Micro- and Nano- ElectroMechanical Systems (MEMS/NEMS) and optomechanical transduction

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Topics

• Intro to MEMS / NEMS

• Optical measurement of motion in MEMS

• Optical forces and their effects
Today’s discussion

• Where do MEMS come from?

• Some design issues: sensing, actuation and analysis for design
MEMS and NEMS Transducers

- **Sensors**
  - Unknown force/torque affects mechanical motion
  - Mechanical motion is detected: electrically, optically, etc.

- **Actuators**
  - Controlled forces are applied to induce mechanical motion
  - Mechanical motion modulates some process or device

- Transducer may combine sensing and actuation
Surface Micromachining

Deposit and pattern polysilicon interconnect layer

Deposit and pattern first PSG sacrificial oxide

Deposit and pattern first polysilicon mechanical layer

Deposit and pattern second PSG sacrificial oxide

Deposit and pattern second polysilicon mechanical layer

Deposit and pattern metal layer

Release
Bulk Micromachining

Starting silicon-on-insulator (SOI) wafer

- Handle Wafer
- Buried Oxide (BOX)
- Device Layer

Front side (mirror) patterning

Back side (cavity) patterning

Single (or double) side mirror metalization

Release

Spacer formation and frontside (or backside) attachment to multi-conductor electrode
The basic lithography process

1. Substrate (wafer)
2. Coat with light sensitive polymer (photoresist)
3. Expose to ultraviolet light or write with electron beam
4. Develop pattern
5. Etch substrate (exposed areas)
6. Strip photoresist
Isotropic and Anisotropic Etching

- $A = \text{Anisotropy} = 1 - \frac{\text{Lateral Etch Rate}}{\text{Vertical Etch Rate}}$
- Isotropic Etch, $A = 0$
- Anisotropic Etch, $A = 1$
- Wet etching is isotropic
- Plasma etching can be isotropic or anisotropic
Wet Etching

- Wet etching is isotropic
  - A line will narrow
  - A space will widen
- Not suitable for fine geometries (except in special circumstances)
Deep silicon etching

- Patterning of Mask
- Initial Polymer Deposition
- Isotropic Etch
- Polymer dep. for sidewall passivation
- Isotropic Etch
- Repeat cycle
- Polymer Deposition

≈ 1mm diameter
Focused Ion Beam direct write

S. Koev, Plasmonics, V.7, N. 2 (2012), p269-277

B. Dennis, G. Bloomberg, V. Aksyuk in preparation
Layers of **structural materials**, **sacrificial layers**, and **interconnects or electrodes** are deposited and patterned.

The **sacrificial layers** are selectively removed, releasing the moving parts.

**Supercritical drying.**

Some micromachines are assembled or self-assemble during release.
MEMS / NEMS Sensors

Electrostatic (C)


Optical

D. Antonio et.al., Nature Communications 3, 806

Magnetic induction

Piezoresistive, piezoelectric, tunneling, etc


# Actuation Mechanisms

<table>
<thead>
<tr>
<th></th>
<th>Voltage Needs</th>
<th>Switching Speed</th>
<th>Compatibility</th>
<th>Current consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrostatic</strong></td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Magnetic</strong></td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td>Low</td>
<td>Slow</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

*Other:* piezoelectric, shape memory, optical, surface tension, ……
Beam Deformations

\[ z(x) = -F \cdot \frac{x^2(3L-x)}{6EI}; \quad z(L) = -F \cdot \frac{L^3}{3EI} \]

- \( L \) length
- \( E \) Young's modulus
- \( a \) width
- \( G \) shear modulus
- \( b \) thickness

\[ I = \frac{wt^3}{12} \]

\[ \varphi(x) = T \cdot \frac{x}{CG}; \quad \varphi(L) = T \cdot \frac{L}{CG} \]

\[ C = \frac{wt^3}{3} \quad \text{for} \quad t << w \]
Resonance Modes

1. 258 Hz
2. 430 Hz
3. 1786 Hz
4. 2153 Hz
5. 2345 Hz
6. 3586 Hz
7. 6869 Hz
### Single Crystal Springs - Crystalline Direction Dependence

<table>
<thead>
<tr>
<th>Mode #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 (45 degrees)</td>
<td>258</td>
<td>430</td>
<td>1786</td>
<td>2153</td>
<td>2345</td>
<td>3586</td>
<td>6869</td>
</tr>
<tr>
<td>110 (90 degrees)</td>
<td>286</td>
<td>477</td>
<td>1881</td>
<td>2409</td>
<td>2632</td>
<td>4048</td>
<td>7239</td>
</tr>
<tr>
<td>100 Experiment</td>
<td>260</td>
<td>430</td>
<td>1700</td>
<td></td>
<td></td>
<td></td>
<td>6900</td>
</tr>
</tbody>
</table>

Approximation - beam X-section rectangular, $w = (a+b)/2 = 1.6\text{um}$ instead of real-life trapezoidal $a = 1.4\text{um}$, $b = 1.8\text{um}$.

Si elasticity tensor components:

\[
\begin{align*}
\lambda_{xxxx} &= 165.5 \text{ GPa}, \\
\lambda_{xxyy} &= 64.18 \text{ GPa}, \\
\lambda_{xyxy} &= 79 \text{ GPa}
\end{align*}
\]

Single crystal Si is “brittle” material – fracture occurs before plastic deformation

- predictable, stable, reliable
- high control accuracy is possible open-loop

Metals often show “ductile” behavior: hysteresis, fatigue, etc.

- metals should be avoided on/in springs and other elastic elements if highly-accurate open-loop operation is required
Nonlinear Mechanics

Instability

$F_{cr} = \frac{4.01}{L^2} \sqrt{EGIC} = 31 \mu N$

(Landau, Lifshitz, “Theory of elasticity”)
Frequency Analysis
Linear Elastic Element Design

Sources of stress:
- residual
- packaging
- thermal mismatch

Some elastic elements *change their stiffness* considerably with applied external stress. 

*Nonlinear* behavior results. 

*Buckling* instabilities in extreme cases.
Straight Rod Design - Mechanical Modes

How do mode frequencies depend on stress?
Resonance Frequency $\rightarrow 0$ : Buckling

Mode Frequency, a.u.

Stress, MPa

Rod
- m1
- m2
- m3
- m4
- m5
- m6
- m7

Serpentine
Strain-relieving Spring Is Linear

Mode Frequency, a.u.

Stress, MPa

Rod

Serpentine

m1
m2
m3
m4
m5
m6
m7

Mode Frequency, Hz

Stress, MPa

Rod

m1
m2
m3
m4
m5
m6
m7

Serpentine

m1
m2
m3
m4
m5
m6
Electrostatic Sensing and Actuation

- high bandwidth
- no heat dissipation
- calculable
- localized fields (good conductors) - no crosstalk
- no special materials - wide range of fabrication processes

Excellent for vacuum, cryogenics, dense integration.

Challenge:
- impedance matching to small capacitors
- effective designs with nonlinear capacitance and electrostatic force
- achieving large signal without electrostatic backaction
- achieving large amplitude with low voltage
Electrostatic sensing: capacitance

DC or low frequency motion
RF electrical measurement
External or internal bridge C
High or low impedance amplification


On-resonance measurement, self-sustaining oscillator
Electrical signal at mechanical frequency
Local amplification to reduce stray C
PLL, RF and other modifications possible
2H-NbSe$_2$ Single Crystal
22x49x1.6$\mu$m$^3$

Anchor
Paddle
Response
Spring
Excitation

Oscillator Characteristics

Foundry: CRONOS
Resonant Frequency $\approx 45\text{KHz}$
$Q_{4.2K} \approx 250,000$
Paddle Mass: $\approx 20\text{ng}$
Spring Constant: $\approx 0.5 \times 10^{-9}\text{Nm}$
Frequency Resolution: 1 in $10^8$

Driving the Oscillator
Marginal Oscillator

Constant Excitation

Response

Filter

Limiter

Amplitude and Frequency Measurement

Electrostatic Transduction
1 degree of freedom (DOF)

\[ E_{elec}(x) = C(x) \frac{V^2}{2} ; \quad F_{elec} = \frac{dE(x)}{dx} \]

\[ F_{elec} = \frac{V^2}{2} \frac{dC(x)}{dx} \]

\[ k_{elec} = -\frac{dF_{elec}}{dx} = -\frac{V^2}{2} \frac{d^2C(x)}{dx^2} \]

\[ f_{res} = \frac{1}{2\pi} \sqrt{\frac{k_{total}}{m}} ; \quad k_{total} = k_{elec} + k_{mech} \]

\( C(x) \) - actuator capacitance
\( k \) - spring constant
\( x \) - deflection

(Prof. de Rooij group)
Electrostatic Actuator
Multiple DOF

Mechanics:

\[ F_l = \sum_m K_{lm}(\bar{\phi}) \phi_m \]

Electrostatics:

\[ E = \frac{1}{2} \sum_{i,j} V_i V_j C_{ij}(\bar{\phi}) \]

Equilibrium:

\[ \sum_m K_{lm} \phi_m = \frac{1}{2} \sum_{i,j} V_i V_j \frac{\partial C_{ij}}{\partial \phi_l} \]

Often stiffness matrix is linear
(independent of position)
Can diagonalize

\[ K_{lm} = \tau_l \delta_{lm} \]

\[ \tau_l \phi_l = \frac{1}{2} \sum_{i,j} V_i V_j \frac{\partial C_{ij}}{\partial \phi_l} \]
Parallel-Plate Electrostatic Actuation

Flexure-suspended plate

\[
F_{\text{cantilever}} = k_{\text{mech}} (d_0 - d)
\]

\[
C(d) = \frac{\varepsilon_0 A}{d}; \quad F_{\text{electrostatic}} = \frac{V^2}{2} \frac{\varepsilon_0 A}{d^2}; \quad k_{\text{elec}} = -\frac{V^2}{d^3} \frac{\varepsilon_0 A}{d}
\]

Unstable if:

\[
k_{\text{total}} = k_{\text{mech}} + k_{\text{elec}} \leq 0
\]

Snap down:

\[
V_{\text{pull-in}} = \sqrt{8k_{\text{mech}}d_0^3 / 27\varepsilon_0 A}
\]

\[
d = \frac{2}{3} d_0
\]
Torsional Electrostatic Actuation

\[ T_{\text{electrostatic}} = \frac{\varepsilon V^2 W}{2} \int_0^L \frac{x \, dx}{\left( \frac{g}{\sin \alpha} - x \right)^2 \alpha^2} \]

\[ T_{\text{electrostatic}} = \frac{\varepsilon V^2 W}{2\alpha^2} \left\{ \frac{L \sin \alpha}{g - L \sin \alpha} + \ln \left( 1 - \frac{L}{g} \sin \alpha \right) \right\} \]

\[ T_{\text{mechanical}} = \alpha \cdot 2 \frac{G}{3l} \left\{ 1 - \frac{192t}{\pi^5 w} \tanh \left( \frac{\pi w}{2t} \right) \right\} \] (two torsional hinges)

Symbols:
- \( T \): Torque
- \( g \): Gap
- \( \alpha \): Deflection angle
- \( V \): Electrode voltage
- \( W \): Plate width
- \( L \): Plate half-length
- \( w \): Torsion bar width
- \( t \): Torsion bar thickness
- \( l \): Torsion bar length
- \( G \): Shear modulus
Vertical Comb Drive

- \( r \) : motion range
- \( p \) : comb drive pitch
- \( g \) : comb gap

Comb drive produces larger force than parallel plate when motion range is larger than lithography limits.

Both piston motion and 1-axis rotation possible.

\[
C_{comb} = 2N \frac{\varepsilon_0 W x}{g} = \frac{2\varepsilon_0 A}{g} \cdot \frac{1}{p} \cdot x
\]

\[
C_{plate} = \frac{\varepsilon_0 A}{3r - x}; \quad x \in [0, r)
\]

\[
F_{comb} \left/ F_{plate} \right. = \frac{8r^2}{gp}; \quad x = r
\]
Practical Considerations - Dielectrics and Stability

- Dielectric surfaces inside high field regions will accumulate charge
  - Oxide
  - Nitride
  - Native oxide on Aluminum

- Characteristic time scales range from milliseconds to days

- If exposed to sense electrode will result in capacitance error/drift

- If exposed to movable parts, this results in mechanical drift

- Strategies employed to “hide” such surfaces
  - Grounding
  - Overhangs
  - Canyons
For discussion – forces at small scales

Water **surface tension** 70 mN/m; 1 atm = 10^5 Pa

<table>
<thead>
<tr>
<th>Δp for water drops of different radii at <strong>STP</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Droplet radius</td>
</tr>
<tr>
<td>Δp (atm)</td>
</tr>
</tbody>
</table>

**Electrostatic** pressure @ 1V, 200 nm ≈ 100 Pa
~ 1/d^2 for constant voltage

**Casimir** pressure @ 200 nm ≈ 0.5 Pa
~ 1/d^4 (or 1/d^3 for very short distances)