Assessment of polysilicon film properties through on-chip tests

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Research Aim

- Silicon, the most common material used in Microelectromechanical Systems (MEMS).
- Anisotropic crystalline material whose material properties depend on orientation relative to the crystal lattice.
- Characteristic length of mechanical components can be compared to the size of grains.

- Morphology & crystal lattice orientation are not known.

Sources of uncertainties in mechanical response

- These sources of uncertainties should be addressed:
  - Experimentally
  - Analytically and numerically

http://www.ieo.nctu.edu.tw/leo/htms/photon/Laser%20Annealing.htm

Hopcroft, M.A., et al., “What is the Young Modulus of Silicon?”, JMM, 2010
An on-chip test adopted
The specimen is a micro-beam made of polysilicon with average grain size of 500nm

6 devices featuring
  Width: 2μm
  Length: 2, 3, 4, 5, 10, 20 μm

Electrostatic actuation/sensing
Two sets of conductors providing 4 combinations of sensing /actuation

The electromechanical response varies between devices either due to
  Geometrical uncertainties
  Material uncertainties
Experimental tests rotational mode

- The measurement is repetitive and reproducible except for the ones with pull-in
- The bias voltage difference is increased and then decreased to zero (max 40V)

- Pull-in at 39.25-39.75

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
<th>Parameter</th>
<th>value</th>
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</thead>
<tbody>
<tr>
<td>beam length ($l$)</td>
<td>2, 3, 4, 5, 10, 20 µm</td>
<td>referenced initial gap between rotor and stators ($g_o$)</td>
<td>2 µm</td>
</tr>
<tr>
<td>beam thickness ($h$)</td>
<td>2 µm</td>
<td>$a$</td>
<td>17 µm</td>
</tr>
<tr>
<td>out-of-plane thickness ($w$)</td>
<td>22 µm</td>
<td>$b$</td>
<td>100 µm</td>
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</table>
Simplifications:
- Big mass to be rigid
- The micro-beam kinematics to be governed by Euler-Bernoulli
- Electric fringe field neglected
- No deformation at the anchor

Closed form solution for Capacitance change as a function of voltage difference

$$F_{elec} = \frac{1}{2} \varepsilon_0 A V^2 \frac{1}{gap^2}$$

Coulomb's law for parallel charged plates

Graph showing Capacitance change (pF) as a function of rotation angle (radian) with increasing voltage.
Simplifications:
- Electric fringe field neglected
- Parametric geometry
  - Parametric study on overetch values
- Big mass is modelled by homogenized isotropic elastic properties
- Two scenarios for beam modeling
  - Homogeneous model
    - Bounds of response
  - Heterogeneous model

For each given $V$

\[ KU = F_{ext} + F_{elec}(V) \rightarrow \text{Structural domain} \]

\[ K_{dielec}(U)V = Q(U, V) \rightarrow \text{Electrostatic domain} \]

Nonlinear coupled field analysis
- Electrostatic forces on boundary nodes
- Deformation effect the dielectric and electric field

\[ U \text{ is used to update the geometry} \]

Electrostatic analysis for calculation of mutual capacitance between conductor systems
Numerical Modeling
Random Morphology

- Two scenarios for beam modeling
  - Homogeneous model
    - Bounds of response
  - Heterogeneous model
    - Monte Carlo simulation

- Voronoi diagram

- 100 times

- Random mask position
- Random lattice orientation

- Random morphology at beam and its anchors
Numerical and Analytical Model Results

- Three different values for crystalline orientation of silicon
  - Direction $<110>$ $E=169\text{GPa}$ (Stiff)
  - Direction $<100>$ $E=130\text{GPa}$ (Compliant)
  - Homogenized value $E=149.3\text{ GPa}$
- Good bounds are provided for the experimental data

- Overetch can happen
  - Intensity depends on the geometry
  - Geometry can vary slightly from device to device
  - Overetch effect needs to be considered

Sources of material uncertainties in polysilicon film morphology is studied

An on-chip test is designed to study the effect of morphology on the response of a micro beam

The experimental results are modelled analytically and numerically

Both models can bound the response scatterings

The Monte Carlo simulation is carried out

The effects of overetch at the response scattering should be studied

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Thank you for your kind attention!