Electrostatic Zipping Actuators and Their Application to MEMS

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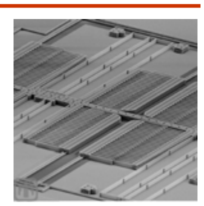
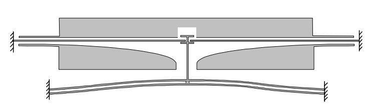
Introduction

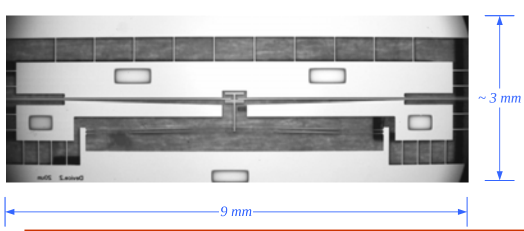
- Problem
  - Need powerful electrostatic actuators for MEMS power relay
  - Huge size using conventional designs

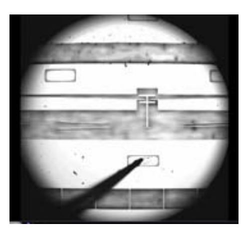


- Solutions
  - Zipping actuator with compliant starting zone



- Results

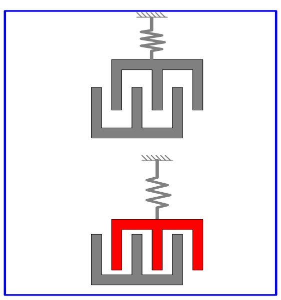




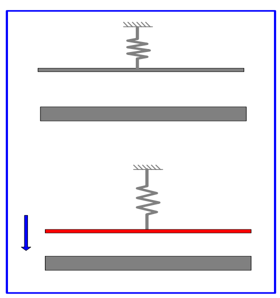
Contributions

- 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

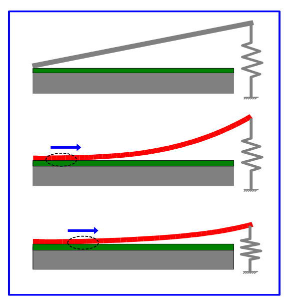
Background: Electrostatic Actuators



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



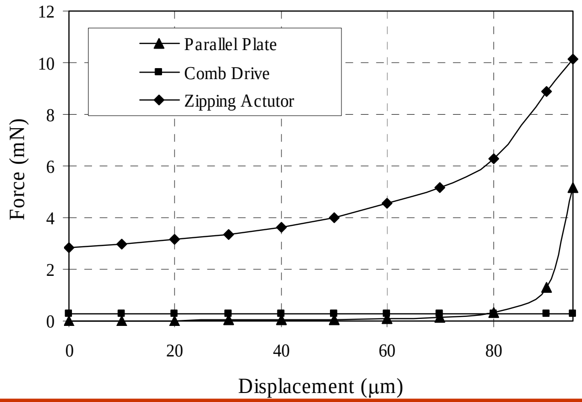
- Parallel Plate
  - Confliction between stroke and force



- "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 an capacitor plate actuators
  - “Zipper” actuator is the only hope to secure milli Newtons of force with a reasonable volume



5

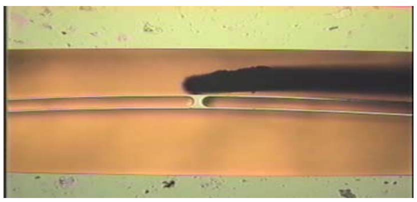
Zipping Actuators: A Survey

Author	***Actuation direction***	***Applica-tion***	***Size (mm^2)***	***Force (mN)***	***Stroke (μm)***
Shikida	Vertical	Valve	5 * 5	N/A (very small)	220
Divoux	Vertical	Mirror	0.8 * 0.8	0.1	6
Legtenberg	Lateral	N/A	0.8 * 0.5	0.02	30
Perregaux	Lateral	Optical shutter	0.5 * 0.2	N/A (very small)	20
Sherman	Lateral	Fluid control	1 * 0.2	N/A (very small)	100
This thesis	Lateral	Relay	9 * 1	2 ~ 10	80

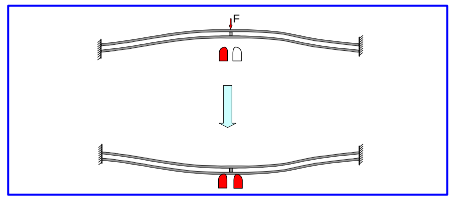
6

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

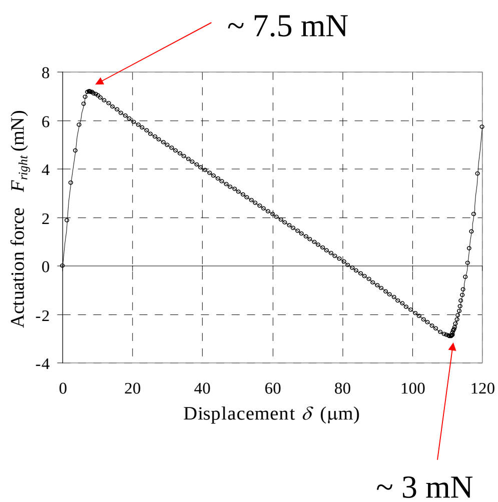


Double beam working as a Relay

Why Is It Hard ? (1)

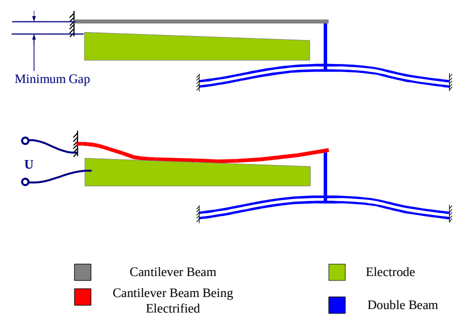
- Stoke: >= 80 µm
- Asymmetric and high actuation/contact force: ~ 7 mN for the first 10 µm to get a 3mN of contact force
- Actuation voltage:

  < 200 V (as small as possible)
- Scale: $7 \times 7 \times 1$ mm^3
- Fabrication: Deep Reactive Ion Etching



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.



Double beam actuated by "Zipper"

9

Contributions

- ***Design: Starting zone to reduce the pull-in voltage***
- Numerical and analytical modeling: easy and accurate
- Optimization of the system
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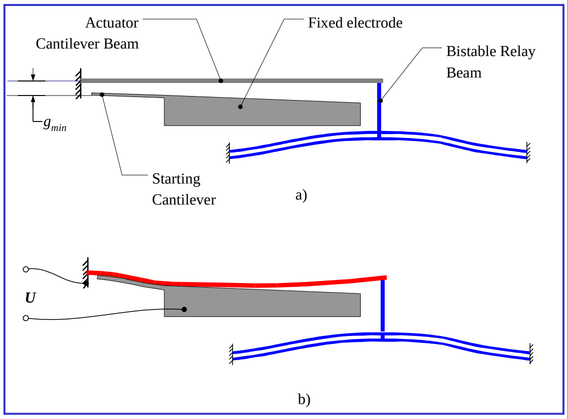
- Wet-anisotropically-etched micro relay contact

10

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



11

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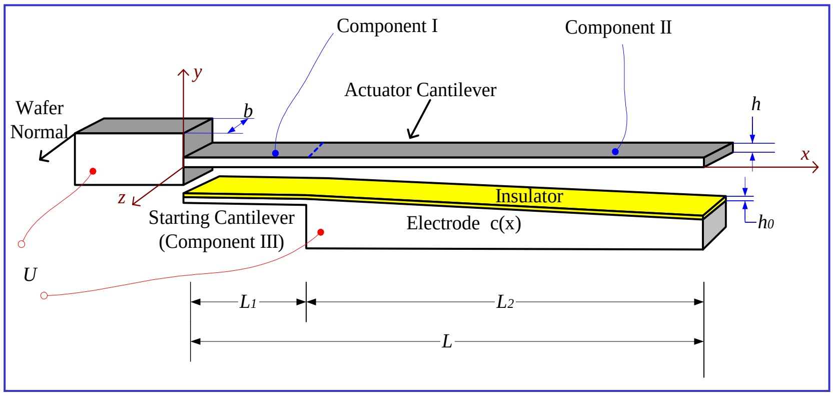
12

Modeling: Overview



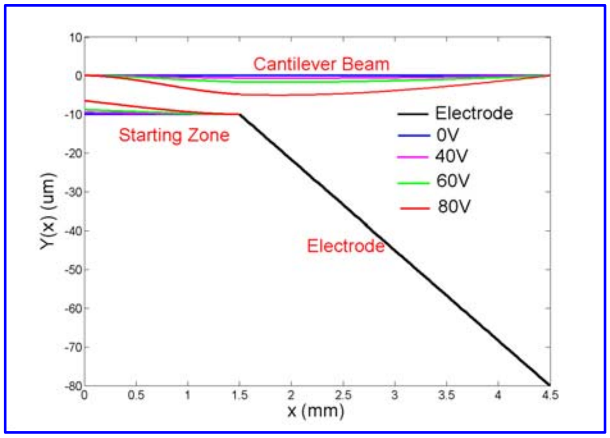
- Beam bending equation in electric field

$$E\left(I(x)y''(x)\right)'' = \frac{-\varepsilon_0 U^2 b}{2\left[y(x) - c(x) + \frac{h_0}{\varepsilon_r}\right]^2}$$

13

Numerical Modeling: Before "Pull-in"

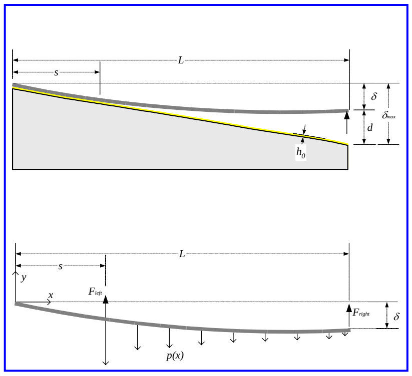
- Numerical Method
  - Modeled as a device with Multiple-beams.
  - Each beam is bent by the electrostatic force.
  - The ODEs are solved simultaneously for each beam
  - Deflection profiles for each beam are given out at different voltages.
  - Actuation force can be calculated.
  - Pull-in voltage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



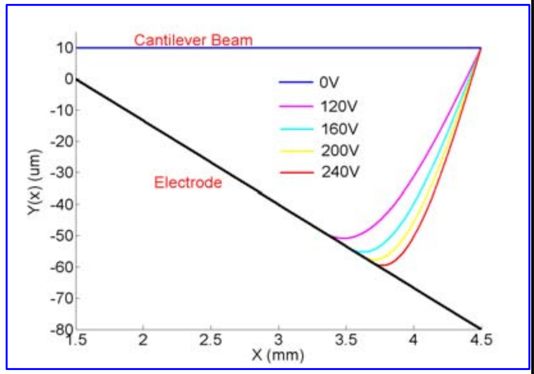
Deflection profiles of the cantilever beam and the starting beam at different voltages when the tip is constrained at zero displacement

14

Numerical Modeling: After "Pull-in"



Model after pull-in

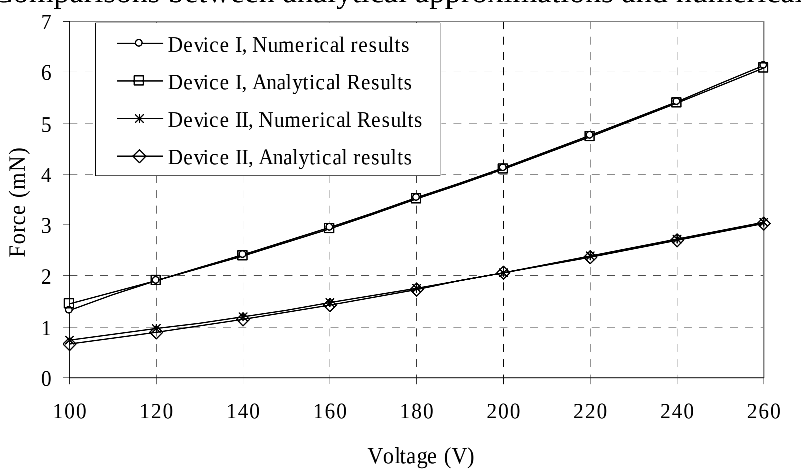


Cantilever Beam Deflection profiles when the tip is constrained at zero displacement(different voltages)

- Beam equation: $EIy''''(x) = p(x) = -\dfrac{\varepsilon_0 b U^2}{2\left[y(x) - c(x) + h_0/\varepsilon_r\right]^2} \qquad s \le x \le L$
- Numerical solutions
  - Eliminate varying B.C by adding parameter $\lambda = 1 - s/L$

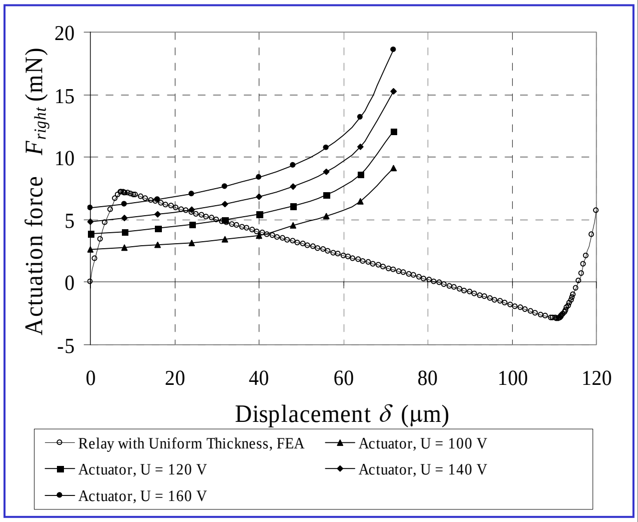
Analytical Modeling: After Pull-in

- Approximation equation: $F_{right} \sim \dfrac{E^{1/4} b}{\sqrt{d}} \left(\dfrac{\varepsilon_0 \varepsilon_r U^2 h}{h_0} \right)^{3/4}$
- 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

17

Contributions

- Design: Starting zone to reduce the pull-in voltage
- Numerical modeling: easier and more accurate
- ***Optimization of the system***
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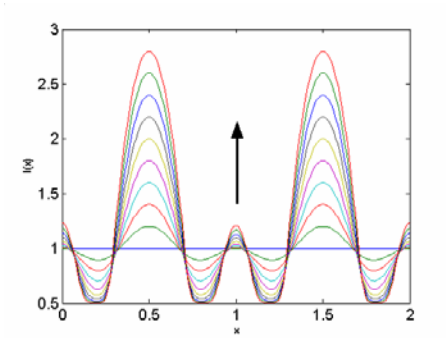
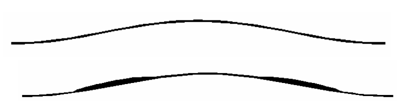
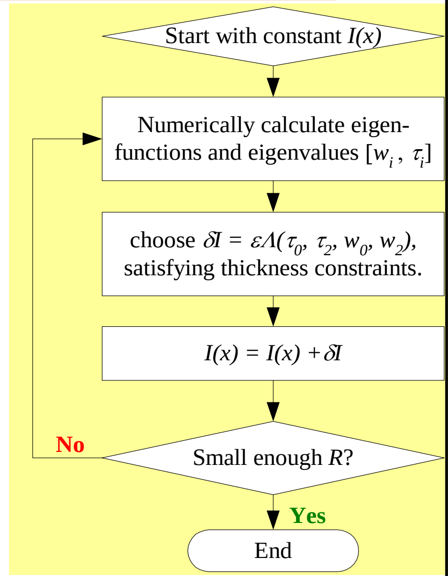
18

Optimization of The Double Beam

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

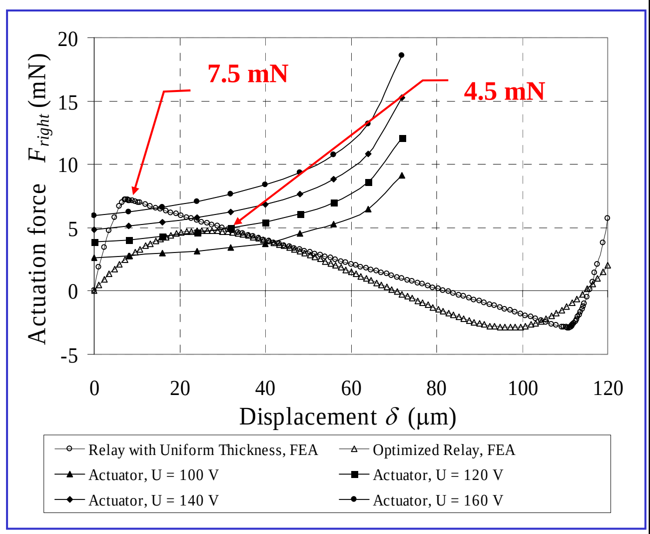






Optimization of The Double Beam (II)

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



Force-Displacement curves of the actuator and the double beam

Contributions

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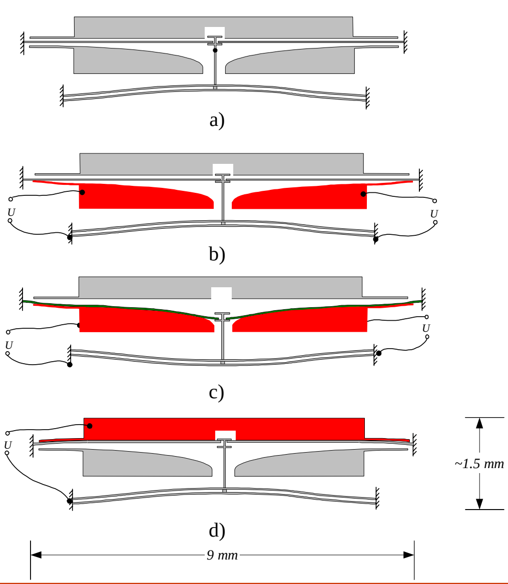
The Relay



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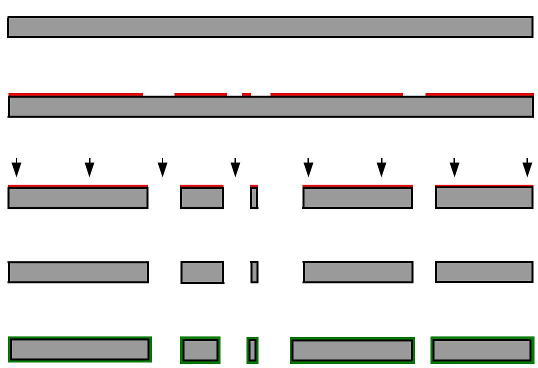
23

Fabrication: Process Flow (1)



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

Spin and pattern 10 μm of photoresist

DRIE etch through

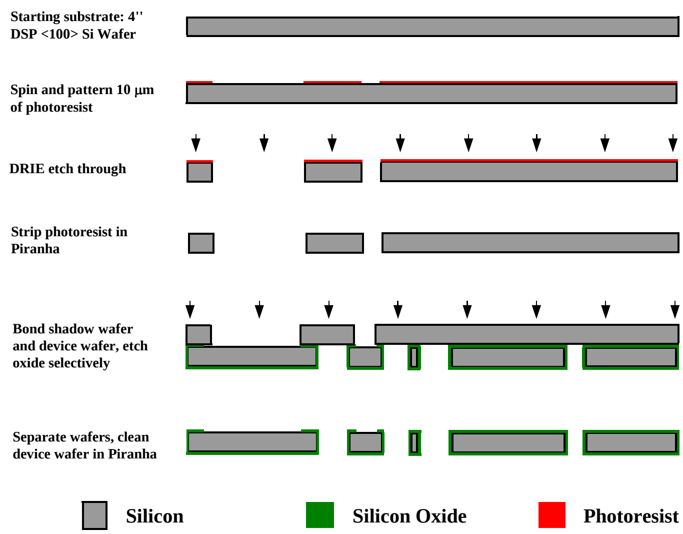
Strip photoresist in Piranha, RCA clean

Grow 0.2 μm of thermal oxide

Silicon **Silicon Oxide** **Photoresist**

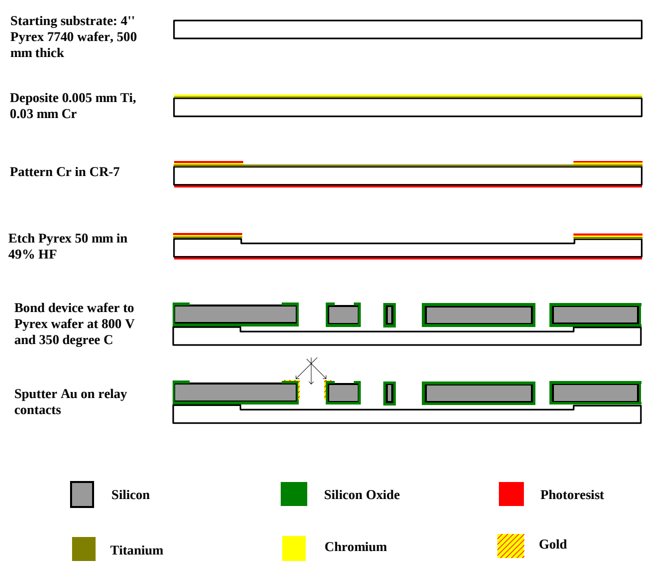
24

Fabrication: Process Flow (2)



25

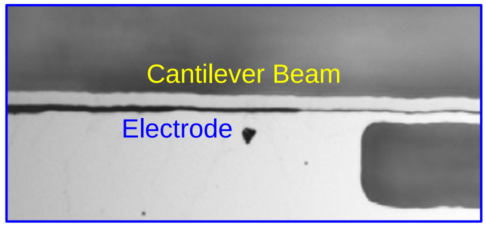
Fabrication: Process Flow (3)



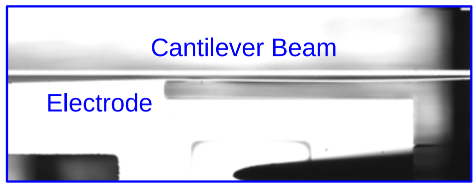
26

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



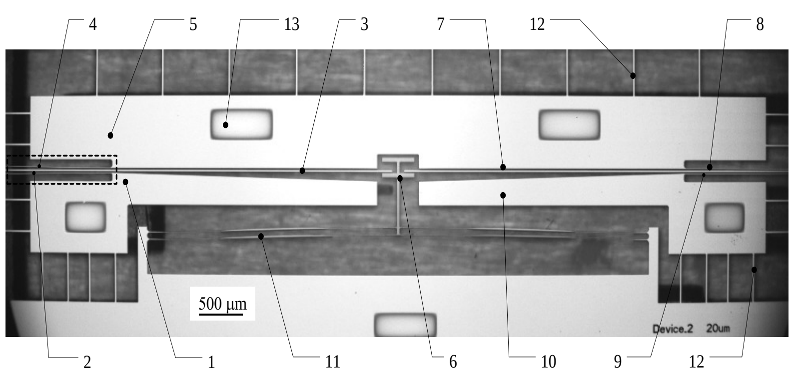
Device made using Transparency Mask



Device made using transparency mask and 10:1 Stepper

27

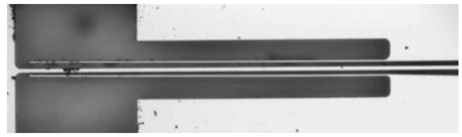
Fabrication Results: Overview



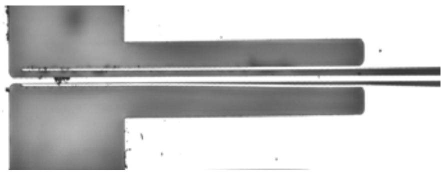
28

Measurement: Pull_in of the Starting Zone

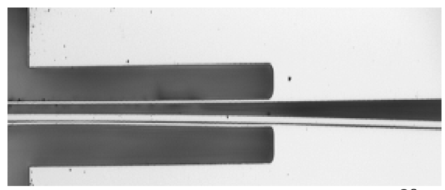
- The starting beam bends up and closes the gap between zipper beam and fixed electrode



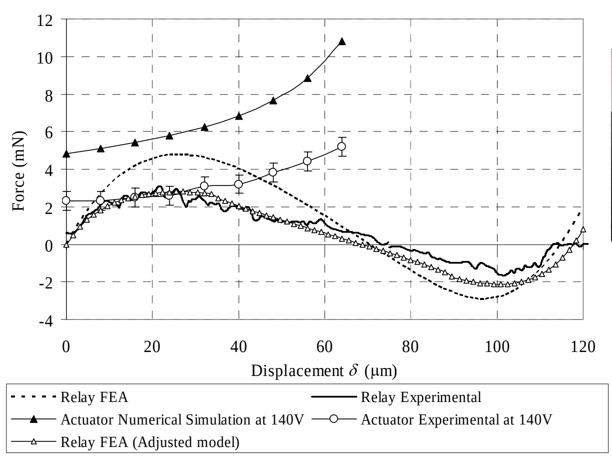
- Pull-in at 75V



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

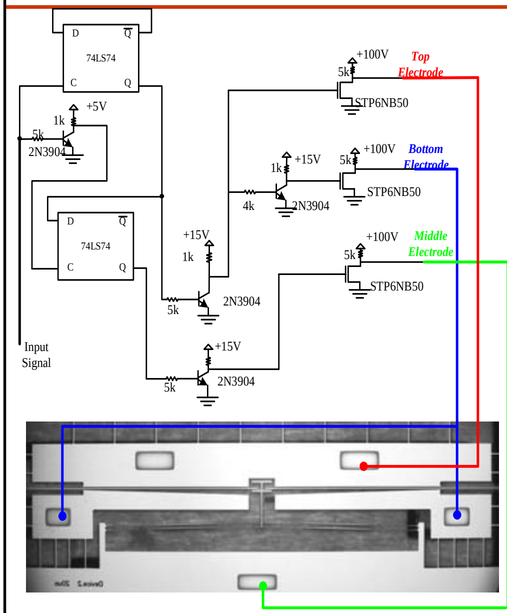


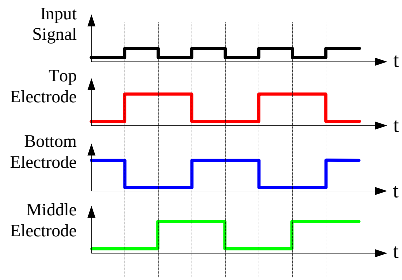
Force Measurement



Flextester

A Bipolar Drive to Avoid Stiction

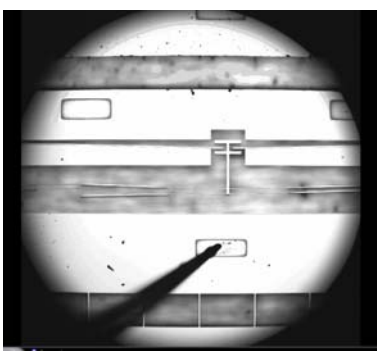




- Change polarity every two actuation cycles

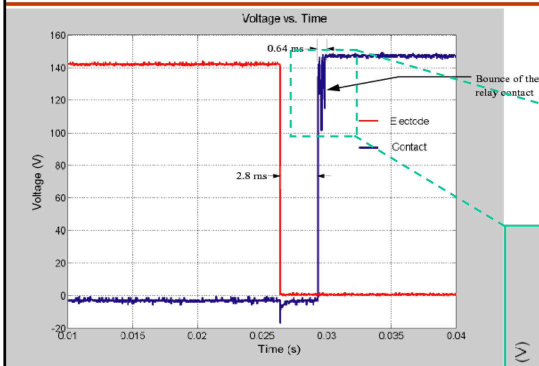
Relay Actuated by Zipping Actuator

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

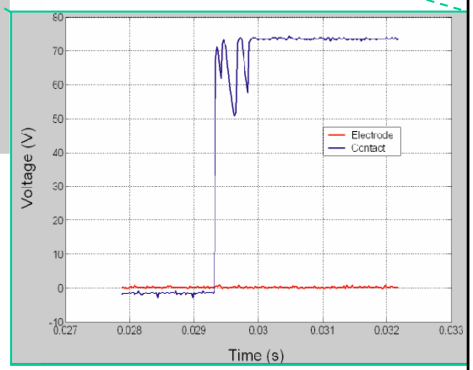


Click for a movie

Switching Time



- Contact bounce time ~ 0.5 ms



- Switching time ~ 3ms

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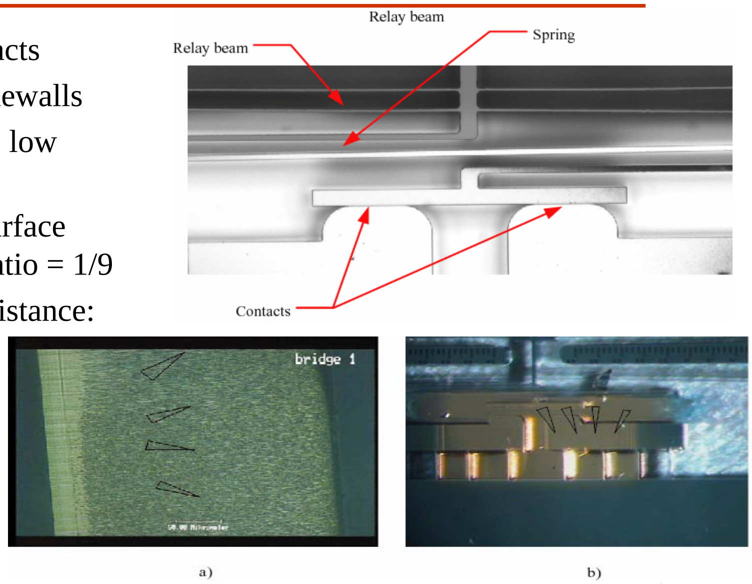
- ***Wet-anisotropically-etched micro relay contact***

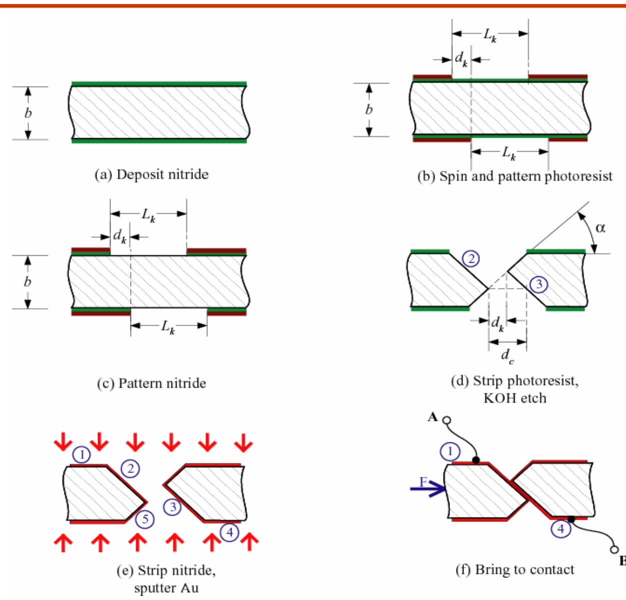
DRIE-etched Relay Contacts

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



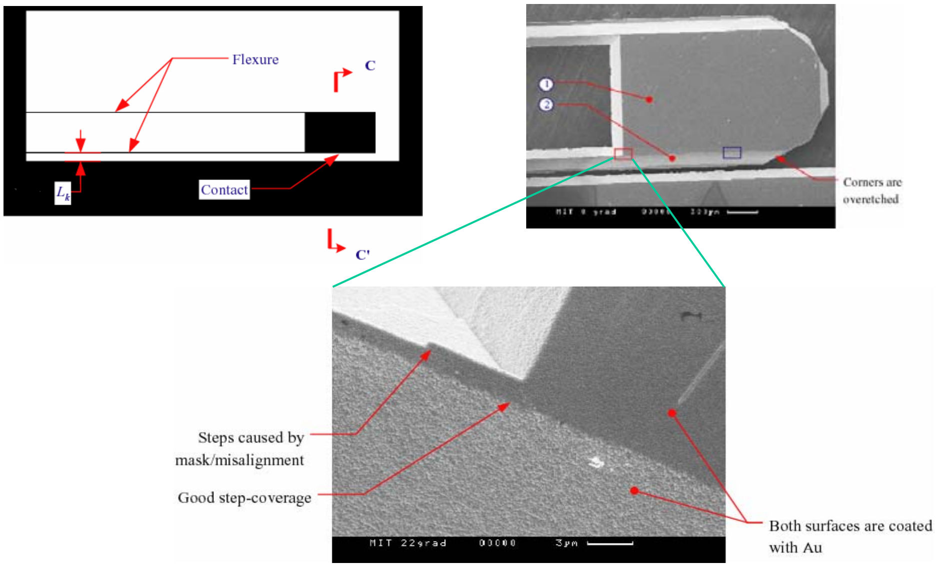
35

KOH-etched Relay Contacts: Design



36

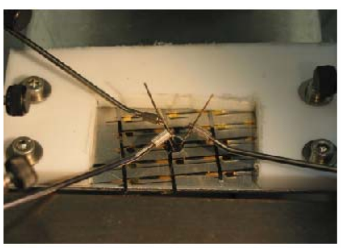
KOH-etched Relay Contacts: Experiments



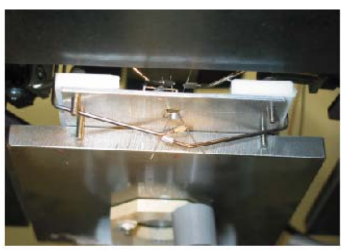
37

KOH-etched Relay Contacts: Tests

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



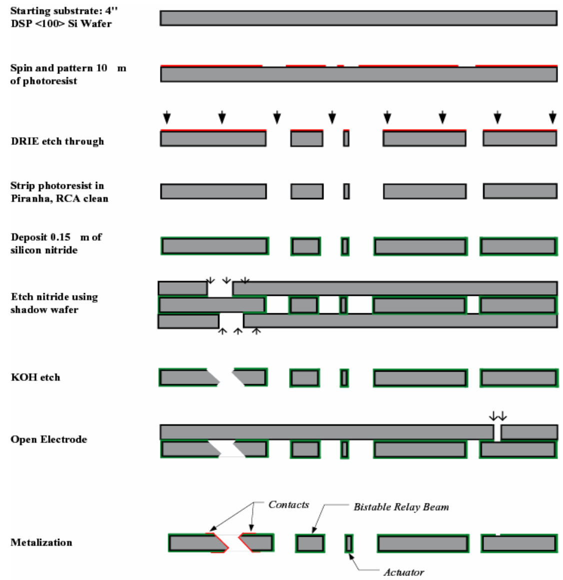
a)



b)

38

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

Acknowledgements

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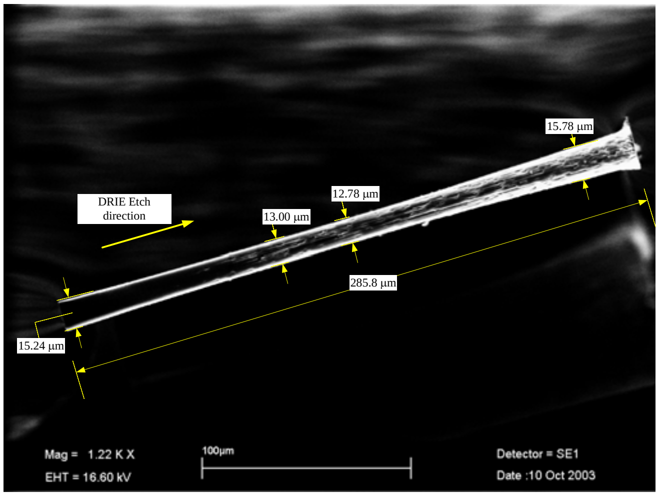
- *Discussion (PERG):* Dr. Jin Qiu, Dr. Joachim Sihler
- *Fabrication (at MTL):* Kurt Broderick, Dennis Ward, Paul Tierney, Linvhu Hol, Dr. Hongwei Sun …
- *Testing (at ABB Research):* Dr. Ralf Struempler, Dr. Sami Kotilainen, Dr. Jan-henning Fabian, Eric Wapelhorst, Jeff Renaud

41

42

Actuator Beam Profile



Optimization: Algorithm (1)

- Beam equation:

$$(E\,I\,w'')''+T\,w''=0$$

$$(E\,I\,\delta w_i'')''+T_i\,\delta w_i''=-\,\delta T_i\,w_i''-(E\,\delta I\,w_i'')''$$

- Fredholm alternative:

$$\int\left(\delta T_i\,w_i''+(E\,\delta I\,w_i'')''\right)w_i\,dx=0$$

$$\delta T_i=-\frac{\int w_i\,(E\,\delta I\,w_i'')''\,dx}{\int w_i''\,w_i\,dx} \qquad \delta T_i=E\,\frac{\int \delta I\,(w_i'')^2\,dx}{\int (w_i')^2\,dx}$$

- Cost function variation:

$$\delta C(\{T_i\})=\int \delta I\left[\sum_{i=1}^{\infty}\frac{dC}{dT_i}\frac{(w_i'')^2}{\int (w_i')^2}\right]=\int \delta I\,\Lambda(T_i,w_i)$$

Optimization: Algorithm (2)

- Beam equation:

$$(E\,I\,(w-w_0)'')''+\tau^2\,w''=f\,\delta(x-L/2)$$

- Transition state

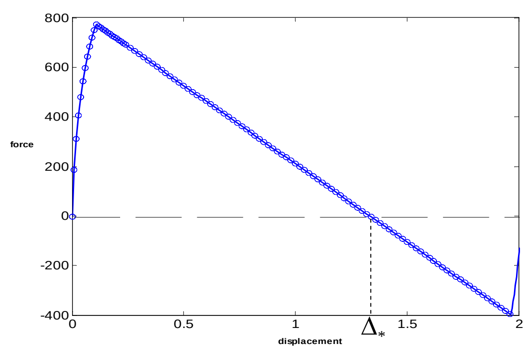
$$w_t=\Gamma\,w_0(x)+A\,w_n$$

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

$$\Delta_*=1-\Gamma$$

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

$$=\frac{(\tau_2/\tau_0)^2}{2-(\tau_2/\tau_0)^2}$$

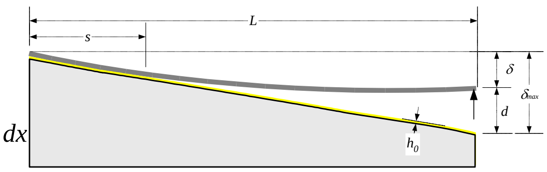


Analytical Analysis (1)

- Beam equation:

$$EI\bar{y}''''(x) = p(x) = -\frac{\Gamma}{\left[\bar{y}(x)+\beta\right]^2} \Rightarrow$$

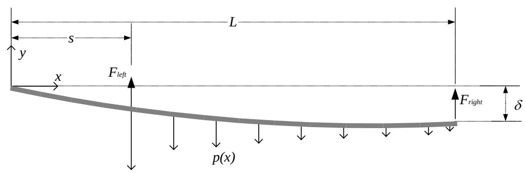
$$\Rightarrow \begin{cases} F_{left} = \frac{1}{L-s}\cdot\int_s^L -p(x)\cdot\left[(L-s)-x\right]dx \\ F_{right} = \frac{1}{L-s}\cdot\int_s^L p(x)\cdot(x-s)dx \end{cases}$$



- Near $x = s$

$$\bar{y}(x) = -\frac{\Gamma}{24EI\beta^2}(x-s)^4 + A(x-s)^3$$

$$\Rightarrow F_{left} = EI\bar{y}'''(s) = 6EIA$$



Analytical Analysis (2)

- Assume most of the force comes from s<x<x*

$$\begin{cases} F_{left} \sim \frac{1}{L-s}\cdot\int_s^{x^*}\frac{\Gamma}{\beta^2}\cdot\left[(L-s)-x\right]dx \sim \frac{\Gamma(x^*-s)}{\beta^2} \\ F_{right} \sim \frac{1}{L-s}\cdot\int_s^{x^*} p(x)\cdot(x-s)dx = \frac{\Gamma}{\beta^2}\frac{(x^*-s)^2}{L-s} \end{cases}$$

$$\left.\begin{array}{l} \beta = \bar{y}(x^*) = A\cdot(x^*-s)^3 - \frac{\Gamma}{24EI\beta^2}(x^*-s)^4 \\ F_{left} = 6EIA \end{array}\right\} \Rightarrow \left.\begin{array}{l} \beta \sim \frac{F_{left}}{6EI}\cdot(x^*-s)^3 - \frac{\Gamma}{24EI\beta^2}(x^*-s)^4 \\ F_{left} \sim \frac{\Gamma(x^*-s)}{\beta^2} \end{array}\right\} \Rightarrow$$

$$\Rightarrow \left.\begin{array}{l} (x^*-s) \sim \left(\frac{EI\beta^3}{\Gamma}\right)^{1/4} \\ F_{right} \sim \frac{\Gamma}{\beta^2}\frac{(x^*-s)^2}{L-s} \end{array}\right\} \Rightarrow F_{right} \sim \frac{1}{L-s}\sqrt{\frac{EI\Gamma}{\beta}}$$

Analytical Analysis (3)

- Far from $x = s$

$$\bar{y}(x) = B(x-s)^2 \Rightarrow \left.\begin{array}{l} B \sim \dfrac{\Gamma}{2EI\beta^2}\left(x^* - s\right)^2 \\ (x^* - s) \sim \left(\dfrac{EI\beta^3}{\Gamma}\right)^{1/4} \end{array}\right\} \Rightarrow \left.\begin{array}{l} B \sim \sqrt{\dfrac{\Gamma}{EI\beta}} \\ d = B(L-s)^2 \end{array}\right\} \Rightarrow$$

$$\Rightarrow \left.\begin{array}{l} L - s \sim \left(\dfrac{EI\beta}{\Gamma}\right)^{1/4}\sqrt{d} \\ F_{right} \sim \dfrac{1}{L-s}\sqrt{\dfrac{EI\Gamma}{\beta}} \end{array}\right\} \Rightarrow F_{right} \sim \frac{1}{\sqrt{d}}(EI)^{1/4}\left(\frac{\Gamma}{\beta}\right)^{3/4} \Rightarrow F_{right} \sim \frac{E^{1/4}b}{\sqrt{d}}\left(\frac{\varepsilon_0\varepsilon_r U^2 h}{h_0}\right)^{3/4}$$

Analytical Analysis (4)