Stiction failure in microswitches due to elasto-plastic adhesive contacts

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• Introduction
  – Stiction in MEMS
  – Multiscale approach developed

• Model Description
  – Basic Theory for One asperity
  – Statistical Model of Rough Surface

• Multiscale Model
  – Polysilicon to Polysilicon Interaction
  – Cantilever beam (FEM): validation with experiments

• Elasto-plastic adhesive contact

• Conclusions
Introduction

- Stiction in MEMS

Reason:
Relatively high surface area: volume ratio (1,000:1 to 10,000:1 m⁻¹)

Adhesive forces:
Electrostatic force, Van der Waals force, Capillary force, Hydrogen bridging…

Stiction failure in a MEMS sensor
(Jeremy A. Walraven Sandia National Laboratories. Albuquerque, NM USA)
• Multiscale approach developed

Single asperity adhesive-micro contact

Adhesive elastic contact model between rough surfaces

Integration with FEM
Single asperity adhesive-micro contact

- **Adhesive-elastic contact (Hertz) theories**
  - **Johnson, Kendall, and Roberts (JKR)**
    - Short ranged surface forces
    - Act only inside the contact area
    - \( \Rightarrow \) Soft, compliant materials with high surface energy
  - **Derjaguin, Muller and Toporov (DMT)**
    - Long-ranged adhesive forces
    - Outside of the contact area
    - \( \Rightarrow \) Harder, less compliant materials with low surface energy and small asperity tip radius
  - **Maugis transition solution**
    - Intermediate cases between JKR and DMT
    - For all elastic materials
Single asperity adhesive-micro contact

- **Maugis transition solution**
  - Based on a Dugdale assumption for interaction potential
  - Constant traction $\sigma_0$ within a critical value of separation $z_0$
  - Zero traction for gap larger than $z_0$
  - **Maugis transition parameter $\lambda$**
    - Representation of the surface properties
      - $R$: asperity radius
      - $K$: equivalent elastic constant
      - $\varpi = \sigma_0 z_0$: adhesive work

\[
\lambda = \frac{2\varpi^{2/3} R^{1/3}}{z_0 (\pi K^2)^{1/3}} \quad \Longrightarrow \quad \varpi \uparrow, R \uparrow, K \downarrow \Rightarrow \lambda \uparrow
\]

\[
\varpi \downarrow, R \downarrow, K \uparrow \Rightarrow \lambda \downarrow
\]
Single asperity adhesive-micro contact

- Maugis transition solution (2)
  - Adhesive-micro (elastic) contact force during unloading

  - In term of Maugis transition parameter \( \lambda = \frac{2\sigma^{2/3} R^{1/3}}{z_0 (\pi K^2)^{1/3}} \)
Adhesive contact between rough surfaces

- **Rough surfaces**
  - Reduced number of interacting asperities
  - In terms of distance $d$

- **Rough surfaces model**
  - Constant asperity tip radius
  - Statistical distribution in height $h$

$$
\varphi(h) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{h^2}{2\sigma^2}\right)
$$
Adhesive contact between rough surfaces

- Micro adhesive contact forces of rough surfaces
  - Integrate Maugis solution using
    \[
    \varphi(h) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{h^2}{2\sigma^2}\right)
    \]

\[
\frac{F_{nT}}{N \pi \sigma R}
\]

\[
\begin{align*}
\text{(-)} & \quad \text{Responsible for stiction}
\end{align*}
\]

\[
\begin{align*}
F_{nT} & \quad \text{(-)} \\
F_{nT} & \quad \text{(-)} \\
d & \quad (+)
\end{align*}
\]
Multiscale Model

- **Design example: cantilevers**
  - **Finite element model**
    - Timoshenko Beams
    - Interacting with pad
  - **Use adhesive micro-contact law at interface**
    - Polysilicon-Polysilicon interactions
    - Surfaces properties from
      - AFM
      - Surface energy measured
        
        | In vacuum  | $\varpi = 2.54 \text{ J/m}^2$ |
        | In air     | $\varpi = 0.167 \text{ J/m}^2$ |
    - Contact remains elastic
  - Validation vs literature experiments*


Multiscale Model

• Design example: cantilevers (2)
  – Initial gap $g = 2.0 \mu m$
  – Admissible thickness $t (\mu m)$ & length $l (\mu m)$ ???
Validation

- **Literature**:  
  - Measures of apparent adhesion energy $\Gamma$  
  - Simplified models of $\Gamma$  

- **Numerical methods**  
  - Extract $\Gamma$ from $s$  
  - Environmental effect

  In vacuum $\omega = 2.54 \text{ J/m}^2$  
  In air $\omega = 0.167 \text{ J/m}^2$

- **Different samples**  
  - Surface roughness

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_q$ (nm)</td>
<td>1.4</td>
<td>2.67</td>
<td>3.47</td>
</tr>
</tbody>
</table>

Elasto-plastic adhesive contact

- Elasto-Plastic materials
  - Plastic deformations of asperities
- Repeated contact
  Tip radii $R$ of a part of asperities $\uparrow$
  Surface roughness $R_q \downarrow$
  Adhesive forces $\uparrow$
  Stiction can appear after some cycles

- Elasto-plastic adhesive contact model is needed!
Basic idea

- Adhesive contact model of the elastic-plastically deformed asperity
  
  Numerical results for an elasto–plastic loaded sphere in contact without adhesive forces

  Maugis’ adhesive contact theory is performed on the equivalent elastic deformed asperity

- Asperity-based rough surface model
• Plastic deformations of a loaded single asperity
  – Curve fitting of FE simulations*
    • Effect of maximum interference $\delta_{\text{max}}$ reached during loading
    • Material parameters: yield $S_Y$, yield interference $\delta_{CP}$
  – Residual interference
    \[
    \delta_{\text{res}} = \delta_{\text{max}} \left(1 - \left(\frac{\delta_{\text{CP}}}{\delta_{\text{max}}}\right)^{0.28}\right)\left(1 - \left(\frac{\delta_{\text{CP}}}{\delta_{\text{max}}}\right)^{0.69}\right)
    \]
  – Residual tip radius
    \[
    R_{\text{res}} = R \left(1 + 1.275 \left(\frac{S_Y}{E}\right)^{0.216} \left(\frac{\delta_{\text{max}}}{\delta_{CP}} - 1\right)\right)
    \]

Elasto-plastic adhesive contact

- Adhesive unloading of a single deformed asperity
  - Define an equivalent elastic asperity
    - Interference
      \[ \delta_{\text{eff}} = \delta - \delta_{\text{res}} \]
    - Asperity tip radius
      \[ R_{\text{eff}} = R_{\text{eff}}(R, \delta, \delta_{\max}) \]
  - Apply Maugis
    - Extract adhesive-micro contact force
      \[ F_n = F_n(\delta - \delta_{\text{res}}, R_{\text{eff}}) \]

Elasto-plastic adhesive contact

- Adhesive loading/unloading of a single asperity
  - Material: Ru
    - Table:
      | $R$ (nm) | $E$ (GPa) | $\nu$ | $S_y$ (GPa) | $z_0$ (nm) | $\sigma$ (J/m²) |
      | 4      | 410      | 0.3   | 3.42        | 0.169      | 1                |
  - Model vs FE*

**Elasto-plastic adhesive contact**

- **Adhesive unloading of rough surfaces**
  - Different Ru samples
  - Effect of impact energy at pull-in on plastic deformations

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<th>C</th>
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<td>$R_q$ (nm)</td>
<td>2.03</td>
<td>3.99</td>
<td>7.81</td>
</tr>
</tbody>
</table>

![Graphs showing adhesive contact](image)
Elasto-plastic adhesive contact

- **Time life of MEMS**
  - Repeated loading/unloading ⇒ changes in surfaces profile
  - Asperity profile can be updated by tracking history $\delta_{\text{max}}(h)$
  - Ru sample

<table>
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<tr>
<th>Sample</th>
<th>Rq (nm)</th>
<th>$E_1$ (J/m²)</th>
</tr>
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<tbody>
<tr>
<td>C</td>
<td>7.81</td>
<td>0.5</td>
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![Graph showing dimensionless force as a function of dimensionless distance for different loading cycles](image)
Conclusions

- The adhesion between the contact surfaces has large influence on the design of MEMS switches, and need to be considered carefully.
- The adhesive work and the surface roughness are the main factors of adhesive force.
- The analytical adhesive contact results can be combined with FEM to predict the stiction of more complicated structures.
- Effect of plasticity can be accounted for.
- The other kinds of adhesive forces, such as capillary force, electrostatic force from dielectric charging, are not considered.
Thank you!