Electrostatic Zipping Actuators and Their Application to MEMS

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Introduction

Problem
- Need powerful electrostatic actuators for MEMS power relay
- Huge size using conventional designs

Solutions
- Zipping actuator with compliant starting zone

Results

9 mm

3 mm
Contributions

- Design: Starting zone to reduce the pull-in voltage
- Numerical and analytical modeling: easy and accurate
- Optimization of the system
- Specified design for implementation in a relay
- Fabrication and measurement of the actuator-relay
- Wet-anisotropically-etched micro relay contact

Background: Electrostatic Actuators

- **Comb Drive**
  - Force independent of stroke: large stroke
  - Very small force, large deflection

- **Parallel Plate**
  - Confliction between stroke and force

- **“Zipper”**
  - Large force and large deflection
  - High voltage for pull_in
F-D Curve of Three Electrostatic Actuators

- Force-Displacement Character of the three actuators
  - With the same volume and same voltage, the “zipper” actuator achieves a much larger force than comb drive and capacitor plate actuators.
  - “Zipper” actuator is the only hope to secure milli Newtons of force with a reasonable volume.

Zipping Actuators: A Survey

<table>
<thead>
<tr>
<th>Author</th>
<th>Actuation direction</th>
<th>Application</th>
<th>Size (mm²)</th>
<th>Force (mN)</th>
<th>Stroke (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shikida</td>
<td>Vertical</td>
<td>Valve</td>
<td>5 * 5</td>
<td>N/A (very small)</td>
<td>220</td>
</tr>
<tr>
<td>Divoux</td>
<td>Vertical</td>
<td>Mirror</td>
<td>0.8 * 0.8</td>
<td>0.1</td>
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<tr>
<td>Legtenberg</td>
<td>Lateral</td>
<td>N/A</td>
<td>0.8 * 0.5</td>
<td>0.02</td>
<td>30</td>
</tr>
<tr>
<td>Perregaux</td>
<td>Lateral</td>
<td>Optical shutter</td>
<td>0.5 * 0.2</td>
<td>N/A (very small)</td>
<td>20</td>
</tr>
<tr>
<td>Sherman</td>
<td>Lateral</td>
<td>Fluid control</td>
<td>1 * 0.2</td>
<td>N/A (very small)</td>
<td>100</td>
</tr>
<tr>
<td>This thesis</td>
<td>Lateral</td>
<td>Relay</td>
<td>9 * 1</td>
<td>2 ~ 10</td>
<td>80</td>
</tr>
</tbody>
</table>
Example Load: Double Beam

- A pre-curved bistable MEMS mechanism
- Promising as a micro relay structure
  - Simple structure
  - No residual stress
  - High contact force: good for on-state performance
- Need an electrostatic actuator to make the MEMS relay

![Double beam](image1)

![Double beam working as a Relay](image2)

Why Is It Hard? (1)

- Stroke: $\geq 80 \mu m$
- Asymmetric and high actuation/contact force: 
  - $\sim 7$ mN for the first 10 $\mu m$ to get a 3mN of contact force
- Actuation voltage:
  - $< 200$ V (as small as possible)
- Scale: $7 \times 7 \times 1$ mm$^3$
- Fabrication: Deep Reactive Ion Etching

![Graph](image3)
Why Is It Hard? (2)

- **Initial Design:**
  - DRIE etch through
  - Attach the cantilever beam to the double beam
  - Apply voltage between electrode and the cantilever beam.

- **Problem:**
  - Minimum gap due to DRIE aspect ratio of ~5%
  - Very High pull-in voltage because of the gap, about 250 V for a 15 µm thick and 4.5 mm long zipping beam.

Contributions

- **Design:** Starting zone to reduce the pull-in voltage
- Numerical and analytical modeling: easy and accurate
- Optimization of the system
- Specified design for implementation in a relay
- Fabrication and measurement of the actuator-relay
- Wet-anisotropically-etched micro relay contact
Design: Compliant Starting Zone

- To reduce the pull-in voltage:
  - A compliant starting zone
  - Reciprocity: remove material not needed and not useful
  - The starting zone bends up when voltage is applied between electrode and the beam
  - The cantilever beam pulls-in and keep zipping at low voltage

Contributions

- Design: Starting zone to reduce the pull-in voltage
- Numerical and analytical modeling: easy and accurate
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Modeling: Overview

Beam bending equation in electric field

\[ E \left( I(x)y'(x) \right) = -\frac{\varepsilon_0 U^2 b}{2 \left[ y(x) - c(x) + \frac{h}{\varepsilon_r} \right]} \]

Numerical Modeling: Before “Pull-in”

Numerical Method
- Modeled as a device with Multiple-beams.
- Each beam is bent by the electrostatic force.
- The ODEs are solved simultaneously for each beam.
- Deflection profiles for each beam are given out at different voltages.
- Actuation force can be calculated.
- Pull-in voltage can be found.

Deflection profiles of the cantilever beam and the starting beam at different voltages when the tip is constrained at zero displacement.
Numerical Modeling: After “Pull-in”

Beam equation: \[ E I y'''(x) = p(x) = -\frac{\varepsilon_e \rho U^2}{2[y(x) - c(x) + h_0/\varepsilon_e]} \quad s \leq x \leq L \]

Numerical solutions
- Eliminate varying B.C by adding parameter \( \lambda = 1 - s / L \)

Analytical Modeling: After Pull-in

Approximation equation: \[ F_{right} \approx \frac{E I^{1.4} b}{\sqrt{d}} \left( \frac{\varepsilon_e \varepsilon_0 U^2 h_0}{h_0} \right)^{3/4} \]

Comparisons between analytical approximations and numerical results:
Forces: Actuator vs. Switch Beam

- Force-Displacement curves of the actuator and the double beam
- > 160V is needed to actuate the double beam with ~ 3 mN of contact force
- Can we change the force-displacement curve of the double beam without reducing the contact force?

![Force-Displacement curves of the actuator and the double beam](image)

<table>
<thead>
<tr>
<th>Actuation force $F_{act}$ (mN)</th>
<th>Displacement $\delta$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

- Relay with Uniform Thickness, FEA
- Actuator, $U = 100$ V
- Actuator, $U = 120$ V
- Actuator, $U = 140$ V
- Actuator, $U = 160$ V

Contributions

- Design: Starting zone to reduce the pull-in voltage
- Numerical modeling: easier and more accurate
- **Optimization of the system**
- Specified design for implementation in a relay
- Fabrication and measurement of the actuator-relay
- Wet-anisotropically-etched micro relay contact
Optimization of The Double Beam

- Force ratio \( R = C(\tau_0, \tau_2) \)
- \( \delta C(\tau_0, \tau_2) = \int (\delta I)\Lambda(\tau_0, \tau_2, w_0, w_2) \)

Start with constant \( I(x) \)

Numerically calculate eigenfunctions and eigenvalues \([w_i, \tau_i]\)

choose \( \delta l = \epsilon A(\tau_0, \tau_2, w_0, w_2) \), satisfying thickness constraints.

\[ I(x) = I(x) + \delta I \]

Small enough \( R \)?

\[ \text{No} \]

\[ \text{Yes} \]

End

Optimization of The Double Beam (II)

- Actuation force/Contact force ratio starts from \( \sim 2.5:1 \).
- Beam was modulated, force ratio was optimized to \( \sim 1.5:1 \).
- \( \sim 120 \) V is needed to actuate the relay.

![Force-Displacement curves of the actuator and the double beam](image)
Contributions

- Design: Starting zone to reduce the pull-in voltage
- Numerical modeling: easier and more accurate
- Optimization of the system
- Specified design for implementation in a relay
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The Relay
Contributions

- Design: Starting zone to reduce the pull-in voltage
- Numerical modeling: easier and more accurate
- Optimization of the system
- Specified design for implementation in a relay
- *Fabrication and measurement of the actuator-relay*
- Wet-anisotropically-etched micro relay contact

Fabrication: Process Flow (1)

- Starting substrate: 4" DSF-<100> Si Wafer
- Spin and pattern 10 µm of photoresist
- DRIE etch through
- Strip photoresist in Piranha, RCA clean
- Grow 0.2 µm of thermal oxide

- Silicon
- Silicon Oxide
- Photoresist
Fabrication: Process Flow (2)

Starting substrate: 4'' DSP <100> Si Wafer

Spin and pattern 10 µm of photoresist

DRIE etch through

Strip photoresist in Piranha

Bond shadow wafer and device wafer, etch oxide selectively

Separate wafers, clean device wafer in Piranha

Fabrication: Process Flow (3)

Starting substrate: 4'' Pyrex 7740 wafer, 500 mm thick

Deposite 0.005 mm Ti, 0.03 mm Cr

Pattern Cr in CR-7

Etch Pyrex 50 mm in 49% HF

Bond device wafer to Pyrex wafer at 800 V and 350 degree C

Sputter Au on relay contacts

Silicon
Silicon Oxide
Photoresist
Titanium
Chromium
Gold
Fabrication: Transparency Mask

- Transparency mask for device wafer:
  - Much faster and much cheaper
  - Low resolution: 3-4 µm

- Electrostatic force is very sensitive to the recess at electrode

- Print the mask 10 times larger and use 10:1 stepper to shrink it down

Fabrication Results: Overview
Measurement: Pull_in of the Starting Zone

- The starting beam bends up and closes the gap between zipper beam and fixed electrode

- Pull-in at 75V

- 140 V. Zipper beam collapse to the fixed electrode, relay is closed

Force Measurement

<table>
<thead>
<tr>
<th>Displacement $\delta$ (µm)</th>
<th>Force (mN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>40</td>
<td>4</td>
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<tr>
<td>60</td>
<td>6</td>
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<td>80</td>
<td>8</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>120</td>
<td>12</td>
</tr>
</tbody>
</table>

- Relay FEA
- Relay Experimental
- Actuator Numerical Simulation at 140V
- Actuator Experimental at 140V
- Relay FEA (Adjusted model)
A Bipolar Drive to Avoid Stiction

- Change polarity every two actuation cycles

Relay Actuated by Zipping Actuator

- > 40 millions of life cycles were achieved
- Maximum toggling speed: 160 Hz
- Shortest excitation pulse: 400 µs
Switching Time

- Contact bounce time ~ 0.5 ms
- Switching time ~ 3 ms

Contributions

- Design: Starting zone to reduce the pull-in voltage
- Numerical modeling: easier and more accurate
- Optimization of the system
- Specified design for implementation in a relay
- Fabrication and measurement of the actuator-relay
  - *Wet-anisotropically-etched micro relay contact*
DRIE-etched Relay Contacts

- Relay contacts
- Vertical sidewalls
- Sputter Au: low efficiency.
- Sidewall/surface thickness ratio = 1/9
- Contact resistance: ~1 Ω

KOH-etched Relay Contacts: Design

- Deposit resist
- Spin and pattern resist
- Strip resist
- KOH etch
- Bring to contact
KOH-etched Relay Contacts: Experiments

- Steps caused by mask/misalignment
- Good step-coverage
- Both surfaces are coated with Au
- Contacts are overetched

KOH-etched Relay Contacts: Tests

- Sputter Au: high efficiency.
- Sidewall/surface thickness = 1/1.4
- Very low contact resistance: ~50 mΩ
Proposed Full Relay Process Flow

Conclusions and Future Work

- **Conclusions:**
  - Design, modeling, optimization, fabrication and measurement of an actuator-relay system
  - Develop wet-anisotropically-etched relay contacts

- **Future work:**
  - Combine the actuator and the KOH-etched contacts
  - Vertically moving zipping actuators
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Actuator Beam Profile

**Actuator Beam Profile**
Optimization: Algorithm (1)

- Beam equation:
  
  \[ (EIw'')'' + Tw'' = 0 \]

  \[ (EI\delta w_i'')'' + T_i \delta w_i'' = -\delta T_i w_i'' - (E \delta I w_i'')'' \]

- Fredholm alternative:
  
  \[ \int (\delta T_i w_i'' + (E \delta I w_i'')'') w_i \, dx = 0 \]

  \[ \delta T_i = -\frac{\int w_i(E \delta I w_i'')'' \, dx}{\int w_i'' \, w_i \, dx} \]

- Cost function variation:
  
  \[ \delta C(T_i) = \delta I \left[ \sum_n \frac{dC_n}{dT_i} \left( \frac{w_i''}{w_i'} \right)^2 \right] = \delta I \Lambda(T_i, w_i) \]

Optimization: Algorithm (2)

- Beam equation:
  
  \[ (EI(w - w_0)''')'' + \tau^2 w'' = f (x - L / 2) \]

- Transition state
  
  \[ w_t = \Gamma w_0(x) + A w_i \]

  \[ \Gamma = (1 - (\tau / \tau_0)^2)^{-1} \]

  \[ \Delta_* = 1 - \Gamma \]

  \[ R = \frac{\Delta_*}{2 - \Delta_*} = \frac{(1 - \Gamma)}{2 - (1 - \Gamma)} \]

  \[ = \frac{(\tau_0 / \tau)^2}{2 - (\tau_0 / \tau)^2} \]
Analytical Analysis (1)

- Beam equation:

\[ EI \gamma''''(x) = p(x) = -\frac{\Gamma}{[\gamma(x) + \beta]} \]

\[
\left\{ \begin{align*}
F_{\text{left}} &= \frac{1}{L-s} \int_s^L p(x) \cdot [(L-s)-x] dx \\
F_{\text{right}} &= \frac{1}{L-s} \int_s^L p(x) \cdot (x-s) dx
\end{align*} \right.
\]

- Near \( x = s \)

\[ \gamma(x) = -\frac{\Gamma}{24EI\beta^2} (x-s)^4 + A(x-s)^3 \]

\[ \Rightarrow F_{\text{left}} = EI \gamma'''(s) = 6EIA \]

Analytical Analysis (2)

- Assume most of the force comes from \( s < x < x^* \)

\[
\left\{ \begin{align*}
F_{\text{left}} &\sim \frac{1}{L-s} \int_s^{x^*} \frac{\Gamma}{\beta^2} [(L-s)-x] dx - \frac{\Gamma (x^*-s)^3}{\beta^2} \\
F_{\text{right}} &\sim \frac{1}{L-s} \int_{x^*}^L p(x) \cdot (x-s) dx = \frac{\Gamma (x^*-s)^2}{\beta^2} \frac{L-s}{L-s}
\end{align*} \right.
\]

\[ \beta = \gamma(x^*) = A \cdot (x^*-s)^3 - \frac{\Gamma (x^*-s)^2}{24EI\beta^2} \]

\[ F_{\text{left}} = 6EIA \]

\[ \Rightarrow \beta \sim \frac{F_{\text{left}}}{6EIA} (x^*-s)^3 - \frac{\Gamma (x^*-s)^2}{24EI\beta^2} \]

\[ F_{\text{left}} = \frac{\Gamma (x^*-s)}{\beta^2} \]

\[ \Rightarrow (x^*-s) \sim \left( \frac{EI\beta^2}{\Gamma} \right)^{1/4} \]

\[ F_{\text{right}} = \frac{\Gamma (x^*-s)^2}{\beta^2} \frac{L-s}{L-s} \]

\[ \Rightarrow F_{\text{right}} \sim \frac{1}{L-s} \sqrt{\frac{EI\Gamma}{\beta}} \]
Analytical Analysis (3)

- Far from $x = s$
  \[ y(x) = B(x - s)^2 \Rightarrow B \sim \frac{\Gamma}{2EI\beta^2(x' - s)^2} \Rightarrow B \sim \frac{\Gamma}{\sqrt{EI\beta}} \left( \frac{EIZ^3}{D} \right)^{1/4} \Rightarrow \]
  \[ d = B(L - s)^2 \]

\[ \Rightarrow L - s \sim \left( \frac{EI\beta}{\Gamma} \right)^{1/4} \sqrt{d} \Rightarrow F_{\text{right}} \sim \frac{1}{L - s} \left( \frac{EI}{\Gamma} \right)^{1/4} \left( \frac{\Gamma}{\beta} \right)^{3/4} \Rightarrow F_{\text{right}} \sim \frac{E^{3/4}b}{\sqrt{d}} \left( \frac{\varepsilon \sigma U^2h^2}{h_0} \right)^{1/4} \]

Analytical Analysis (4)

- Device I, Numerical results
- Device I, Analytical Results
- Device II, Numerical Results
- Device II, Analytical results

![Graph of Force vs. Voltage](image)