An Electrothermally-Actuated Bistable MEMS Relay for Power Applications

Ph.D. Thesis Defense

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Presentation Overview

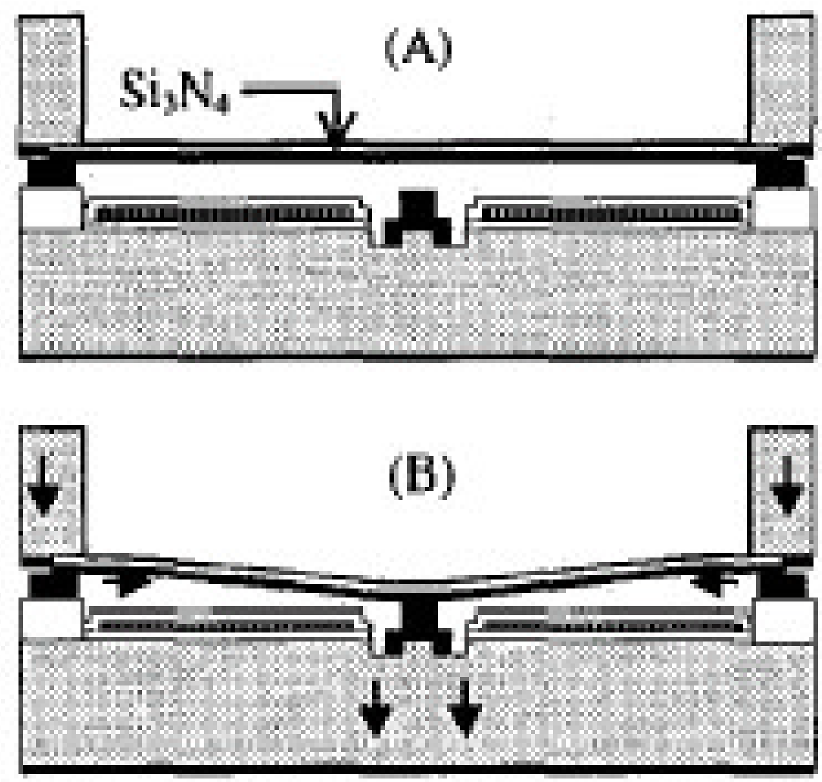
- Device background and overview, 5 slides
- Components design and fabrication
  1. Bistable structure, 4 slides
  2. Thermal actuator, 4 slides
  3. Sidewall contact, 4 slides
- Conclude, 3 slides

MEMS Technology

- MEMS = **M**icro**E**lectro**M**echanical **S**ystems
- 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 …

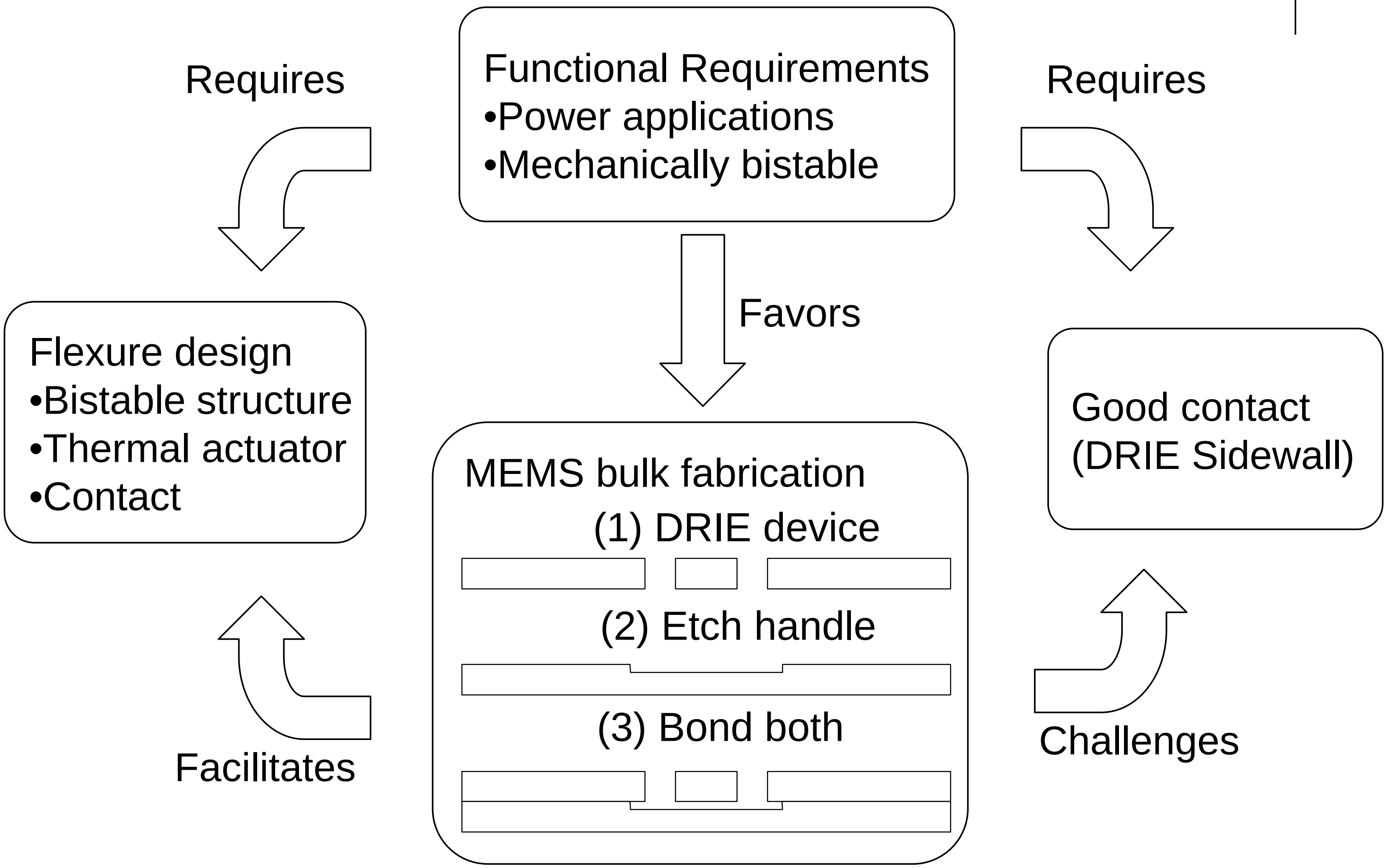
MEMS Relay Background

- Mechanical relay: $R_{on\text{-}state} \approx 0$, $R_{off\text{-}state} \approx \infty$
- 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

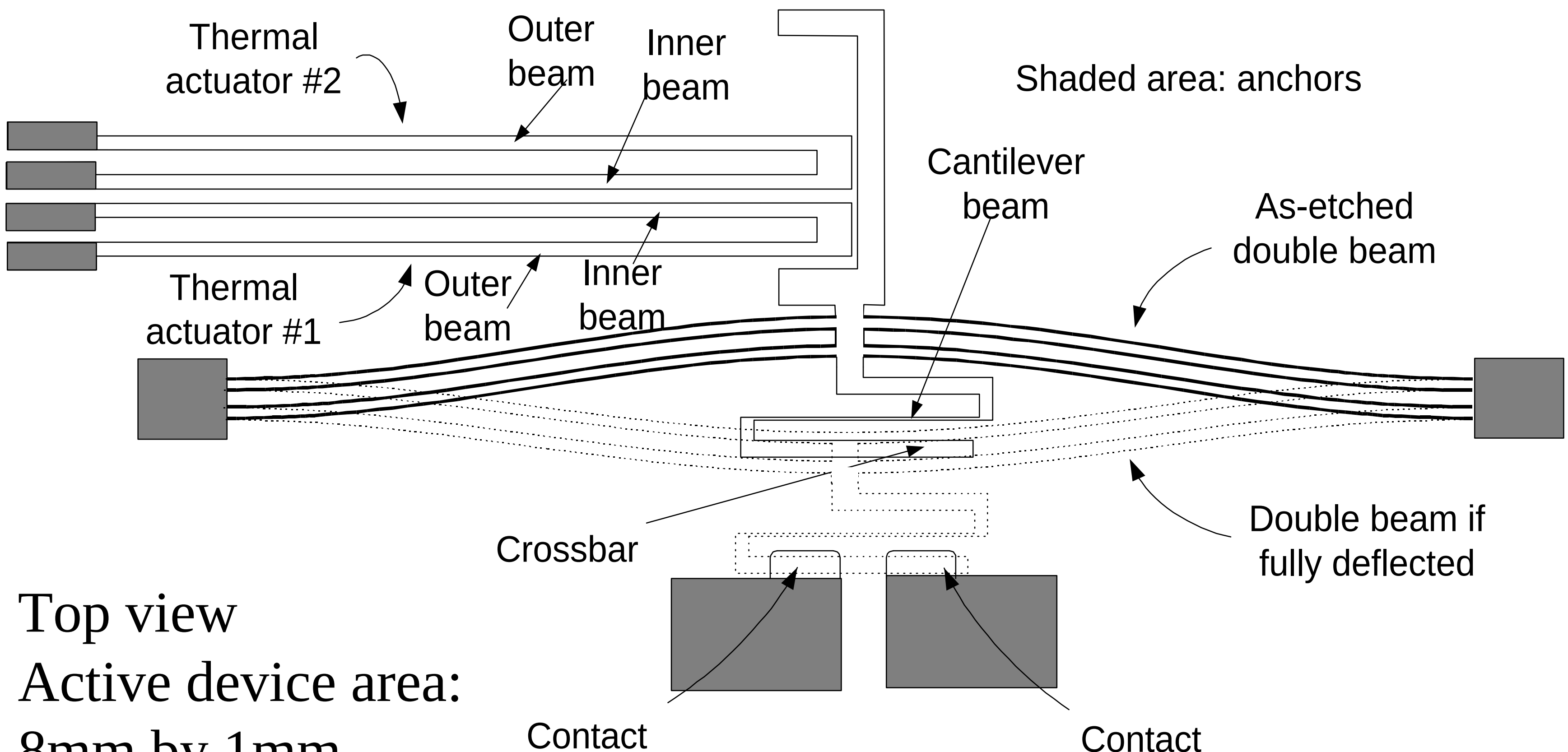


Cross section view

Development Logic

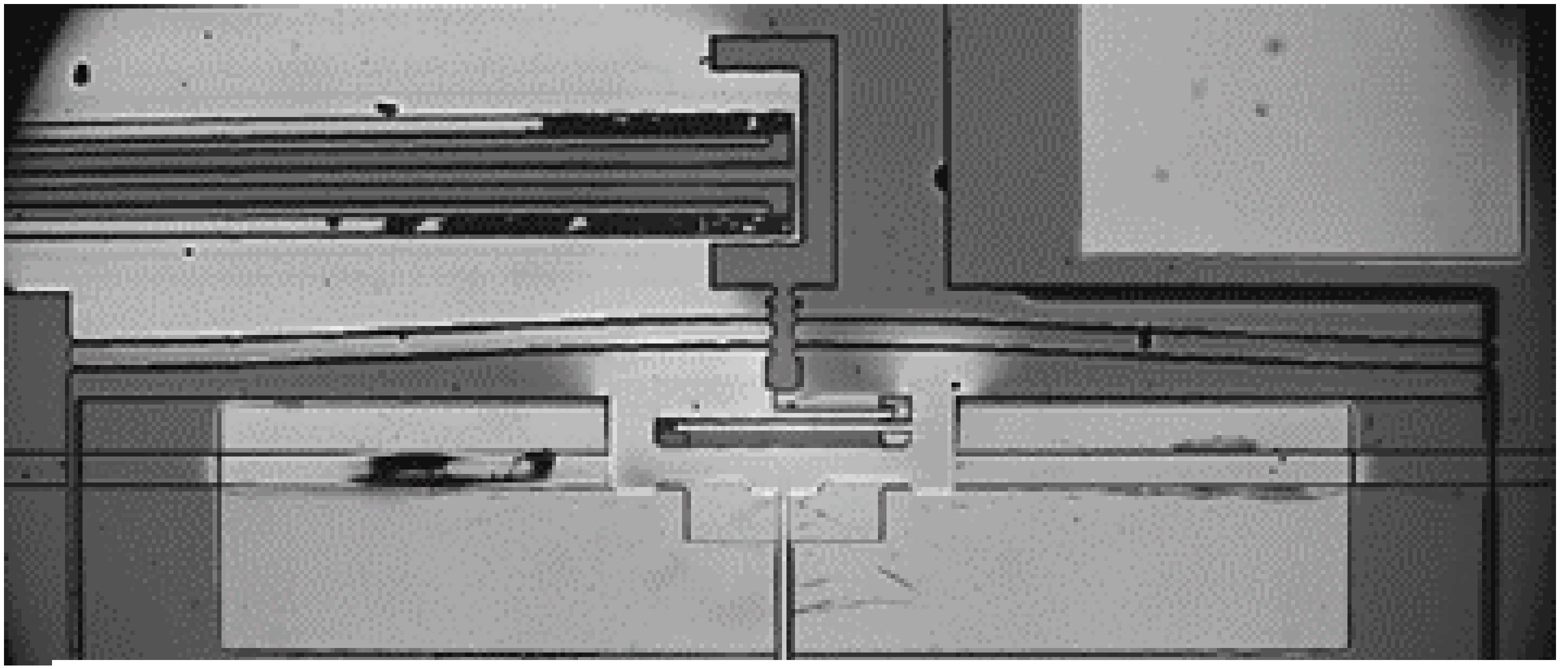


Relay Configuration

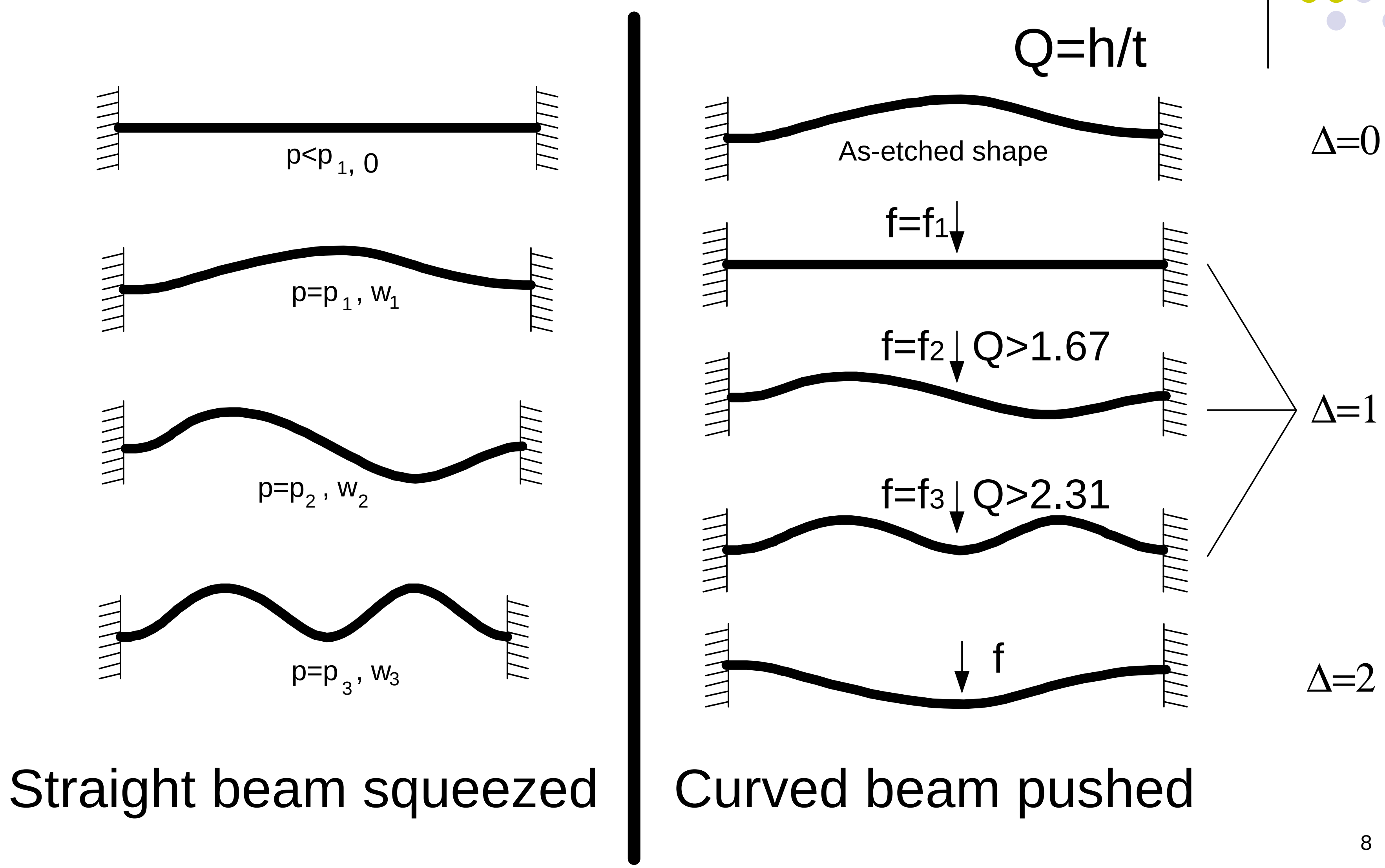


Top view
Active device area:
8mm by 1mm

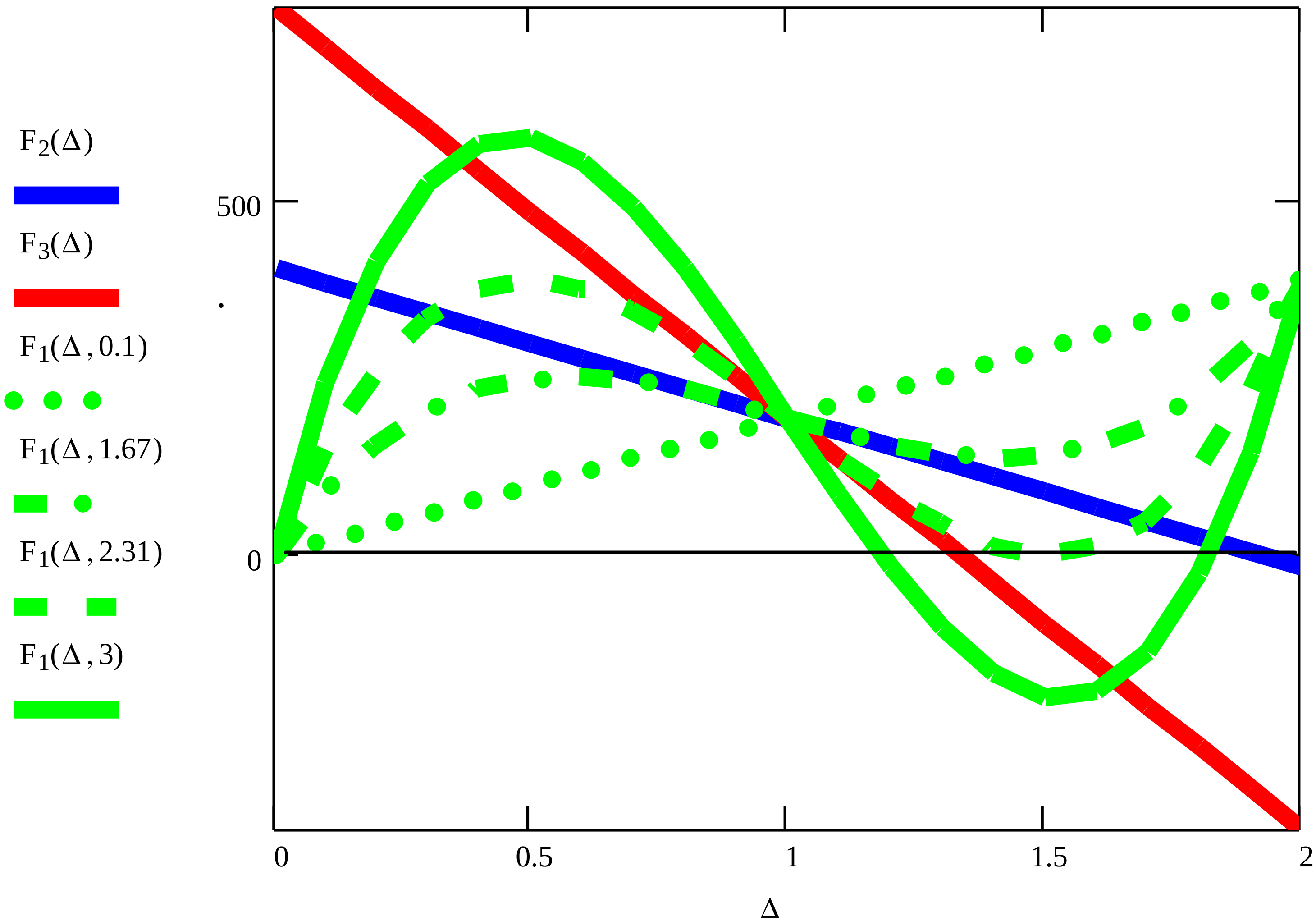
Device and FEA Movies



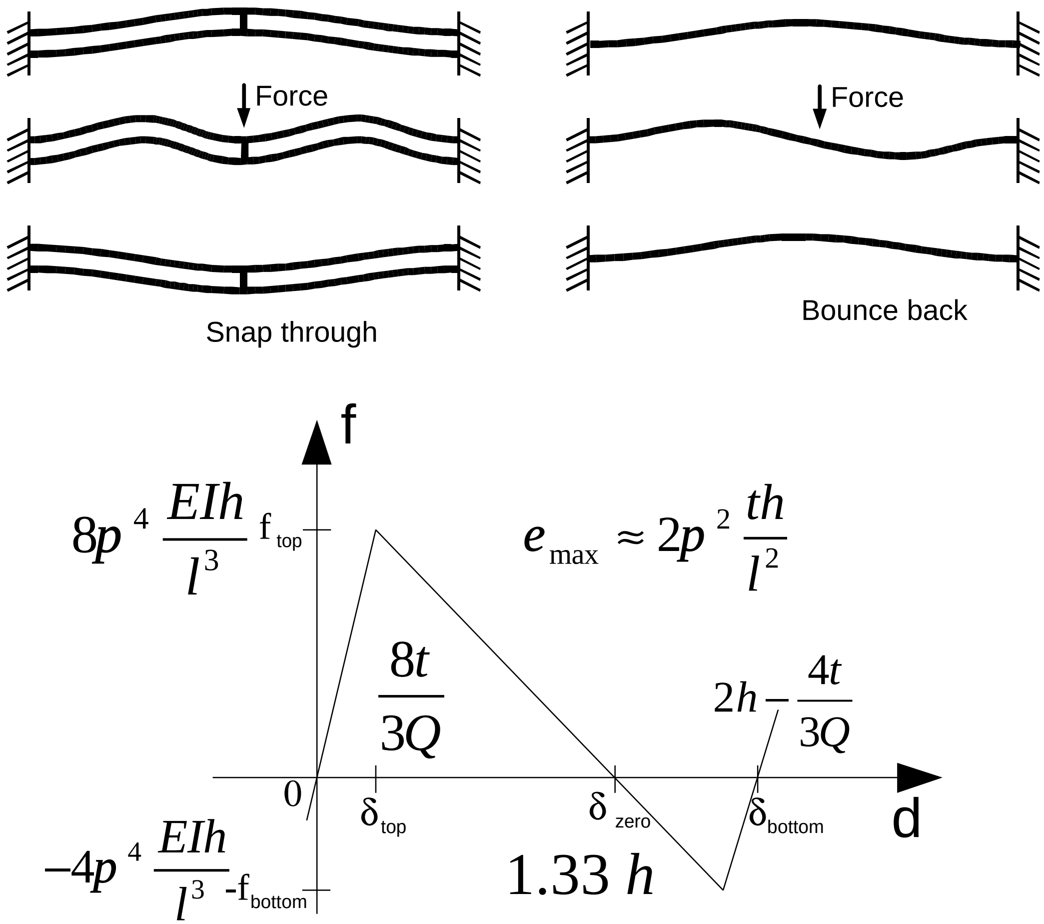
Curved Beam Modal Analysis



Curved Beam F- D Curves

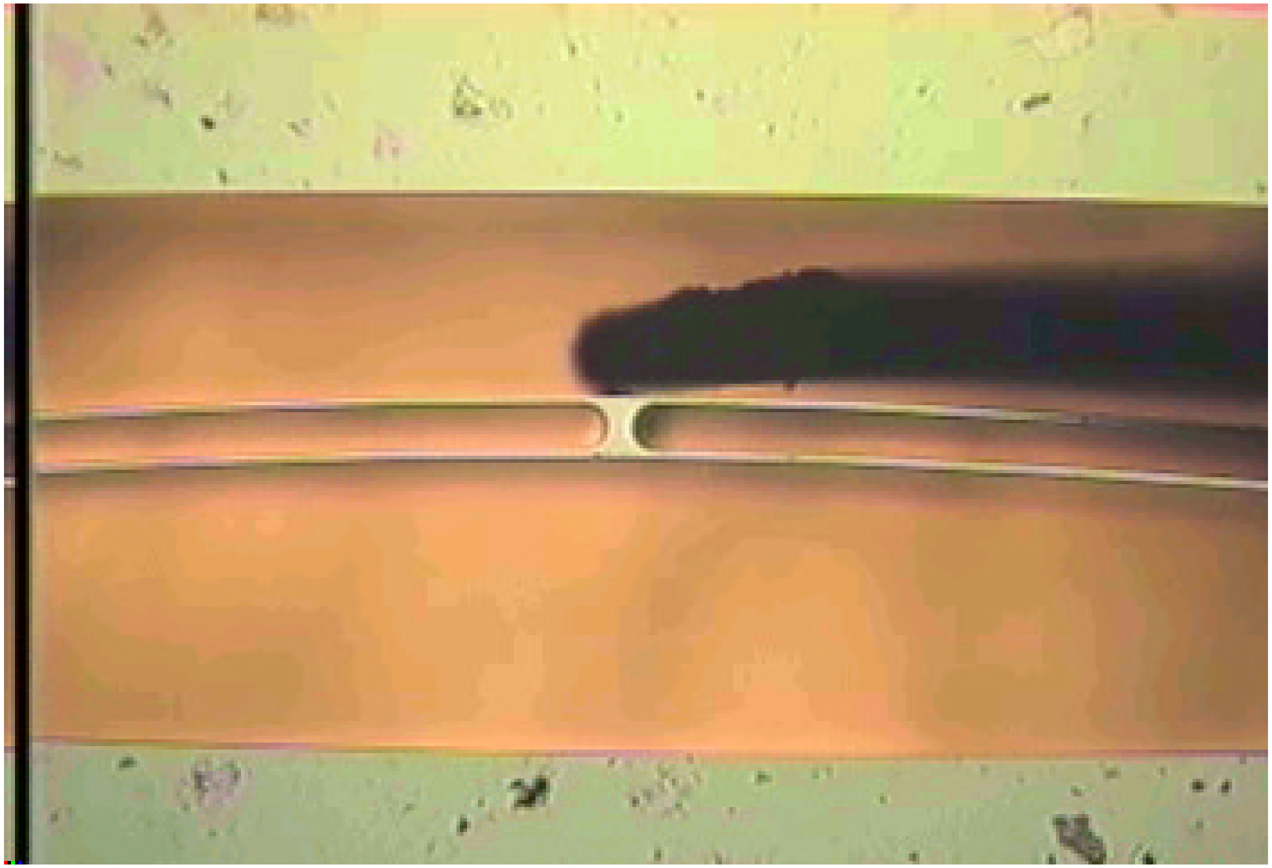


Bistable Double Beam



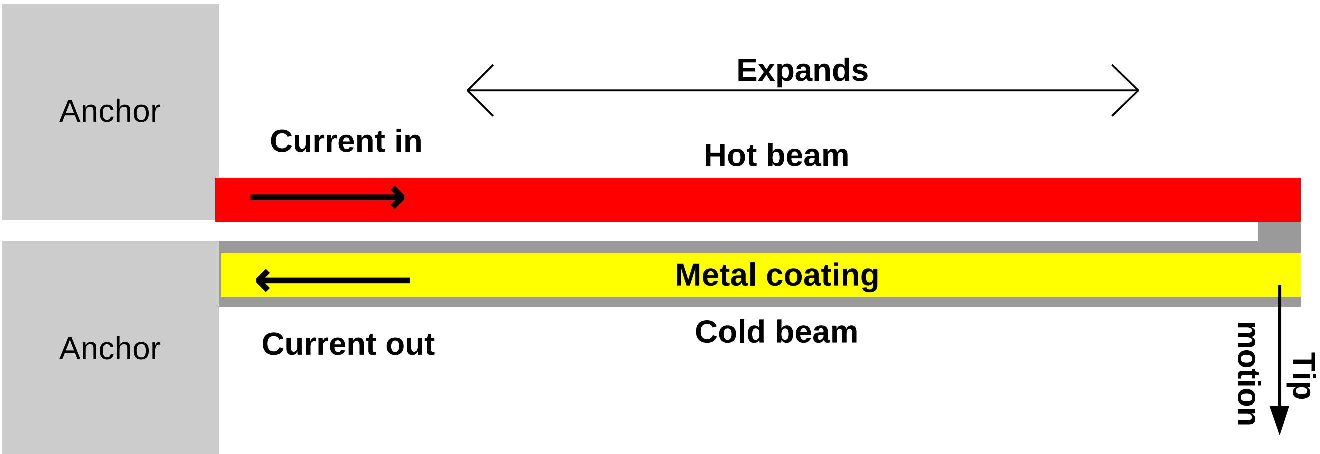
- Center clamp [Vangbo] constraints twisting mode
- Double beam bistable, single beam mono-stable
- l=4 mm, t=12 um, h=72 um, total force near 2nd stable position 5.7mN

Snap-Through Movie



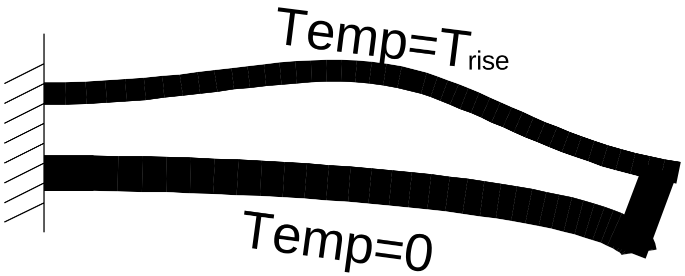
100 µm

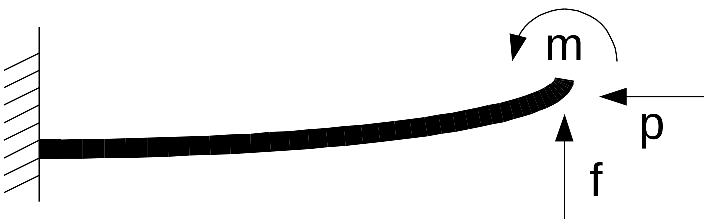
Transient Thermal Actuator

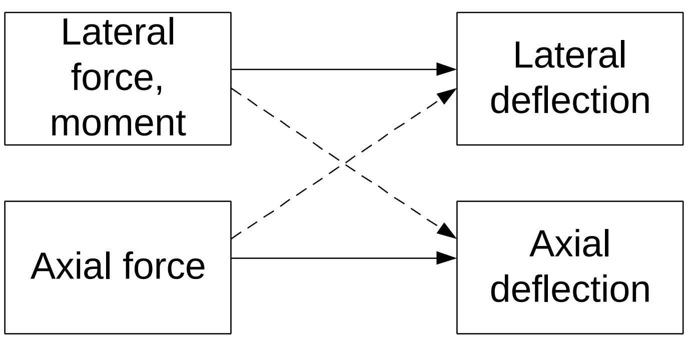


- >10 mN, >100 μm required, thermal actuator selected
- Selective metal coating to create resistance difference
- In transient, hot beam has uniform temp., cold beam has zero temp
- Thermal expansion difference creates lateral tip motion
- Design requirement: blocked force, free displacement
- One beam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

Mechanical Models







(1) Basic model

Cantilever: $W(X) = F\left(\frac{X^2}{2} - \frac{X^3}{6}\right) + M\frac{X^2}{2}, h = e = \frac{N^2}{12}\left(\frac{t}{l}\right)^2$

Actuator: if $t_h = t_c = t_g = t, l_h = l_c = l$:

$$\frac{f_{block}}{d_{free}} = \frac{13Eb}{8}\left(\frac{t}{l}\right)^3, \; f_{block} = l\left(aT_{rise}\right)\left(\frac{t}{l}\right)^2\frac{3Eb}{8}$$

(2) Complete model

$$\text{Cantilever: } W = F\frac{\sin(NX) - \tan N\cos(NX) + \tan N - NX}{N^3}$$

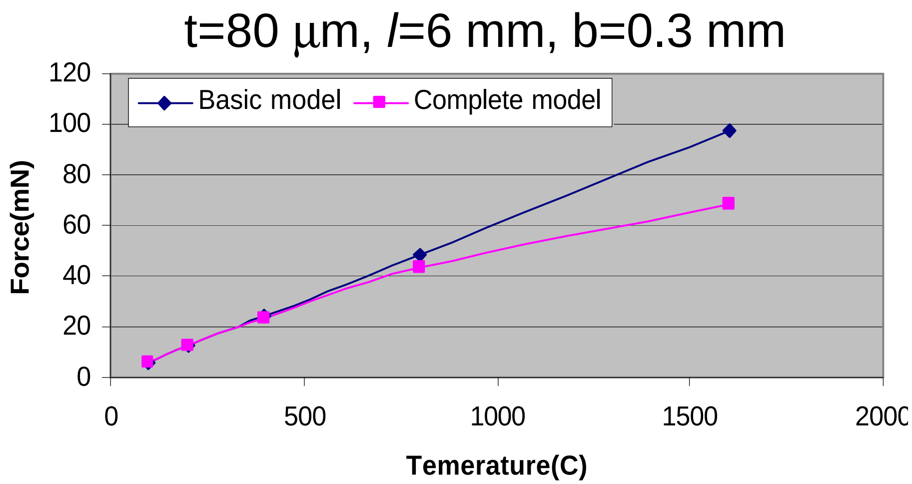
$$+ M\frac{1 - \cos(NX)}{N^2\cos N},$$

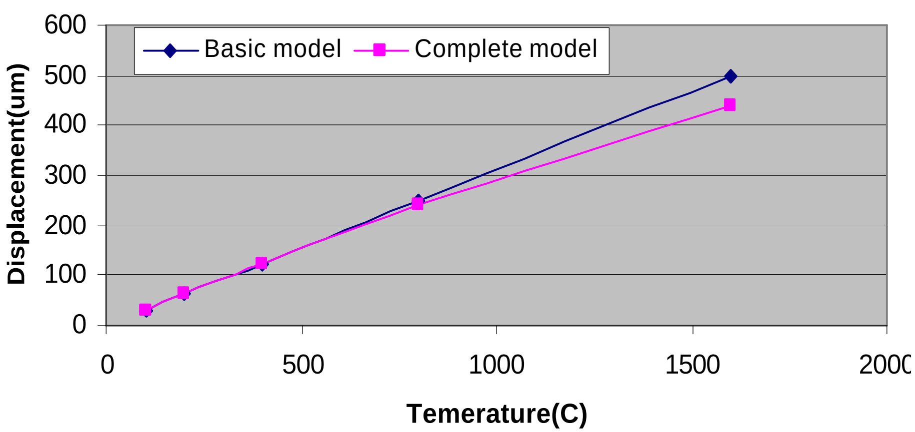
$$h = e + \left(\frac{t}{l}\right)^2\left[c_{hF}(N)F^2 + c_{hM}(N)M^2 + c_{hFM}(N)FM\right]$$

Actuator: an equation array reduced to a quadradic equation

$$q_1(N_h)\Theta_h^2 + q_2(N_h)\Theta_h + q_3(N_h) + aT_{rise} = 0$$

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

- Electrical pulse of 1ms generated by external circuit
- Wafer resistivity determines electrical actuation. 0.02 Ω-cm wafer requires 50V, 1A
- 0.5 μm Au on cold beam provides 1/10 Resistance of hot beam

Fabricated Relay Chart

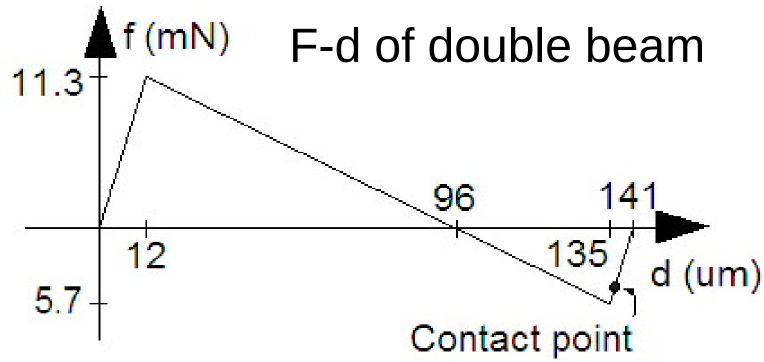
Year	Wafer # Mask#	Asher	Oxide	Handle wafer	Metalization	Bottom etch	Anneal
01	Tt M2	No	No	Si	Ebeam 0.3um	No	No
01	G1 M3	No	No	Si	Ebeam 0.3um	No	No
01	G2 M3	No	No	Si	Ebeam 0.3um	No	No
01	G3 M3	No	No	Si	Ebeam 0.3um	No	No
01	G4 M5	No	No	Si	Ebeam 0.3um	No	No
01	G5 M6	Yes	Yes	Pyrex	Sputter 0.9um	No	No
01	G6 M7	Yes	Yes	Pyrex	Sputter 0.9um	Yes	No
02	G7 M8	Yes	Yes	Pyrex	Ebeam 0.3um	Yes	No
02	G8x M8	Yes	Yes	Pyrex	Ebeam 0.3um	Yes	No
02	G9 M8	Yes	Yes	Pyrex	Ebeam 0.3um	Yes	No
02	G10 M10	Yes	No	Pyrex	Sputter Au	Yes	No
02	G11 M10	Yes	No	Pyrex	Sputter Au Plate Au	Yes	No
02	G12 M10	Yes	No	Pyrex	Sputter Au Plate Cu	Yes	No
02	G13 M11	Yes	No	Pyrex	Sputter Au Plate Cu	Yes	No
02	G14 M12	Yes	No	Pyrex	Sputter Au Plate Au	Yes	No
02	G15 M12	Yes	No	Pyrex	Sputter Au plate Cu	Yes	Both
03	G16 M13	Yes	No	Pyrex	Sputter Cu	Yes	Both

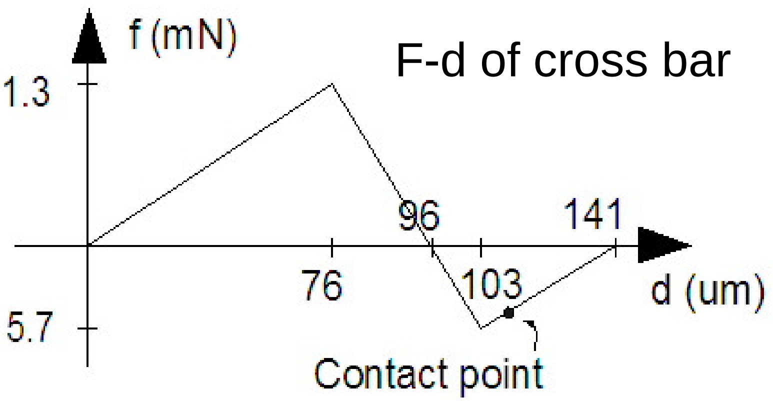
100 Ω

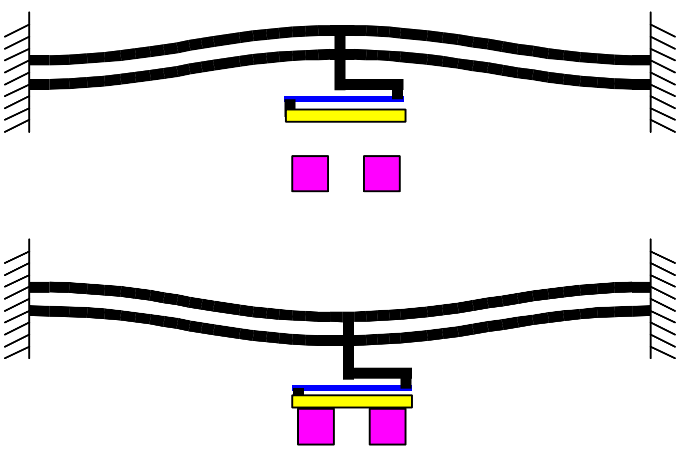
R

0.1 Ω

Contact Compliance, Shape

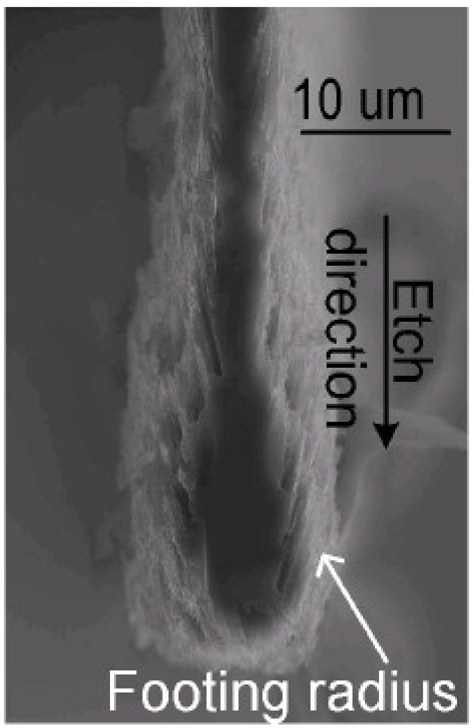


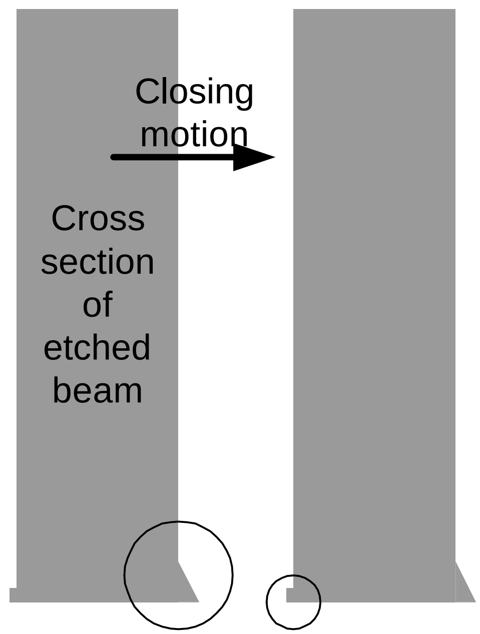




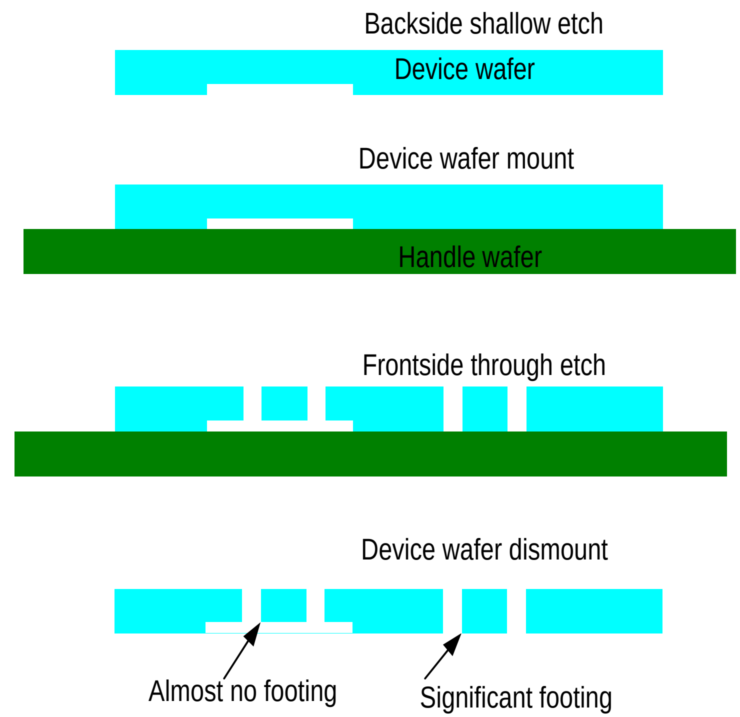
- f-d curve, gap, contact shape all vary with fabrication
- Cantilever beam improves f-d curve
- Compliance also balances forces on two contacts
- Flat crossbar and contacts provide the best contact
- Fabrication tolerance is now less critical

Bottom-of-Etch-Problem Solution



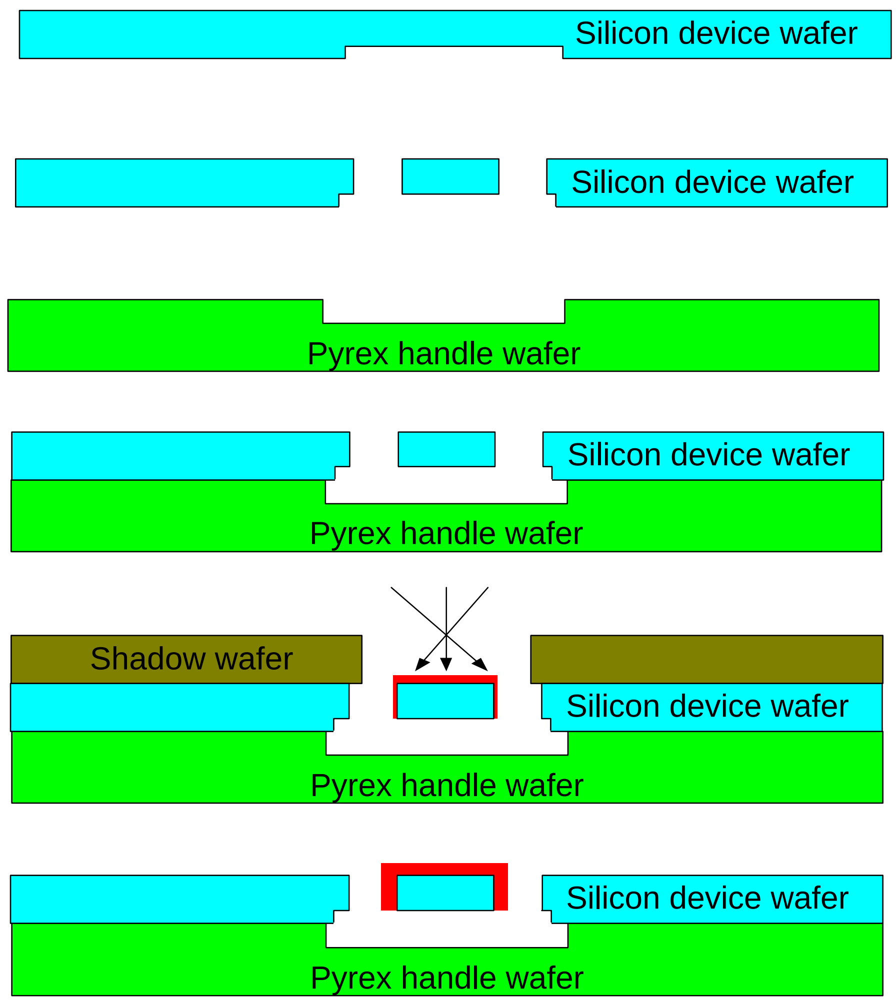


Si residue, cannot be avoided by over-etching



Backside etch method

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

Switching:

- Actuation pulse: 1 ms
- Bounce: 1-5 times
- Switch-on settle time: 2 ms
- Voltage = 50-60V, 85V
- Stroke = 120 µm
- 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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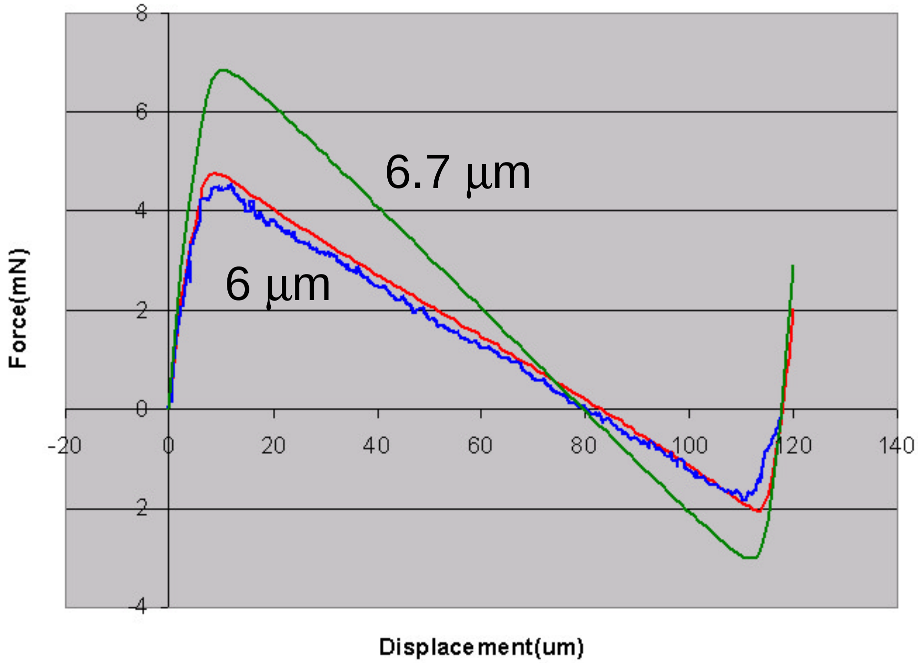
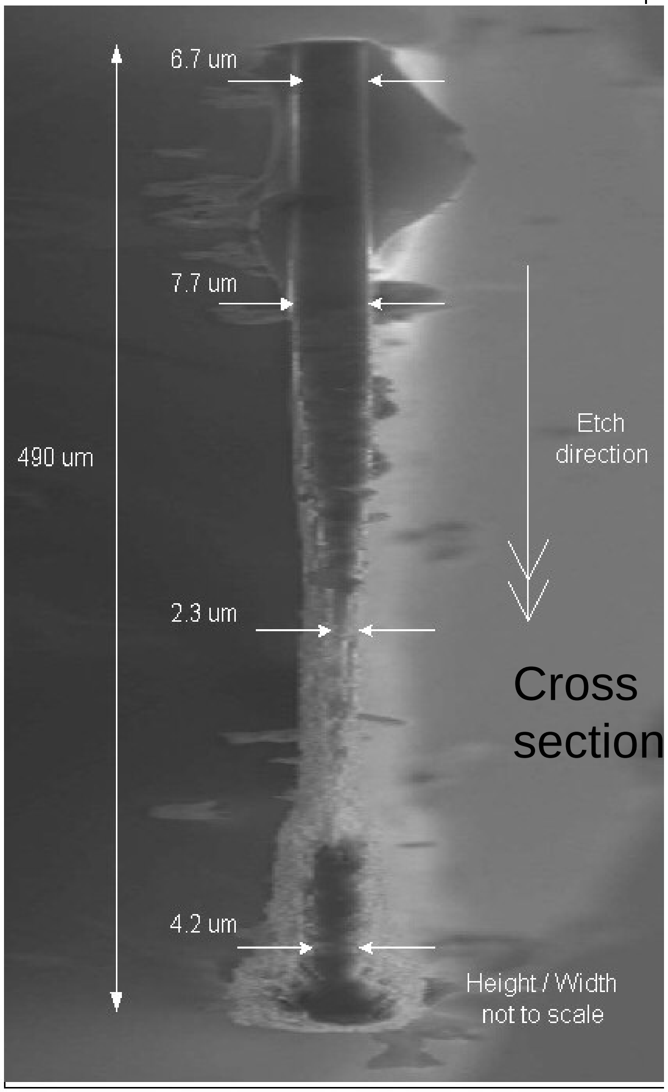
- Sponsor: ABB

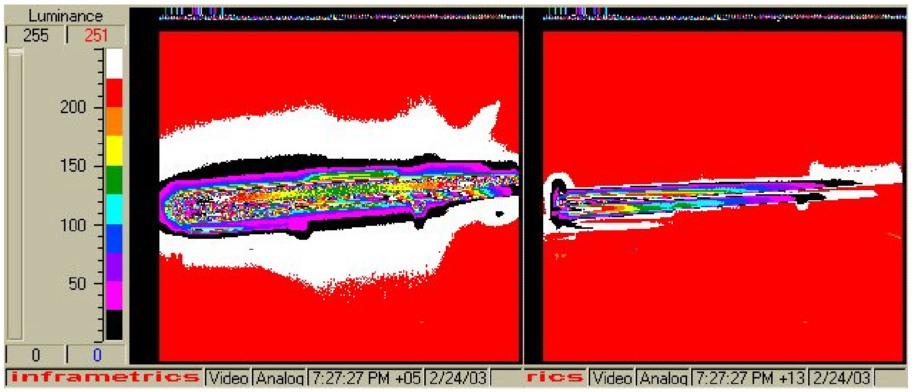
f-d Curve Measurement



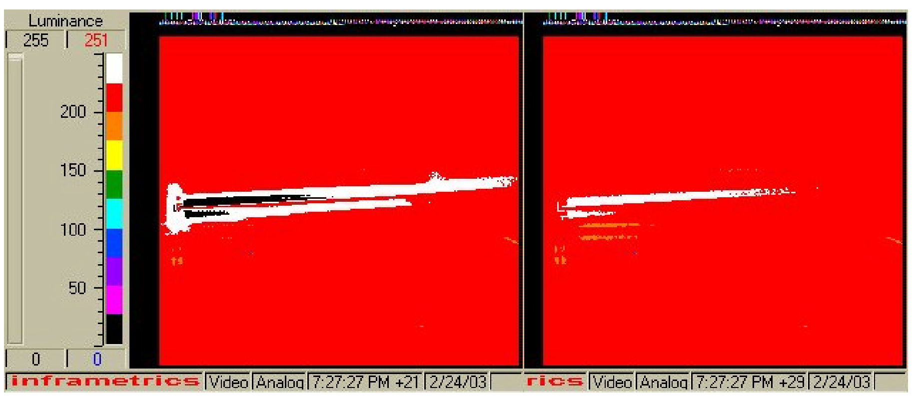
- Beam thickness profile, <10 µm mask value
- Measured by flextester
- f-d theory for cubic average thick beam agrees with measurement



Thermal Measurement



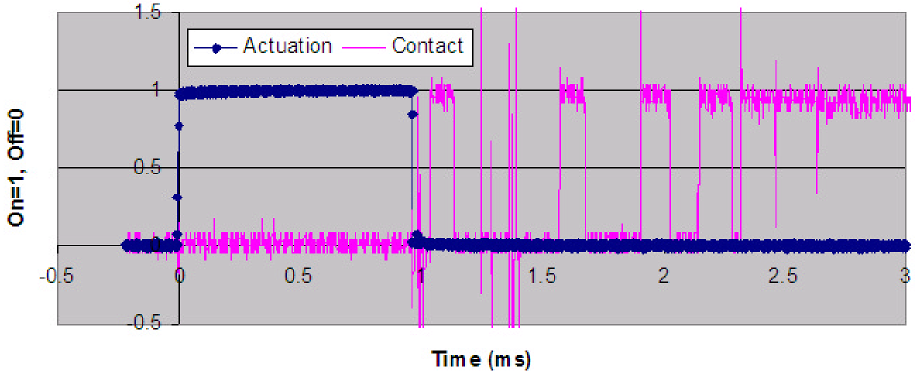
time=0-66 ms time=132-198 ms

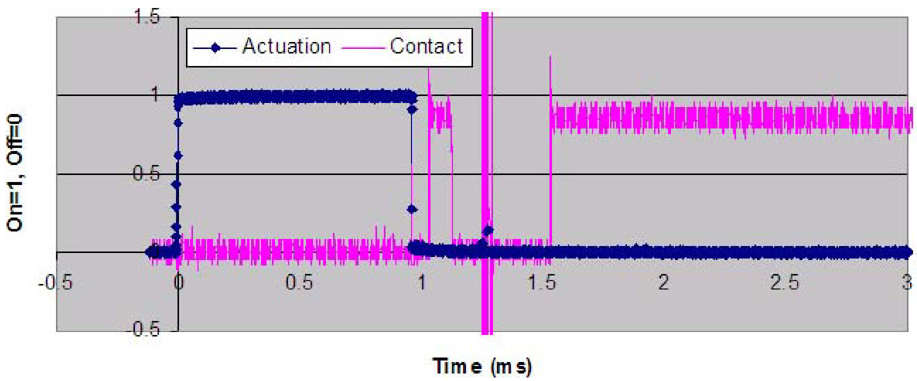


time=264-330 ms time=442-508 ms

- 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%

Switch-on Measurement

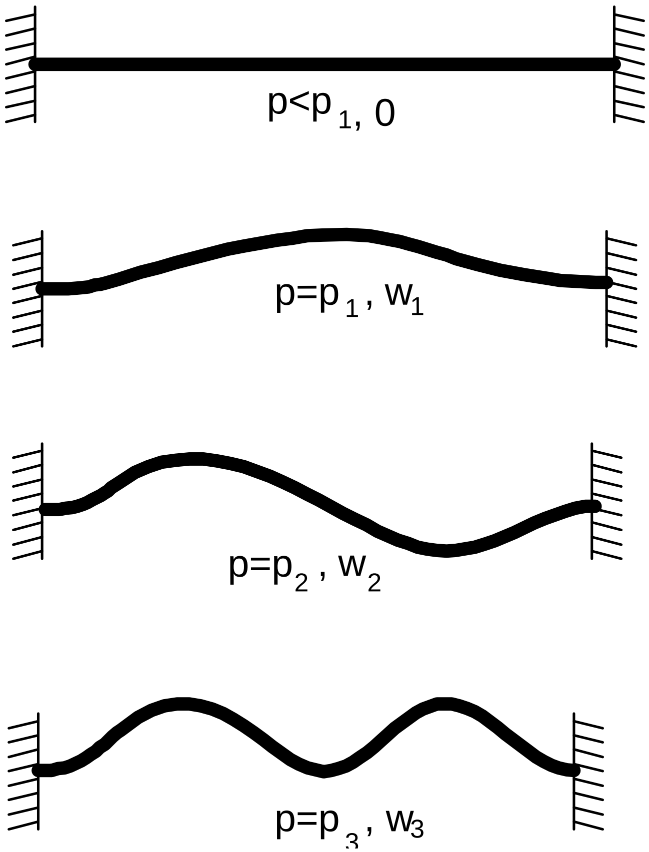




- Actuation time 1 ms
- Voltage just enough to switch
- Snap-through time ~ 50 µs
- Contact bounces 1-5 times
- Time from actuation to good contact 1.5-2.5 ms

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_1 pushed by f at the center?

(1) Normalization: F-force, Δ-center displacement, N^2-axial force, $N^2_{1,2,3}$,mode axial force, Q-ratio of curved beam height and thickness, W-Beam shape, $\bar{W}$-as-etched shape, $A_{1,2,3}$-mode amplitudes

(2) Write the shape by buckling modes:

$$\bar{W}(X)=\frac{1}{2}W_1(X), W(X)=\sum_{j=1}^{3}A_jW_j(X), \Delta=1-2A_1.$$

(3) $Variation(Total\ structural\ energy)=0$

result #1: $A_1=-\dfrac{N_1^2}{2(N^2-N_1^2)}+\dfrac{4F}{N_1^2(N^2-N_1^2)}.$

result #2: $\begin{cases}(N^2-N_2^2)A_2=0\\(N^2-N_3^2)A_3=0\end{cases}$, which implies three kinds of solutions,

$$\begin{cases}N^2=?, A_2=A_3=0\\ A_1=?\\ F=F_1\end{cases},\quad \begin{cases}N^2=N_2^2, A_3=0\\ A_1=?, A_2=?\\ F=F_2\end{cases},\quad \begin{cases}N^2=N_3^2, A_2=0\\ A_1=?, A_3=?\\ F=F_3\end{cases}$$

(4) Hooke's Law, $\dfrac{N_1^2}{16}-\sum_{j=1,2,3}\dfrac{A_j^2N_j^2}{4}=\dfrac{N^2}{12Q^2}$

(5) F-Δ curves obtained from equations above