>
<td>310 310</td>
<td>350 350</td>
<td>370 370</td>
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<td>- W W W 690 630</td>
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<td></td>
<td>Technics FE II-A Plasma</td>
<td>100W, 250mT, gap=2.6cm, 50kHz sq. wave</td>
<td>300 1000</td>
<td>730 1000</td>
<td>670 760</td>
<td>310 310</td>
<td>350 350</td>
<td>370 370</td>
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<tr>
<td>CF&lt;sub&gt;4&lt;/sub&gt;·CF&lt;sub&gt;4&lt;/sub&gt;·He (10:5:10 sccm)</td>
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<td>Silicon nitrides</td>
<td>1100 1100</td>
<td>1900 1900</td>
<td>920 730</td>
<td>920 730</td>
<td>1500 1500</td>
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<tr>
<td></td>
<td>Lam 480 Plasma</td>
<td>150W, 375mT, gap=1.3mm, 13.5 MHz</td>
<td>1100 1100</td>
<td>1900 1900</td>
<td>920 730</td>
<td>920 730</td>
<td>1500 1500</td>
<td>1300 1300</td>
<td>1100 1100</td>
<td>- W W W 690 690</td>
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<td>Thin silicon nitrides</td>
<td>6400 8400</td>
<td>7000 9200</td>
<td>7000 9200</td>
<td>800 800</td>
<td>300 300</td>
<td>300 300</td>
<td>540 540</td>
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<td>- W W W 1400</td>
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<td></td>
<td>Lam 480 Plasma</td>
<td>150W, 375mT, gap=1.3mm, 13.5 MHz</td>
<td>6400 8400</td>
<td>7000 9200</td>
<td>7000 9200</td>
<td>800 800</td>
<td>300 300</td>
<td>300 300</td>
<td>540 540</td>
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<tr>
<td>SF&lt;sub&gt;6&lt;/sub&gt;·He (195:50 sccm)</td>
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<td>Thick silicon nitrides</td>
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<td>9200 9200</td>
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<td>800 800</td>
<td>300 300</td>
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<td>Lam 480 Plasma</td>
<td>200W, 375mT, gap=1.3mm, 13.5 MHz</td>
<td>8400 8400</td>
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<td>9200 9200</td>
<td>800 800</td>
<td>300 300</td>
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<td>- W W W 1400</td>
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<td>SF&lt;sub&gt;6&lt;/sub&gt;·He (25 sccm)</td>
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<td>2800 1100</td>
<td>1100 1100</td>
<td>1400 1400</td>
<td>2800 2800</td>
<td>2300 2300</td>
<td>- W W W 3400 3100</td>
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<tr>
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<td>Tegal Inline Plasma 701</td>
<td>250W, 300mT, 40°C</td>
<td>1700 1700</td>
<td>2800 1100</td>
<td>1100 1100</td>
<td>1400 1400</td>
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<td></td>
<td>Tegal Inline Plasma 701</td>
<td>100W, 300mT, 13.5 MHz</td>
<td>350 350</td>
<td>360 360</td>
<td>320 320</td>
<td>320 320</td>
<td>530 530</td>
<td>450 450</td>
<td>760 760</td>
<td>600 600</td>
<td>- W W W 400 360</td>
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</table>
More Involved Criteria

• For a two layer process

• The deposition of the structural layer must not damage the sacrificial layer
  – Thermal stability

• The patterning of the structural layer must not damage the sacrificial layer
  – Chemical and thermal stability

• The removal of the sacrificial layer must not damage the structural layer
  – Chemical and thermal stability

• The structural layer should not bend uncontrollably
• The structural layer should not be stuck to the bottom
Surface Micromachined Inductor

- Air bridge can be formed using sacrificial etching.
Inductor - By Lucent Technologies
Stress can be an enemy, or a friend. Most likely an enemy though 😊
Surface Micromachined, Out of Plane Structures
Metal Sacrificial Layers

- Aluminum (0.3µm)
- Permalloy (>20µm)
- PR 4620 (10µm each)
- Copper (9µm each)
A New Method

layer 2

layer 1

substrate
Hinges

- Used in micro optics component assembly.
Hinge Fabrication

- Step 1: deposition of sacrificial layer.
- Step 2: deposition of structural layer.
- Step 3: deposition of second sacrificial layer.
- Step 4: etching anchor to the substrate.
- Step 5: deposition of second structural layer.
- Step 6: patterning of second structural layer.
- Step 7: Etch away all sacrificial layer to release the first structural layer.
For a four layer process ...

- Sacrificial layers (Sac1, sac2)
- Structural layers (str 1, str 2)

- Str1 deposition must not affect sac1
- Str1 patterning must not affect sac1
- Sac2 deposition must not affect sac1
- Sac2 deposition must not affect str1
- Sac2 patterning must not affect str1
- Sac2 patterning must not affect sac1 (if sac 1 is exposed)
- Str 2 deposition must not affect sac2
- Str 2 deposition must no affect str1
- Str 2 deposition must not affect sac1
- Str 2 patterning must not affect sac2, str1, sac1
- Sac 1 removal must not affect str 2, str1
- Sac 2 removal must not affect str 2, str1
To make things more complex and challenging

- Certain layers need to be made of a certain material;
- Stress control issues may dictate certain layer materials;
- Electrical performances may dictate certain layer materials;
- Economic issues may dictate certain layer materials;
Three Pillars of MEMS

Design (physics, Principle)

Goals:
- Better performance
- Better yield
- Unique advantages
- Lower cost
- Higher yield
- ...

Materials

Fabrication

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Stiction = Sticking and Friction
Origin of Stiction

- As the liquid solution gradually vaporizes, the trapped liquid exert surface tension force on the microstructure, pulling the device down.
- Surfaces can form permanent bond by molecule forces when they are close.
Antistiction Method I - Active Actuation Method

- Use magnetic actuation to pull structures away from the surface
  - reduced surface tension length of arm

- Limitations
  - only works for structures with magnetic material.
Antistiction Method II - Organic Pillar

- Use organic pillar to support the structure during the liquid removal.
- The organic pillar is removed by oxygen plasma etching.
Analyze selectivity and choose etchants
Antistiction Drying Method III - Phase Change Release Method
Supercritical CO₂ Drying

- Avoid surface tension by relaying on phase change with less surface tension than water-vapor.
- * p. 128-129
- Supercritical state: temp > 31.1 °C and pressure > 72.8 atm.
- Step 1: change water with methanol
- Step 2: change methanol with liquid carbon dioxide (room temperature and 1200 psi)
- Step 3: content heated to 35 °C and the carbon dioxide is vented.

- Free-standing cantilever beams upto 850 µm can stay released.
Super Critical Drying

- When a substance in the liquid phase at a pressure greater than the critical pressure is heated, it undergoes a transition from a liquid to a supercritical fluid at the critical temperature.
- This transition does not involve interfaces.

- Criteria
  - chemically inert, non-toxic
  - low critical temperature
- CO$_2$
  - critical temperature 31.1 $^\circ$C
  - critical pressure 72.8 atm.(or 1073 psi)

- Exchange methanol with liquid CO$_2$ at 25$^\circ$C and 1200 psi
- closeoff vessel and heated to 35 $^\circ$C, no interface is formed.
- Vent vessel at a constant temperature above critical temperature.
Antistiction Method III - Self-assembled Monolayer

- Forming low stiction, chemically stable surface coating using self-assembly monolayer (SAM)
- SAM file is comprised of close packed array of alkyl chains which spontaneously form on oxidized silicon surface, and can remain stable after 18 months in air.
- OTS: octadecyltrichlorosilane (forming $\text{C}_{18}\text{H}_{37}\text{SiCl}_3$)
Result of SAM Assembly

- Surface oxidation: H₂O₂ soak
- SAM formation
  - isopropanol alcohol rinse
  - CCl₄ rinse
  - OTS solution
  - CCl₄ rinse
# Structural-Sacrificial Compatibility

## TABLE 11.1 Possible Combination of Sacrificial Layer (Columns) and Structural Layer (Rows). “No” Indicates Generally Impossible Combinations.

<table>
<thead>
<tr>
<th>Structural layer</th>
<th>CVD PSG or thermal oxide</th>
<th>Photoresist</th>
<th>Parylene</th>
<th>Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPCVD polysilicon</td>
<td>OK</td>
<td>No, deposition temperature too high for resist</td>
<td>No, deposition temperature too high for Parylene</td>
<td>No, many metals cannot sustain the high temperature of LPCVD polysilicon</td>
</tr>
<tr>
<td>LPCVD silicon nitride</td>
<td>OK</td>
<td>No, deposition temperature too high for resist</td>
<td>No, deposition temperature too high for resist</td>
<td>No, deposition temperature too high for resist</td>
</tr>
<tr>
<td>Metal</td>
<td>OK(^1)</td>
<td>OK(^2)</td>
<td>OK(^3)</td>
<td>OK (if different metals)</td>
</tr>
<tr>
<td>Photoresist</td>
<td>No, HF etching solution may attack resist</td>
<td>No, structural layer and sacrificial layer are etched simultaneously</td>
<td>No, all methods for etching Parylene (including dry etching) attack the resist structural layer</td>
<td>OK</td>
</tr>
<tr>
<td>Parylene</td>
<td>OK</td>
<td>OK, organic solvents may attack resist but not Parylene</td>
<td>N/A</td>
<td>OK</td>
</tr>
</tbody>
</table>

\(^1\)Certain oxide etchants (such as concentrated HF) may attack certain metal.

\(^2\)Evaporated metal may increase the temperature of wafer and cause polymer to locally melt. Carefully processing control is required.

\(^3\)The Parylene (as sacrificial layer) must be removed using oxygen plasma, which may oxidize certain metals.
Actuators that Use Fringe Electric Field - Rotary Motor

- Three phase electrostatic actuator.
- Arrows indicate electric field and electrostatic force. The tangential components cause the motor to rotate.
Three Phase Motor Operation Principle
Starting Position -> Apply voltage to group A electrodes
Motor tooth aligned to A -> Apply voltage to Group C electrodes
Motor tooth aligned to C -> Apply voltage to Group B electrodes
Motor tooth aligned to B -> Apply voltage to Group A electrodes
Motor tooth aligned to A -> Apply voltage to Group C electrodes
Foundry Process

• Why:
  – Reduce the cost of development by providing standard and unusual processes at reasonable cost.

• How:
  – Wafer sharing: many processes are performed on one wafer with many users sharing the mask.
    • Drawback: limited process materials and steps
  – Machine sharing: a user’s wafer is dedicated and ships back-and-forth among several vendors.
    • Drawback: long development and transport time
  – Dedicated foundry: a user’s wafer is handled at one site by dedicated personnel.
    • Drawback: highest cost among all forms of foundry process.
The Importance of Design Rules

- Structural layer
  - Perfect alignment
  - Sacrificial etch
  - Closed cavity
  - Intended result

- If misalignment happens...
  - Misalignment
  - Sacrificial etch
  - Leaky cavity
Example: MUMPS Process
Multi User MEMS Process
The Versatility of MUMPS
## Compatibility Table

<table>
<thead>
<tr>
<th></th>
<th>Polysilicon</th>
<th>Silicon oxide</th>
<th>Photoresist (cured)</th>
<th>Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry plasma etching</td>
<td>Yes</td>
<td>Yes, slower speed</td>
<td>Yes, slow</td>
<td>No. Sputtering is possible</td>
</tr>
<tr>
<td>HF wet etching</td>
<td>No</td>
<td>Yes</td>
<td>No, avoid long soak</td>
<td>No, avoid long contact</td>
</tr>
<tr>
<td>Uncured photoresist</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Photoresist developer</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Organic rinse</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Baking</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Metal etchant</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Case 4.1, Electrostatic Actuators

- Curved beam due to intrinsic stress in the cantilever.
- Helps:
  - Release
- Hinders:
  - Capacitance calculation
How good is the design and process?

- **Design:**
  - Advantage:
    - Direct integration of mechanical cantilever with FET transistors
    - Low noise sensor
  - **Materials**
    - Relatively difficult material
    - Exotic wafer
  - **Processes**
    - Difficulties:
      - Cantilever release using web silicon etchant may be a problem
      - Requires foundry process and new process development if industrialized
Case 4.2: Torsional Capacitive Accelerometer

Top view

Suspended plate (moving mass)

Side view (a=0)

Acceleration

Side view (under acceleration)

(a) Silicon wafer (with IC)

(b) Metal 1

(c) Metal 2

(d) Metal 2

(e) Electroplated nickel

(f) Metal 1 under anchor
How good is this design?

• Design:
  – Simple
  – No electronics integration
    • Greater noise

• Material:
  – Simple
  – Readily available

• Fabrication process
  – Does not require exotic materials or processes
  – Sacrificial release may be a problem, like the previous case
Case 4.3: Membrane Parallel Plate Pressure Sensor

(a) silicon wafer

(b) oxide

(c)

(d)

(e) oxide

(f)

(g)

(h) deep doping

(i) oxide thin doping

(j)

(k) dielectric

(l) conductive polysilicon

(m) Cr/Au oxide

(n) metal glass

(sensor cross-section)

(o) diaphragm

(bottom electrode)
Evaluation

• Design:
  – Results in hermetically sealed structures
  – Result in large gap distance to reduce damping

• Materials:
  – Silicon materials
  – Doped silicon

• Fabrication:
  – Length steps
  – Delicate bonding and handling
  – Process development is lengthy
Conclusions

- Electrostatic sensing and actuation
  - Types of electrode configurations
  - Advantages and weaknesses
- Surface micromachining
  - Criteria for designing a successful process
  - Basic knowledge of materials, etchants, and their interactions
  - Analyze the quality of a process