An Electrothermally-Actuated Bistable MEMS Relay for Power Applications

Ph.D. Thesis Defense
by
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Thesis Committee:
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Presentation Overview

- Device background and overview, 5 slides
- Components design and fabrication
  1. Bistable structure, 4 slides
  2. Thermal actuator, 4 slides
  3. Sidewall contact, 4 slides
- Conclude, 3 slides
MEMS Technology

- MEMS = MicroElectroMechanical Systems
- To build moving micro structures/systems on silicon wafer to perform some functions
- Fabrication: Etching, Thin film deposition, Photolithography, Bonding …
- Design: Mechanical, Thermal, Electrical, Optical, Fluidic …
MEMS Relay Background

- Mechanical relay: $R_{\text{on-state}} \approx 0$, $R_{\text{off-state}} \approx \infty$
- Solid state relay: batch process, IC integration
- MEMS relay can have both advantages
- Signal relay vs. power relay
- Jo-ey Wong’s relay: vertical motion, electrostatic actuation, monostable, one contact

Cross section view
Development Logic

Functional Requirements
• Power applications
• Mechanically bistable

Flexure design
• Bistable structure
• Thermal actuator
• Contact

MEMS bulk fabrication
(1) DRIE device
(2) Etch handle
(3) Bond both

Favors

Requires

Good contact (DRIE Sidewall)

Facilitates

Requires

Challenges
Relay Configuration

Top view
Active device area: 8mm by 1mm

Thermal actuator #1
Thermal actuator #2
Outer beam
Inner beam
Cantilever beam
As-etched double beam
Double beam if fully deflected
Shaded area: anchors
Crossbar
Contact
Contact
Curved Beam Modal Analysis

$p < p_1, 0$

$p = p_1, w_1$

$p = p_2, w_2$

$p = p_3, w_3$

Straight beam squeezed

$p = p_1, w_1$

$p = p_2, w_2$

$p = p_3, w_3$

Curved beam pushed

As-etched shape

$f = f_1$

$f = f_2 | Q > 1.67$

$f = f_3 | Q > 2.31$

$Q = h/t$

$\Delta = 0$

$\Delta = 1$

$\Delta = 2$
Curved Beam F- $\Delta$ Curves

F_2(\Delta)
F_3(\Delta)
F_1(\Delta, 0.1)
F_1(\Delta, 1.67)
F_1(\Delta, 2.31)
F_1(\Delta, 3)
Bistable Double Beam

- Center clamp [Vangbo] constraints twisting mode
- Double beam bistable, single beam mono-stable
- \( l=4 \text{ mm}, t=12 \text{ um}, h=72 \text{ um} \), total force near 2\(^{nd}\) stable position 5.7mN

\[ f_{\text{top}} = \frac{8\pi^4 EIh}{l^3} \]
\[ f_{\text{bottom}} = -\frac{4\pi^4 EIh}{l^3} \]

\[ \delta_{\text{top}} = \frac{8t}{3Q} \]
\[ \delta_{\text{bottom}} = 2h - \frac{4t}{3Q} \]

\[ \delta_{\text{zero}} \approx 1.33h \]

\[ \varepsilon_{\text{max}} \approx 2\pi^2 \frac{th}{l^2} \]
Snap-Through Movie

100 µm
Transient Thermal Actuator

- >10 mN, >100 µm required, thermal actuator selected
- Selective metal coating to create resistance difference
- In transient, hot beam has uniform temp., cold beam has zero temp
- Thermal expansion difference creates lateral tip motion
- Design requirement: blocked force, free displacement
- One beam to push the relay on, the other one to pull it back
Mechanical Models

(1) Basic model

Cantilever: \[ W(X) = F\left(\frac{X^2}{2} - \frac{X^3}{6}\right) + M\frac{X^2}{2}\], \[ \eta = \varepsilon = \frac{N^2}{12}\left(\frac{t}{l}\right)^2 \]

Actuator: if \( t_h = t_c = t, l_h = l_c = l \):

\[ \frac{f_{\text{block}}}{\delta_{\text{free}}} = \frac{13Eb}{8}\left(\frac{t}{l}\right)^3, f_{\text{block}} = l(\alpha T_{\text{rise}})\left(\frac{t}{l}\right)^2\frac{3Eb}{8} \]

(2) Complete model

Cantilever: \[ W = F\sin(N X) - \tan N \cos(N X) + \tan N - N X \]

\[ + M\frac{1-\cos(N X)}{N^2 \cos N}, \]

\[ \eta = \varepsilon + \left(\frac{t}{l}\right)^2\left[c_{\eta F}(N)F^2 + c_{\eta M}(N)M^2 + c_{\eta FM}(N)FM\right] \]

Actuator: an equation array reduced to a quadratic equation

\[ q_1(N_h)\Theta_h^2 + q_2(N_h)\Theta_h + q_3(N_h) + \alpha T_{\text{rise}} = 0 \]
Comparison and Design

- Complete model agrees with FEA anytime
- Basic model less adequate with higher expansion and lower $t_h/t_c$
- Basic model can quickly get design, which can be verified/improved by complete model
- For actuation of 13 mN, 120 µm: Design $T_{\text{rise}} = 220$ C, $l = 6$ mm, $t_h = 80$ µm, $t_c = 60$ µm, $t_g = 20$ µm, $b = 300$ µm
Thermal and Electrical Design

- Diffusion $I(t) \approx \sqrt{\frac{\text{Conductance}}{\text{Capacitance}}}$
- With 1 ms pulse the 6 mm actuator undergoes a thermal transient
- Mechanical time constant $<< 1$ ms
- Cold beam tip becomes hot. $T_{\text{rise}} = 220$ C to avoid Au-Si eutectic reaction
- Thermal relaxation time $\approx 0.4$ s

- Electrical pulse of 1ms generated by external circuit
- Wafer resistivity determines electrical actuation. 0.02 $\Omega$-cm wafer requires 50V, 1A
- 0.5 $\mu$m Au on cold beam provides 1/10 Resistance of hot beam
# Fabricated Relay Chart

<table>
<thead>
<tr>
<th>Year</th>
<th>Wafer # Mask#</th>
<th>Asher</th>
<th>Oxide</th>
<th>Handle wafer</th>
<th>Metalization</th>
<th>Bottom etch</th>
<th>Anneal</th>
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<tbody>
<tr>
<td>01</td>
<td>Tt M2</td>
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<td>No</td>
<td>Si</td>
<td>Ebeam 0.3um</td>
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<td>Pyrex</td>
<td>Sputter Cu</td>
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</tbody>
</table>

\[ R = 100 \Omega \]
\[ R = 0.1 \Omega \]
Contact Compliance, Shape

- f-d curve, gap, contact shape all vary with fabrication
- Cantilever beam improves f-d curve
- Compliance also balances forces on two contacts
- Flat crossbar and contacts provide the best contact
- Fabrication tolerance is now less critical
Bottom-of-Etch-Problem Solution

Backside etch method

Almost no footing

Significant footing

Device wafer

Device wafer mount

Handle wafer

Frontside through etch

Device wafer dismount

Cross section of etched beam

Si residue, cannot be avoided by over-etching

Closing motion

Footing radius

Etch direction

10 um
Fabrication Flow

(1) DRIE backside etch
(2) DRIE through etch. Proper cleaning
(3) HF shallow etch
(4) Anodic bonding
(5) Sputter 1 um seed Au (0.1 um at side)
(6) Electroplate 2 um Cu
Measured Performance

Contact:
- Force $\approx 1$ mN/contact, manual pressing doesn’t decrease Resistance
- $R_{\text{on-state}} = 60$-$180$ m$\Omega$, On-state current carrying capacity = 2-$3$A
- $R_{\text{off-state}} \approx \infty$, stands off > 200V

Switching:
- Actuation pulse: 1 ms
- Bounce: 1-$5$ times
- Switch-on settle time: 2 ms
- Voltage = 50-$60$V, 85V
- Stroke = 120 $\mu$m
- Max frequency = 5Hz
Contributions

Development of a MEMS relay

- Design and modeling of a curved beam bistable mechanism
- Design and modeling of a transient thermal actuator
- Design and modeling of relay contact compliance
- Identification of the ideal shape of relay contact
- Process development to metalize sidewall relay contact
- Process development to alleviate bottom-of-etch problem of DRIE through-etched structure
Acknowledgements

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- Fabrication & testing assistance: Kurt Broderick, Dr. Vicky Diadiuk, Gwen Donahue, Ramkumar Krishnan, Chris Spadaccini, Paul Tierney, Dennis Ward
- Sponsor: ABB
f-d Curve Measurement

- Beam thickness profile, <10 µm mask value
- Measured by flextester
- f-d theory for cubic average thick beam agrees with measurement
Thermal Measurement

- Images taken by IR camera
- Low time, spatial, and temperature accuracy
- Cool down time agrees with model
- Measured energy to heat up agrees with theory within 20%

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>IR Camera Images</th>
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<tbody>
<tr>
<td>0-66 ms</td>
<td>[Image 1]</td>
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<tr>
<td>132-198 ms</td>
<td>[Image 2]</td>
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<tr>
<td>264-330 ms</td>
<td>[Image 3]</td>
</tr>
<tr>
<td>442-508 ms</td>
<td>[Image 4]</td>
</tr>
</tbody>
</table>
Switch-on Measurement

- Actuation time 1 ms
- Voltage just enough to switch
- Snap-through time ~ 50 µs
- Contact bounces 1-5 times
- Time from actuation to good contact 1.5-2.5 ms
Curved Beam Modal Analysis

Buckling of a straight beam with initial stress

Hard to control initial stress in bulk fabrication...
How about a curved beam etched as shape \( w_i \) pushed by \( f \) at the center?

1. Normalization: \( F \)-force, \( \Delta \)-center displacement, \( N^2 \)-axial force, \( N_{i,2,3}^2 \), mode axial force, \( Q \)-ratio of curved beam height and thickness, \( W \)-Beam shape, \( \tilde{W} \)-as-etched shape, \( A_{i,2,3} \)-mode amplitudes

2. Write the shape by buckling modes:

\[
\tilde{W}(x) = \frac{1}{2} W_i(x), W(x) = \sum_{j=1}^{3} A_j W_j(x), \Delta = 1 - 2A_i.
\]

3. Variation (Total structural energy) = 0

result #1: \( A_i = -\frac{N_i^2}{2(N^2-N_i^2)} + \frac{4F}{N_i^2(N^2-N_i^2)} \).

result #2: \[
\left\{ \begin{array}{l}
(N^2-N_2^2)A_2 = 0 \\
(N^2-N_3^2)A_3 = 0
\end{array} \right., \text{ which implies three kinds of solutions,}
\]

\[
\left\{ \begin{array}{l}
N^2 = ?, A_2 = A_3 = 0 \\
A_i = ? \quad \text{,} \\
F = F_i
\end{array} \right. \quad \left\{ \begin{array}{l}
N^2 = N_2^2, A_3 = 0 \\
A_i = ?, A_2 = ? \quad \text{,} \\
F = F_2
\end{array} \right. \quad \left\{ \begin{array}{l}
N^2 = N_3^2, A_2 = 0 \\
A_i = ?, A_3 = ? \quad \text{,} \\
F = F_3
\end{array} \right.
\]

4. Hooke’s Law,

\[
\frac{N_i^2}{16} - \sum_{j=1,2,3} \frac{A_j^2 N_j^2}{4} = \frac{N^2}{12Q^2}
\]

5. \( F-\Delta \) curves obtained from equations above