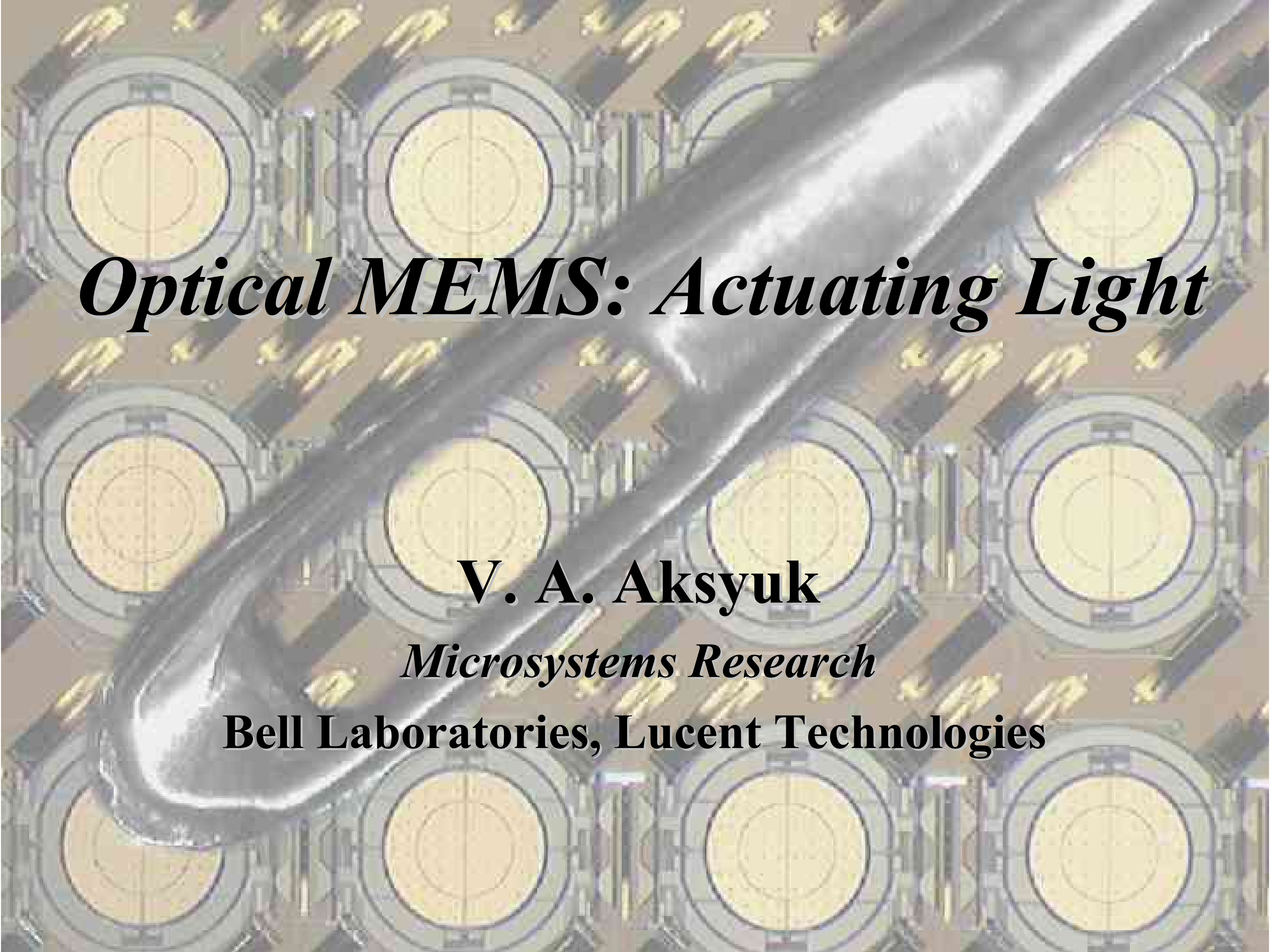


Optical MEMS: Actuating Light

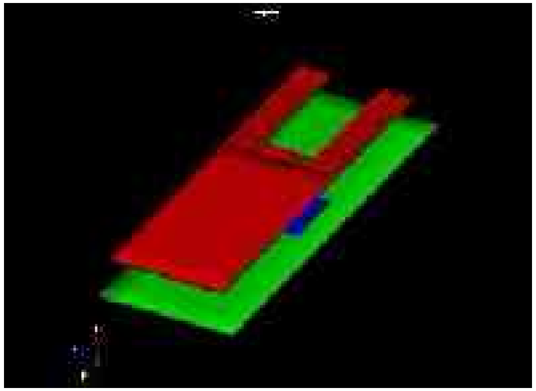
V. A. Aksyuk

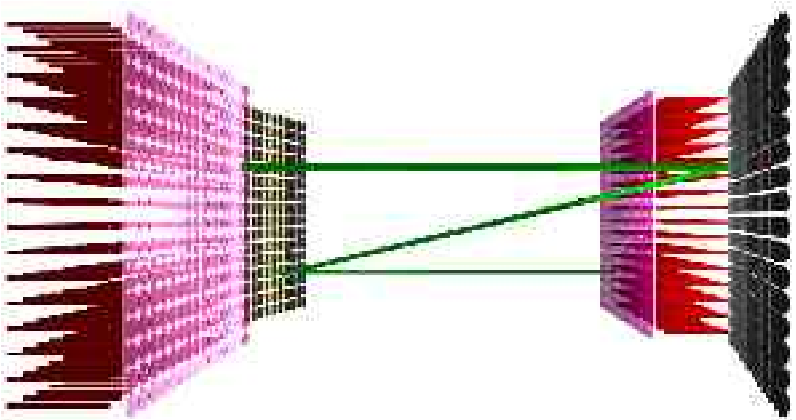
Microsystems Research

Bell Laboratories, Lucent Technologies

Optical MEMS for Telecom:

- Quality optical elements
- Precision positioning actuators
- Moderate speed
- High reliability





- Large number of elements
- High integration density

Key design features:

<u>compliant mechanisms</u>, <u>electrostatics</u>, <u>stress engineering</u>

Nonlinear Effects - Numerical Modeling

Electrostatic Actuation

- *no heat dissipation*
- localized fields (good conductors) - *no crosstalk*
- *no special materials* - wide range of fabrication processes

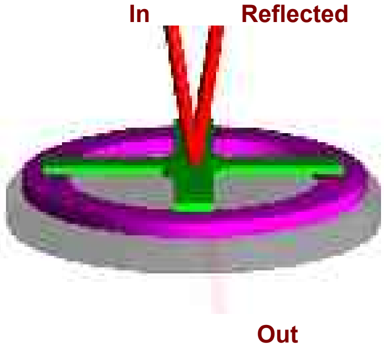
Excellent for ***densely integrating multiple actuators*** for optical applications!

Challenge:

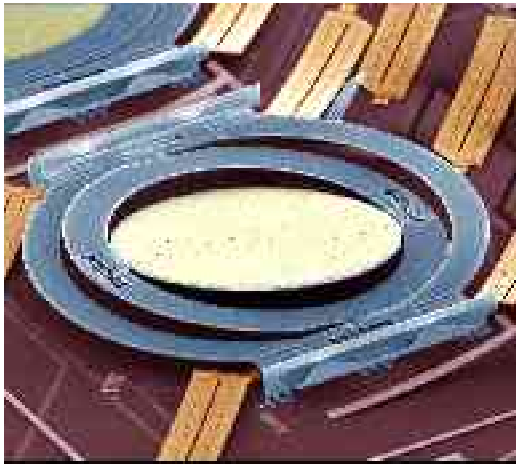
- effective designs with *nonlinear* electrostatic force
- achieving *large amplitude* with low voltage

Compliant Mechanisms

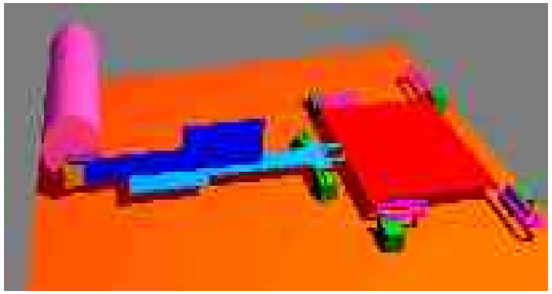
MARS



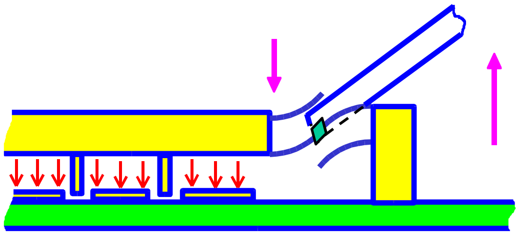
Microstar™ Micromirror



<u>Pure flexure</u>:
no mechanical contact
during operation

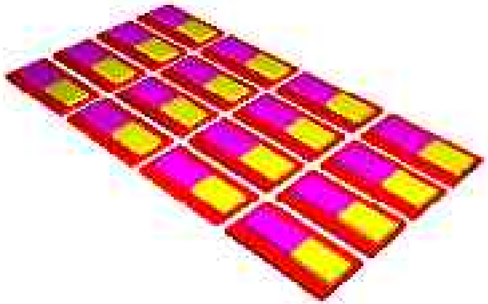


Flag switch / attenuator



<u>Static contact under load</u>:
possible stiction,
no wear

Scratch Drive

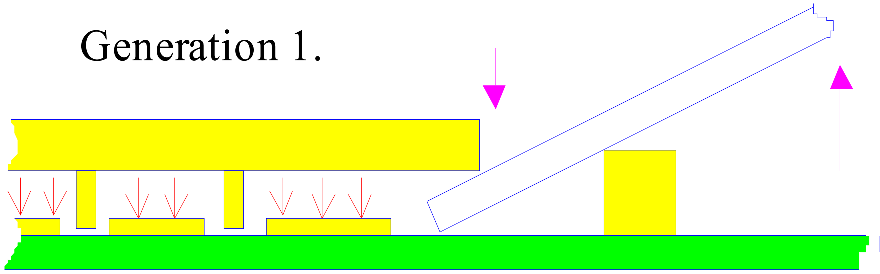


Gears

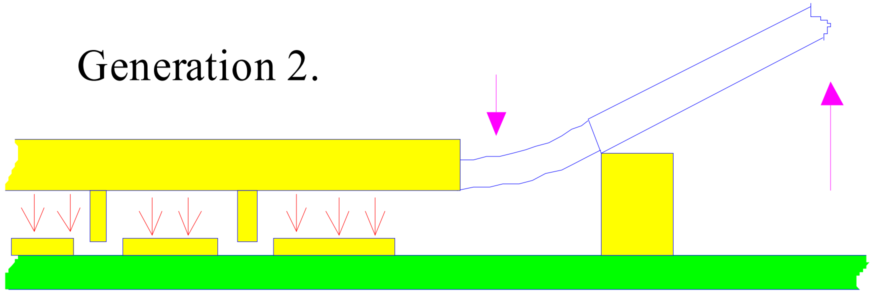
<u>Sliding contact under load</u>:
susceptible to friction,
stiction and wear

Flag switch details.

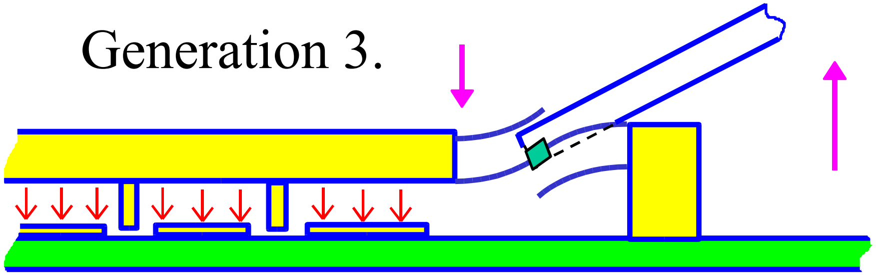
Generation 1.

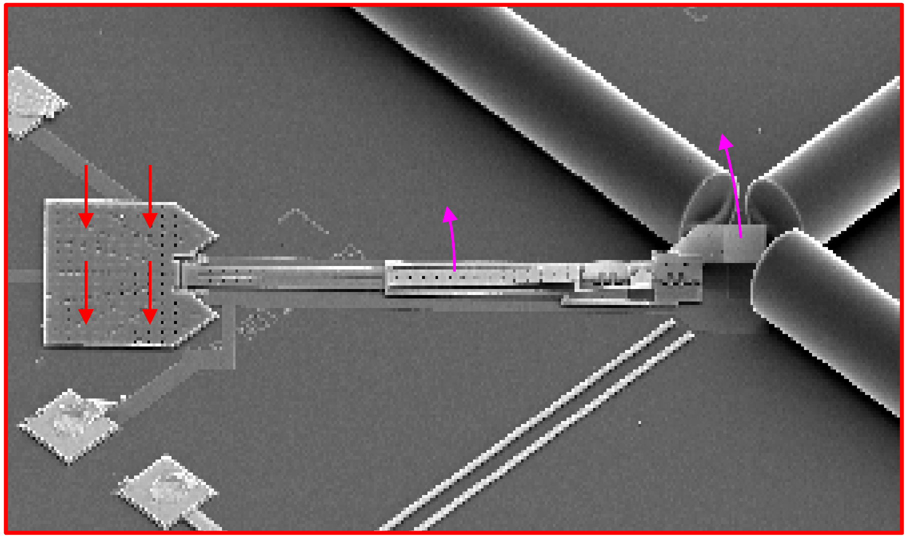


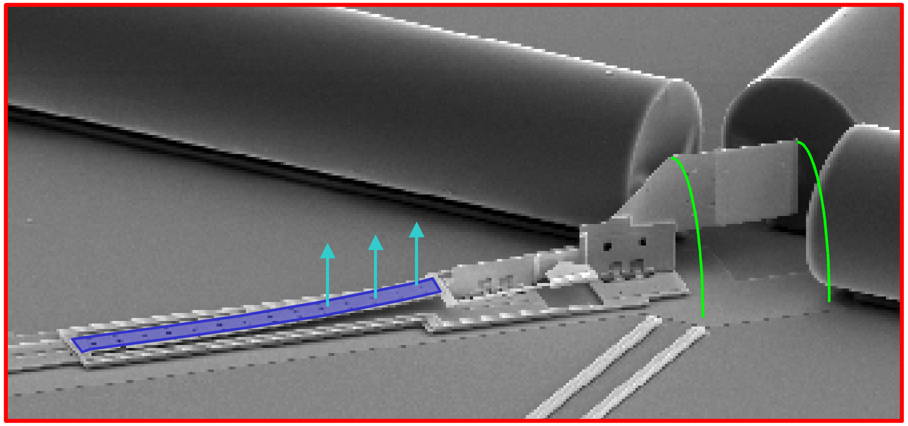
Generation 2.



Generation 3.







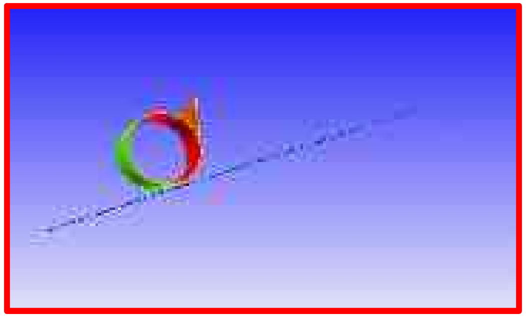
Stress Engineering

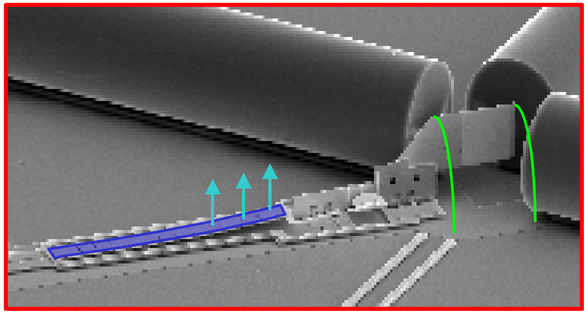
Avoid or relieve: elastic elements

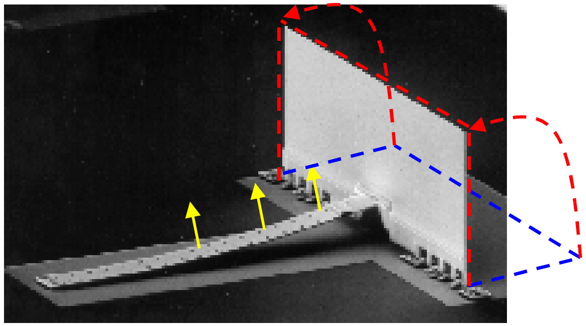
Use: nonlinear elastic elements

Create:

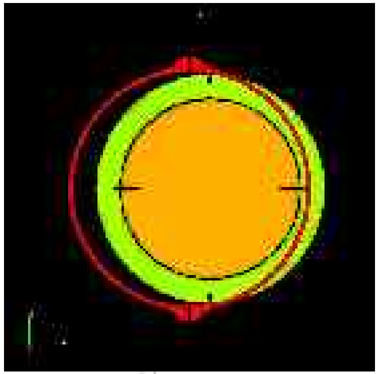
- **use residual stress energy to power mechanical *action*, e.g. self-assembly**
- **use residual stress to achieve desired element *shape***

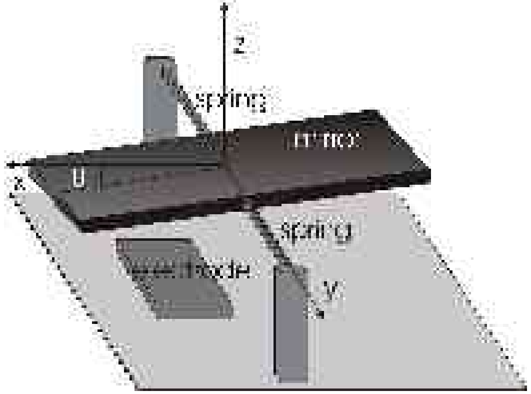


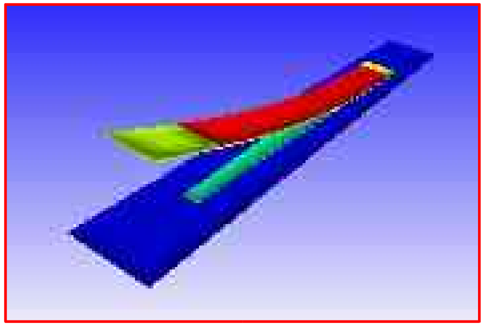




Electrostatic and Mechanical Nonlinearities







<u>Avoid</u>, better design (or an easy way out):

- strain-relieved mechanical elements
- comb drives

<u>Use</u> and control:

- majority of electrostatic actuators

<u>Create</u>:

- nonlinear spring elements
- bi-stable actuators

Effective *analysis techniques* are key
***Numerical tools* are essential**

Numerical Modeling

Electrostatics:

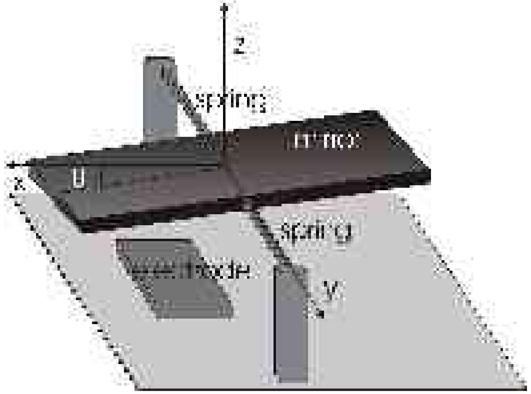
- weakly coupled problems, e.g. 2-axis mirror
- strongly coupled problems, e.g. Party Favor actuator

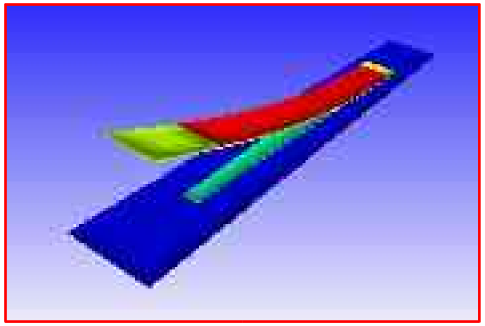
Mechanics:

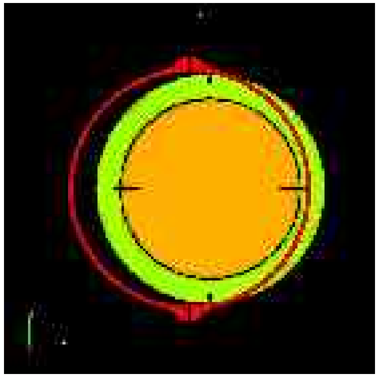
- residual stress and buckling prediction and avoidance, strain-relieving suspension design
- cases involving mechanical contact

Analytical solutions for linear problems

Numerical analysis to check analytical calculations or tackle nonlinear problems







Examples

Key design features:
- *compliant mechanisms*
- *electrostatics*
- *stress engineering*

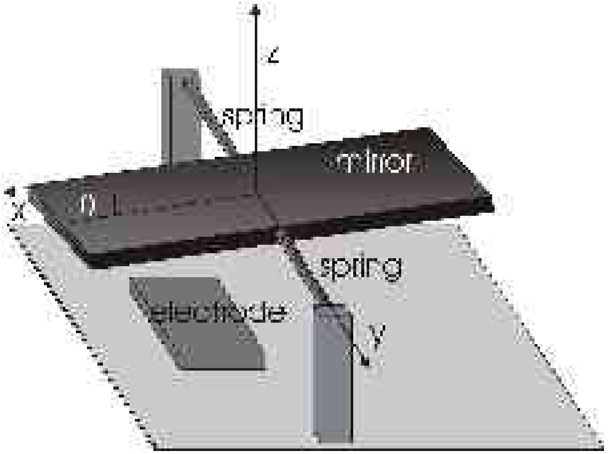
Nonlinear effects
Numerical modeling

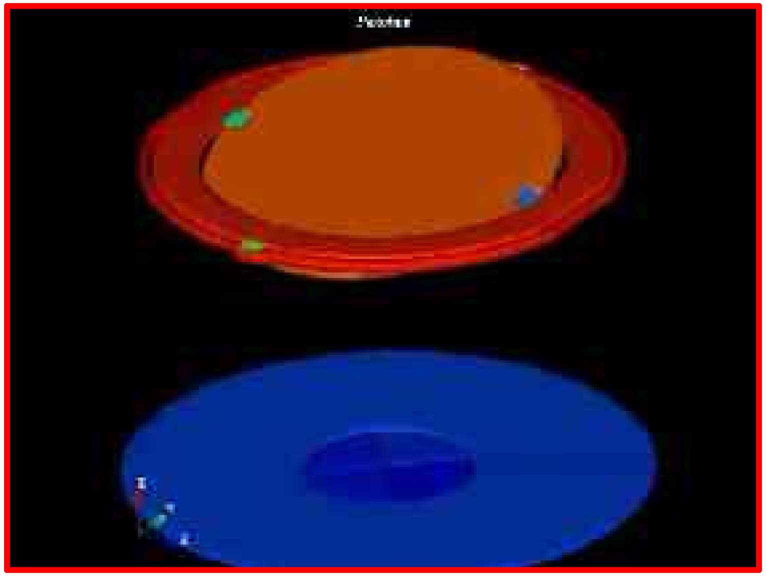
- **Beam-steering mirror:**
  - **electromechanical modeling**
- **Mirror springs:**
  - **residual stress effect**
  - **numerical technique for buckling prediction**
- **Double Hinge Mirror:**
  - **lever amplification, transmission mechanisms**
- **Self-assembly:**
  - **creative use of residual stress**
- **Party Favor tilting mirror:**
  - **residual stress engineering**
  - **zip-lock actuation with mechanical contact**
- **Bi-stable vertical actuator:**
  - **large-stress geometric plate nonlinearity**

Beam-Steering Micromirror Design

Design parameters:

- **Electrode size and shape**
- **Gap size**
- **Spring and gimbal geometry**
- Mirror thickness

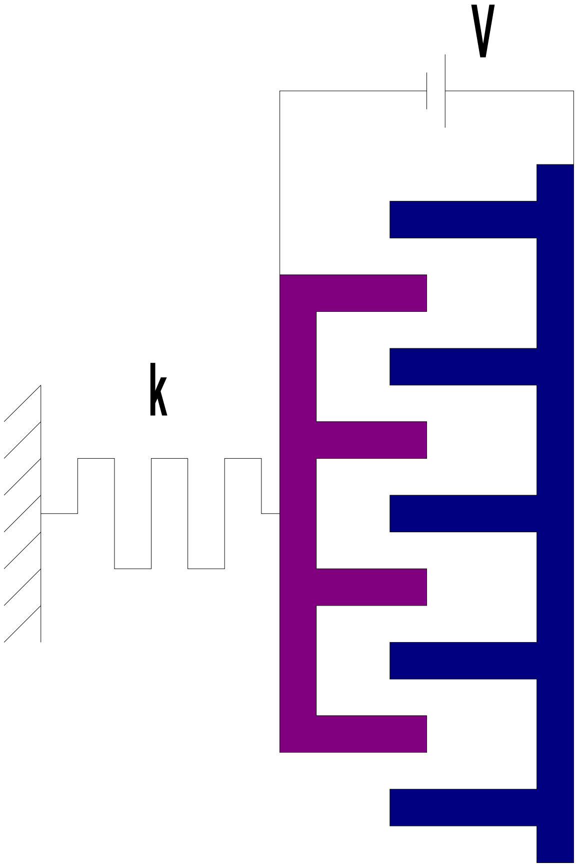




Device characteristics:

- **Angular range**
- **Mirror size**
- Mirror shape - flatness
- Integration density - fill factor - **no crosstalk**
- **Spring stiffness** - speed - vibration sensitivity
- **Drive voltage**, **angle vs. V curve** - control
- Stability and repeatability
- Reliability

Electrostatic Actuator, 1 degree of freedoom



$$E_{elec}(x)=C(x)\frac{V^2}{2}; \quad F_{elec}=\frac{dE(x)}{dx}$$

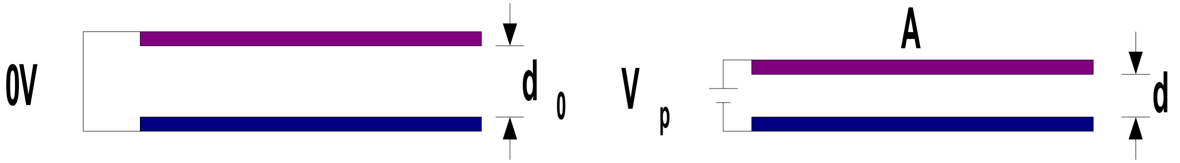
$$F_{elec}=\frac{V^2}{2}\frac{dC(x)}{dx} \qquad F_{mech}=k_{mech}\,x$$

$$k_{elec}=\frac{dF_{elec}}{dx}=\frac{V^2}{2}\frac{d^2C(x)}{dx^2}$$

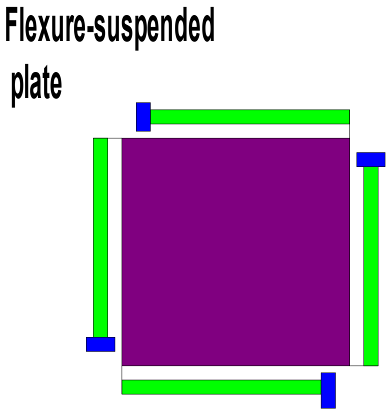
$$f_{res}=\frac{1}{2n}\sqrt{\frac{k_{total}}{m}}; \quad k_{total}=k_{elec}+k_{mech}$$

C	**comb capacitance**
k	**spring constant**
x	**deflection**

Parallel-Plate Electrostatic Actuation



d_0	**undeflected spacing**
d	**deflected spacing**
A	**plate area**
k	**spring constant**
E	**mod. of elasticity**
N	**no. cantilevers**
w	**cantilever width**
t	**cantilever thickness**
l	**cantilever length**



Polysilicon:
E=169GPa
ν=0.22

$$F_{cantilever} = k_{mech}\left(d_0 - d\right)$$

$$C(d) = \frac{\varepsilon r_0 A}{d};\; F_{electrostatic} = \frac{Vr^2}{2}\,\frac{\varepsilon r_0 A}{d\,r^2};\; k\,r_{elec} = -V^2\,\frac{\varepsilon r_0 A}{dr^3}$$

$$F_{mech} = F_{electrostatic}\;;$$

$$k_{mech}\left(d_0 - d\right) = -\frac{1}{2}k_{elec}\;d$$

Unstable if:

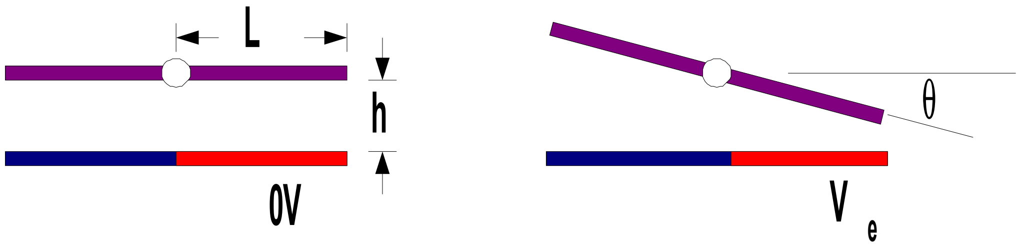
$$k_{total} = k_{mech} + k_{elec} \le 0$$

Snap down:

$$V_{pull-in} = \sqrt{8k_{mech}\,d_0^3/27\varepsilon_0 A}$$

$$d = {}^2\!/_3\,d_0$$

Torsional Electrostatic Actuation



$$T_{electrostatic}=\frac{\varepsilon}{2}V^2W\int_0^L\frac{x\,dx}{\left(\frac{h}{\sin\theta}-x\right)^2\theta^2}$$

$$T_{electrostatic}=\frac{\varepsilon V^2W}{4\theta^2}\left\{\frac{L\sin\theta}{h-L\sin\theta}+\ln\left(1-\frac{L}{h}\sin\theta\right)\right\}$$

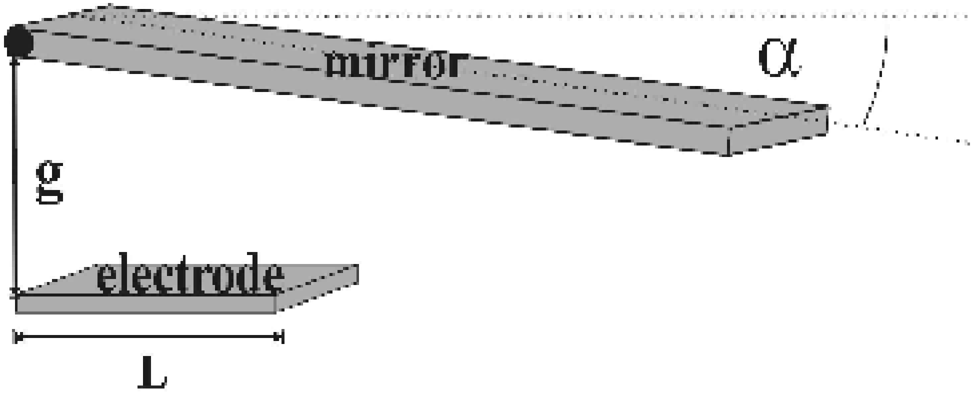
$$T_{mechanical}=\theta\cdot 2\,G\,\frac{wt^3}{3l}\left\{1-\frac{192t}{\pi^5 w}\tanh\left(\frac{\pi w}{2t}\right)\right\}$$

(two torsional hinges)

h	**height**
θ	**deflection angle**
V_e	**electrode voltage**
W	**plate width**
L	**plate half-length**
w	**torsion bar width**
t	**torsion bar thickness**
l	**torsion bar length**
G	**mod. of elasticity**

Analytical

Disregard Fringe Effects



$$T_{electrostatic} = \frac{\varepsilon}{2} V^2 \int_0^L \frac{xW(x)\,dx}{\left(\frac{g}{\sin\alpha} - x\right)^2 \alpha^2}$$

Capacitance, $C(\alpha, L, g) = L\,F(L\tan(\alpha)/g)/g$

Torque, $T = V^2/2\; dC/d\alpha \sim (L/g)^2\; dF/d\alpha$

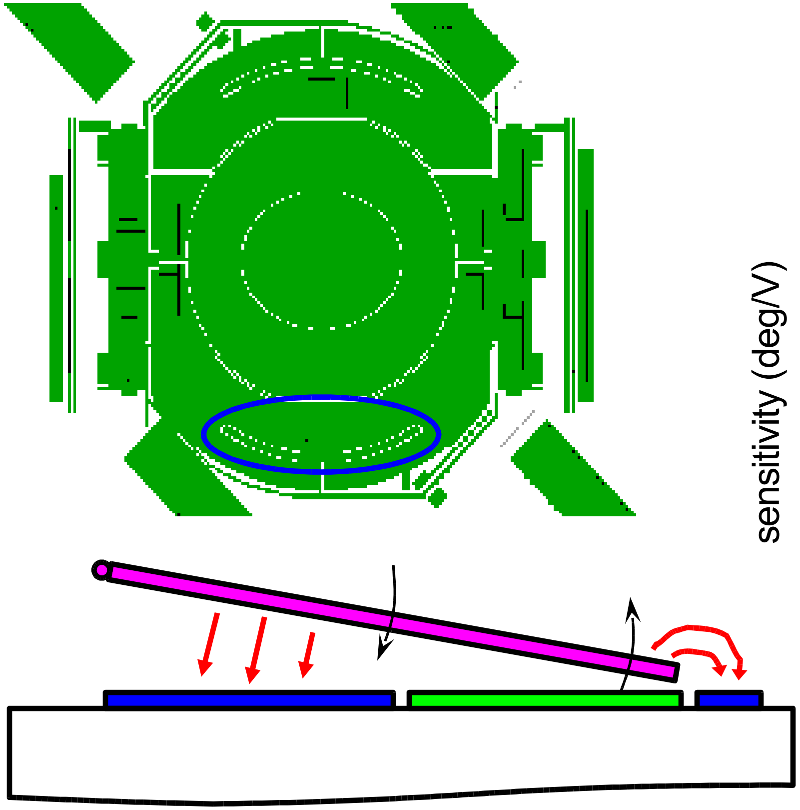
snap-down angle, α_{sd} scales as g/L

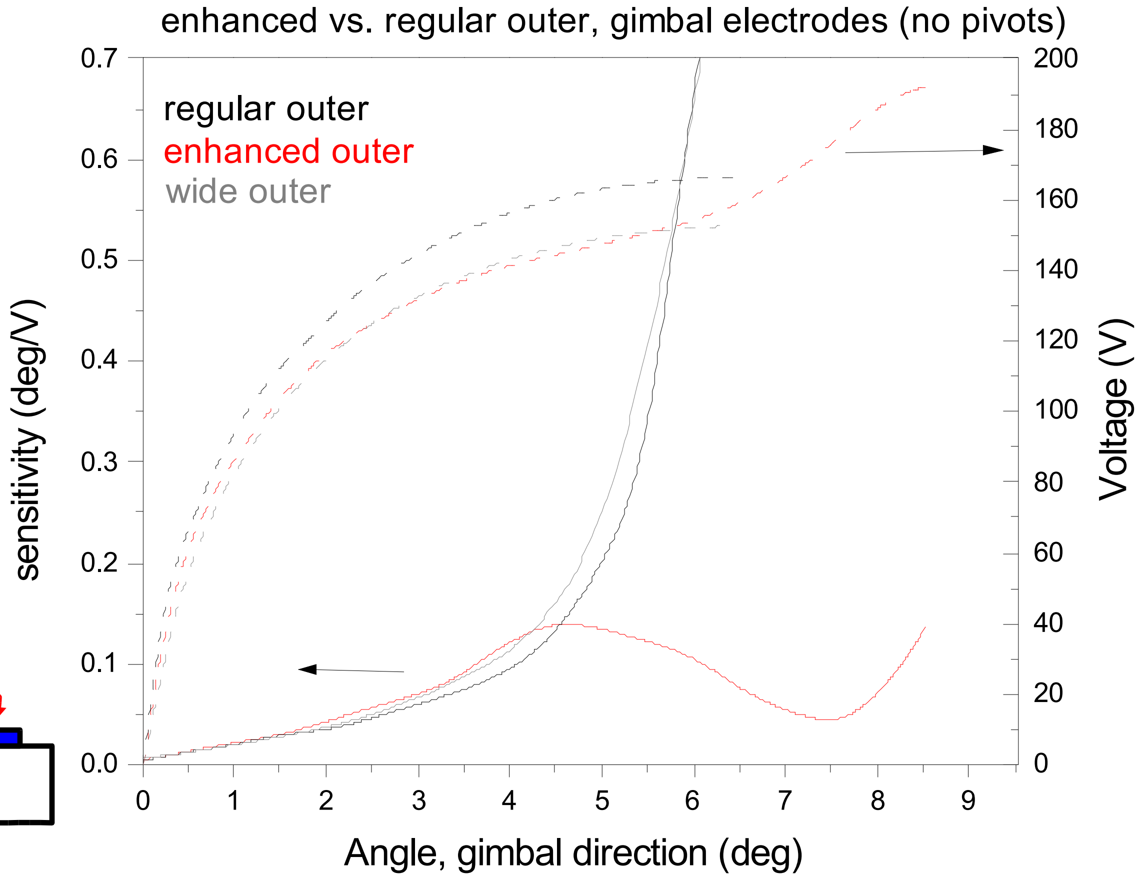
As long as *g* << *L*, works for arbitrary electrode shape.

Analytical solution can be obtained for more than 1 DOF.

Does not work if edge effects are important, e.g.*g~L.*

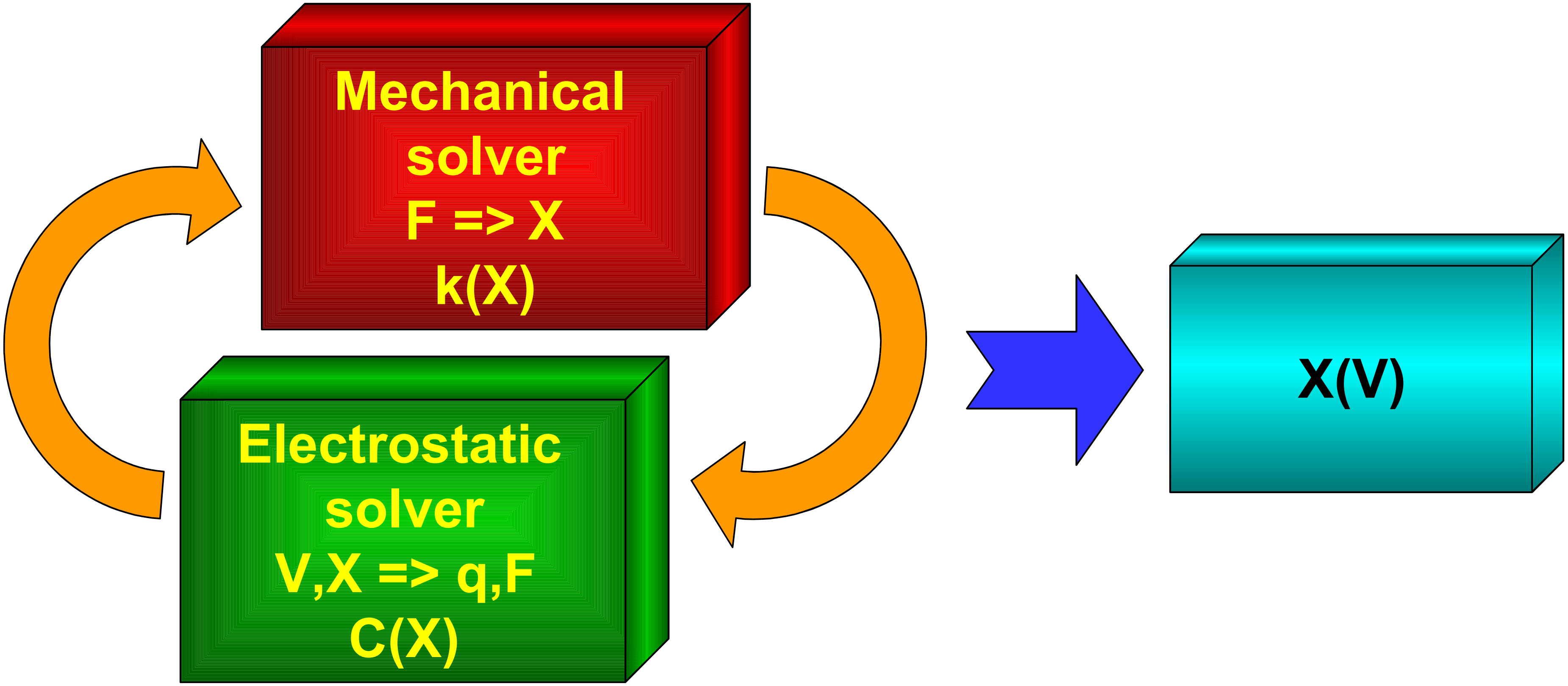
Enhanced Range Electrode Layout





Increased angular range is obtained by using extra electrodes.

Numerical Techniques: Iterative Solver



Mechanical solver
F => X
k(X)

Electrostatic solver
V,X => q,F
C(X)

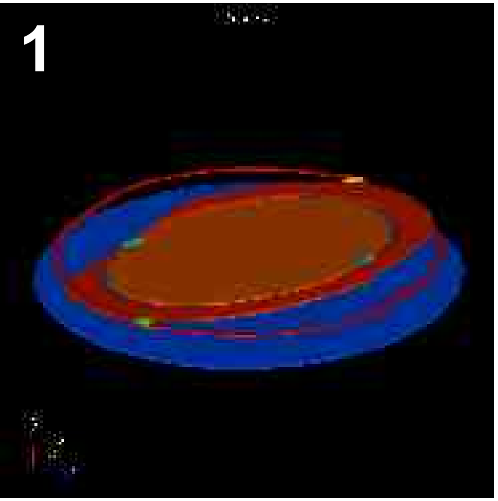
X(V)

Exact calculations of mechanically deforming conductors

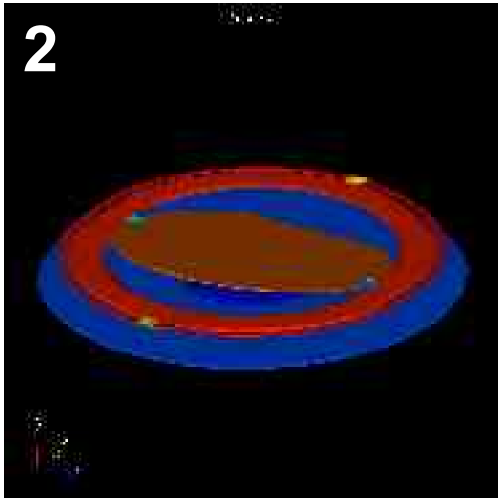
~ 10 cycles per device position, very time consuming for multiple trajectories.

Do we really need coupled analysis?

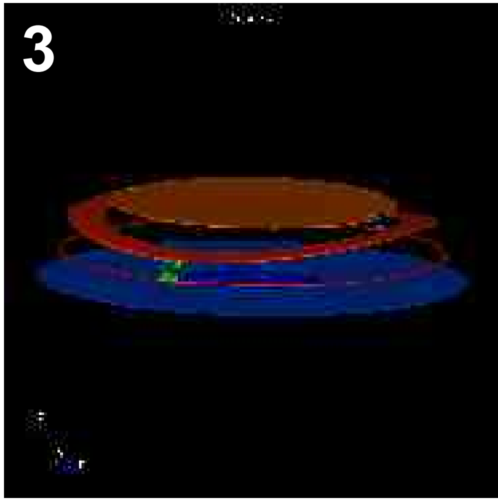
1



2

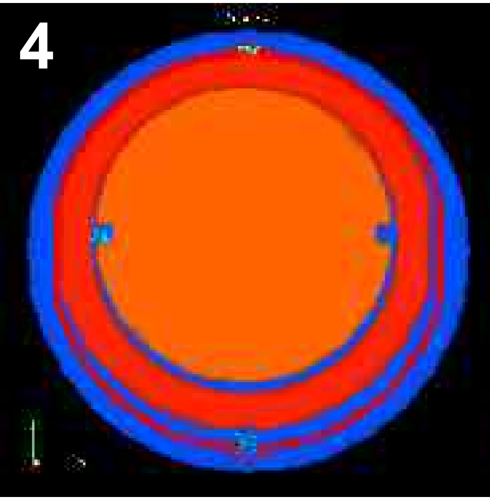


3

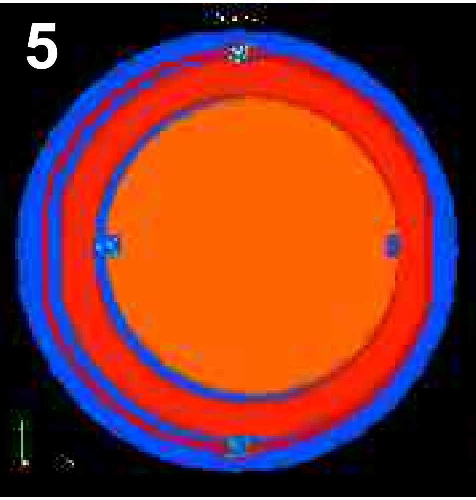


- This mirror moves as a collection of rigid bodies attached by springs
- Springs do not contribute to electrostatic force

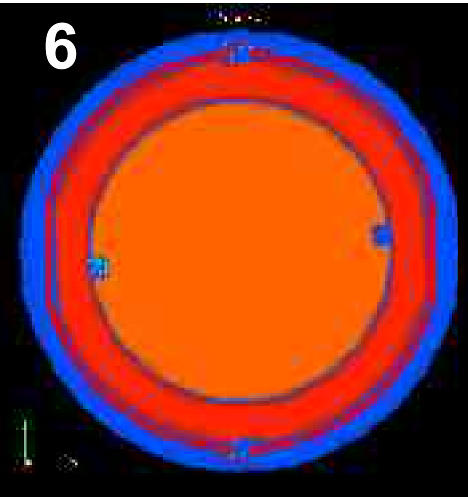
4



5



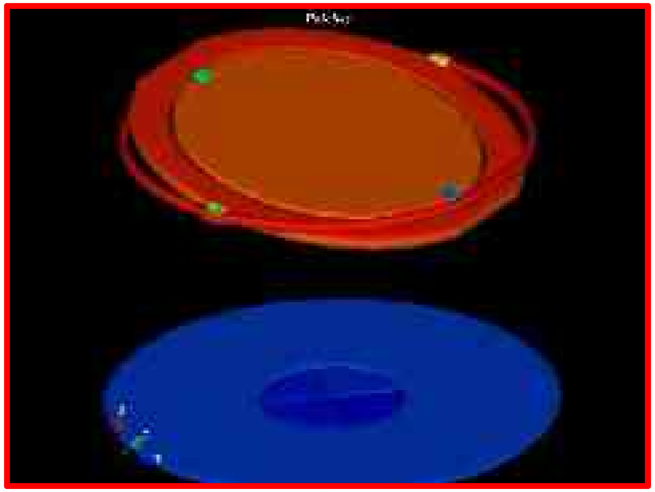
6



7

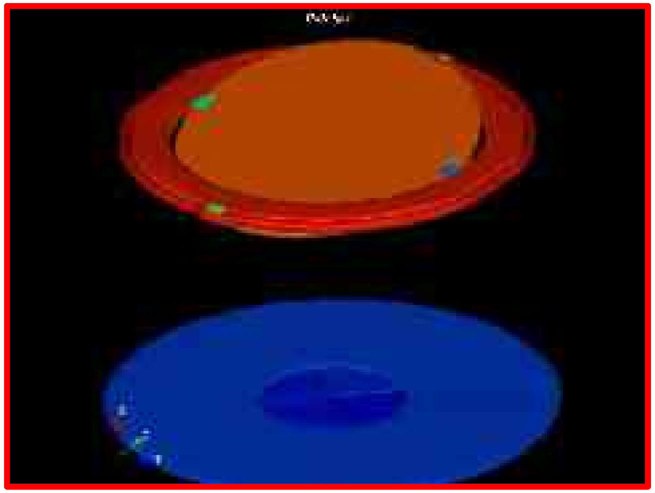
Mirror Moves As Solid Body

Tilts are the important DOF



Θ_x

Θ_y



Mechanics: $\vec{F} = \hat{K}(\vec{x}) \cdot \vec{x}$

Electrostatics: $E = \frac{1}{2} V_i V_j C_{ij}(\vec{x})$

Force or torque: $\vec{F} = \nabla E(\vec{x})$

Equilibrium:

$$\hat{K}(\vec{x}) \cdot \vec{x} = \frac{V_i V_j}{2} \nabla C_{ij}(\vec{x})$$

E.g. 1D tilt case: $\tau\theta = -\frac{1}{2} V^2 \frac{dC(\theta)}{d\theta}$

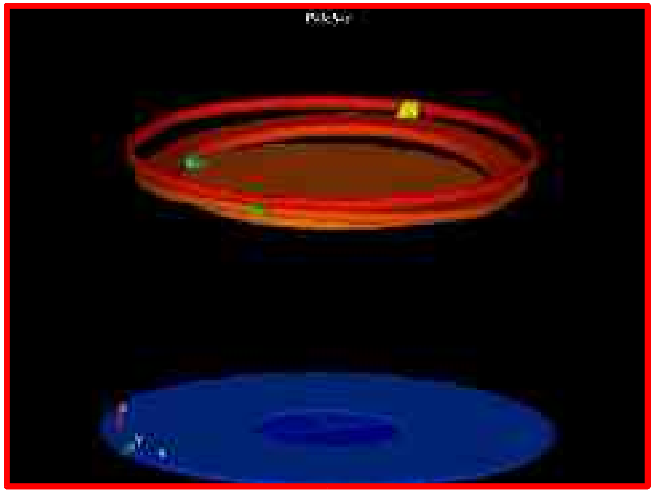
No need to iterate:

- **calculate τ once (Mechanical solver)**
- **calculate $C(\theta)$ for all θ once (Electrostatic solver)**
- **calculate $V(\theta)$ using the above equation**

Works for two tilt angles and voltages as well.

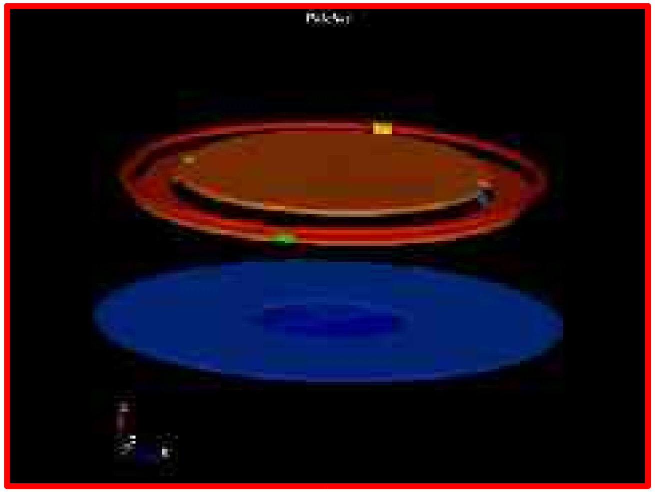
More DOF - NO PROBLEM

Treat Z sag as perturbation



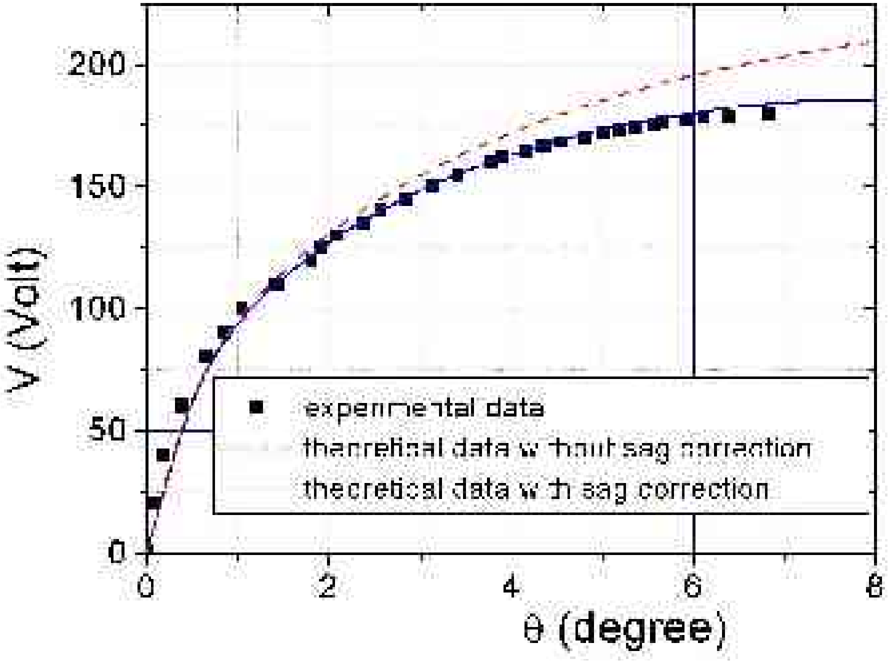
$z_m + z_g$

$z_m - z_g$



$$\boxed{\hat{K}(\vec{x})\cdot\vec{x} = \frac{V_i V_j}{2}\nabla C_{ij}(\vec{x})}$$

1. **Calculate** $V_0(\theta, z=0)$ **as before**
2. **Calculate** $z_1(\theta, V_0)$ **solving the same equation**
3. **Calculate new voltage** $V_1(\theta, z_1(\theta))$
4. **Iterate 2, 3**



Linear Elastic Element Design

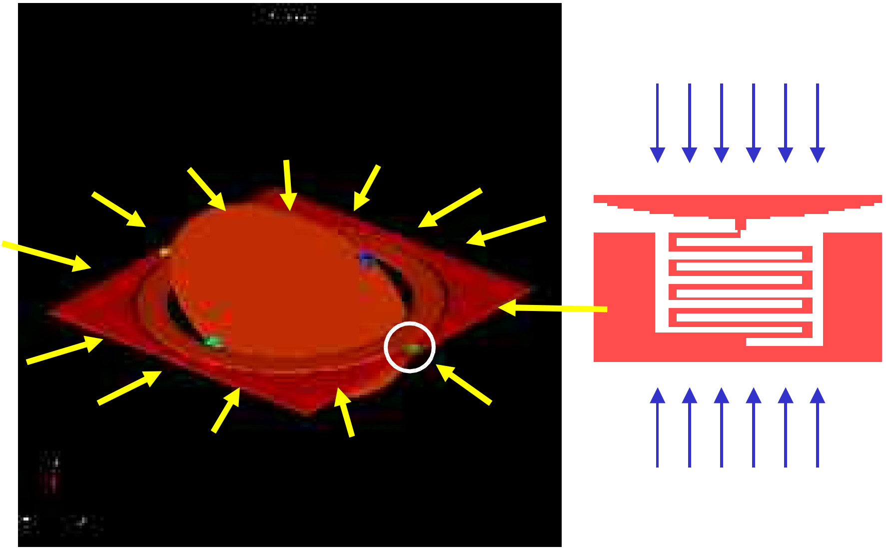
Sources of stress:

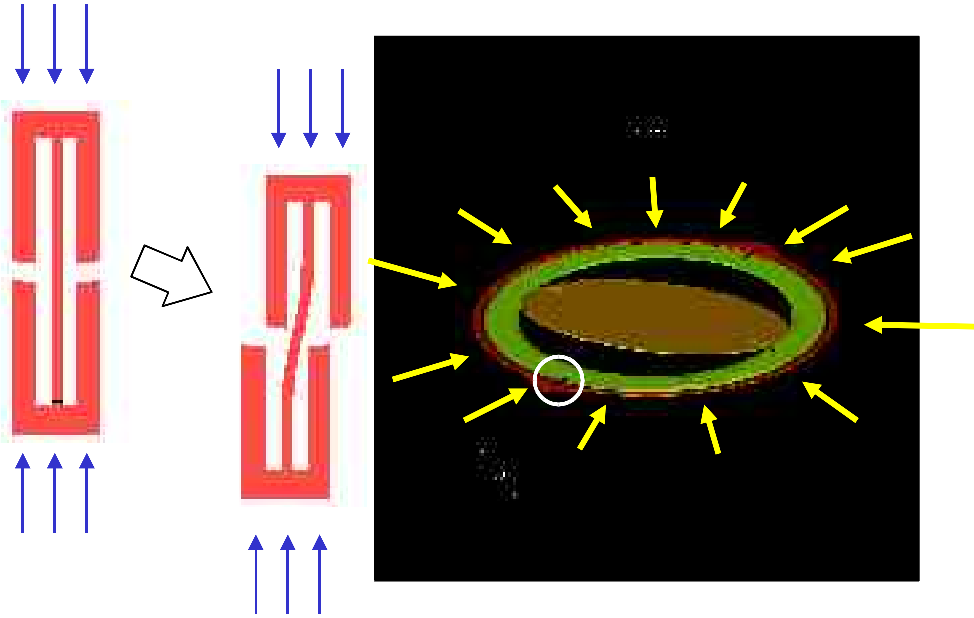
- residual
- packaging
- thermal mismatch

Some elastic elements ***change their stiffness*** considerably with applied external stress.

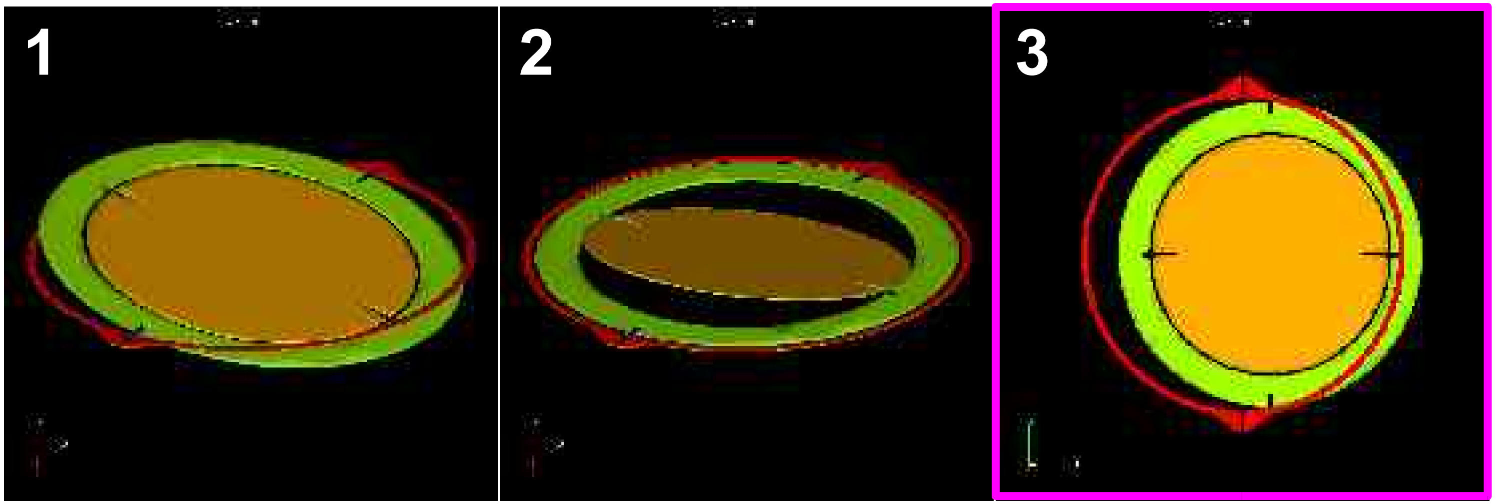
Nonlinear behavior results.

Buckling instabilities in extreme cases.

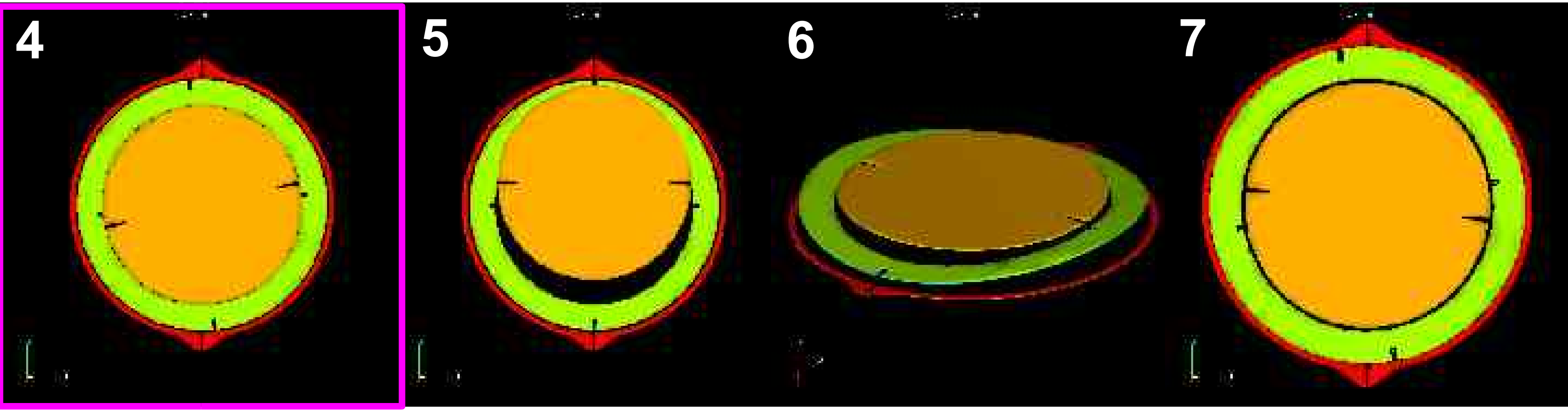




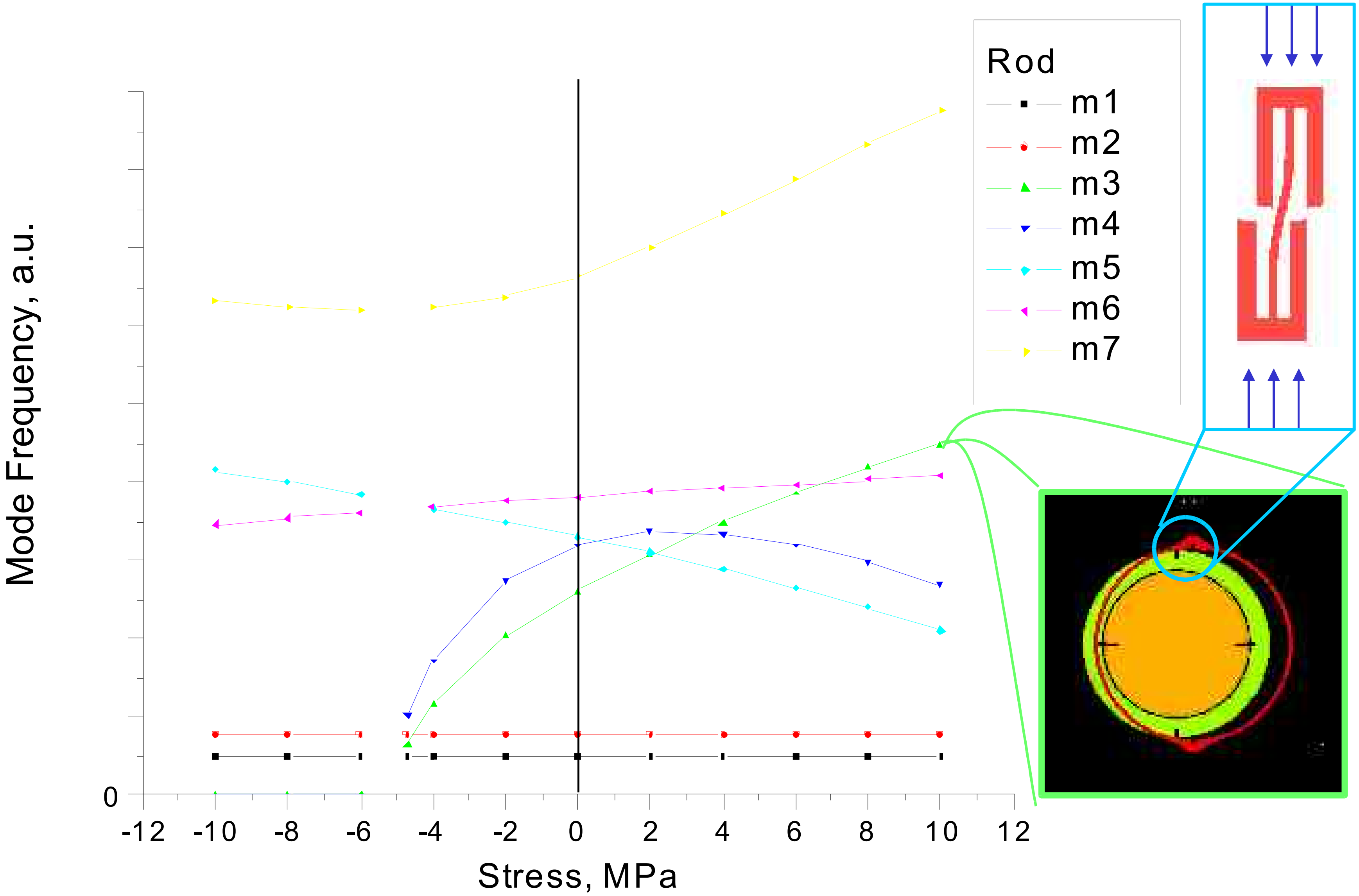
Straight Rod Design - Mechanical Modes



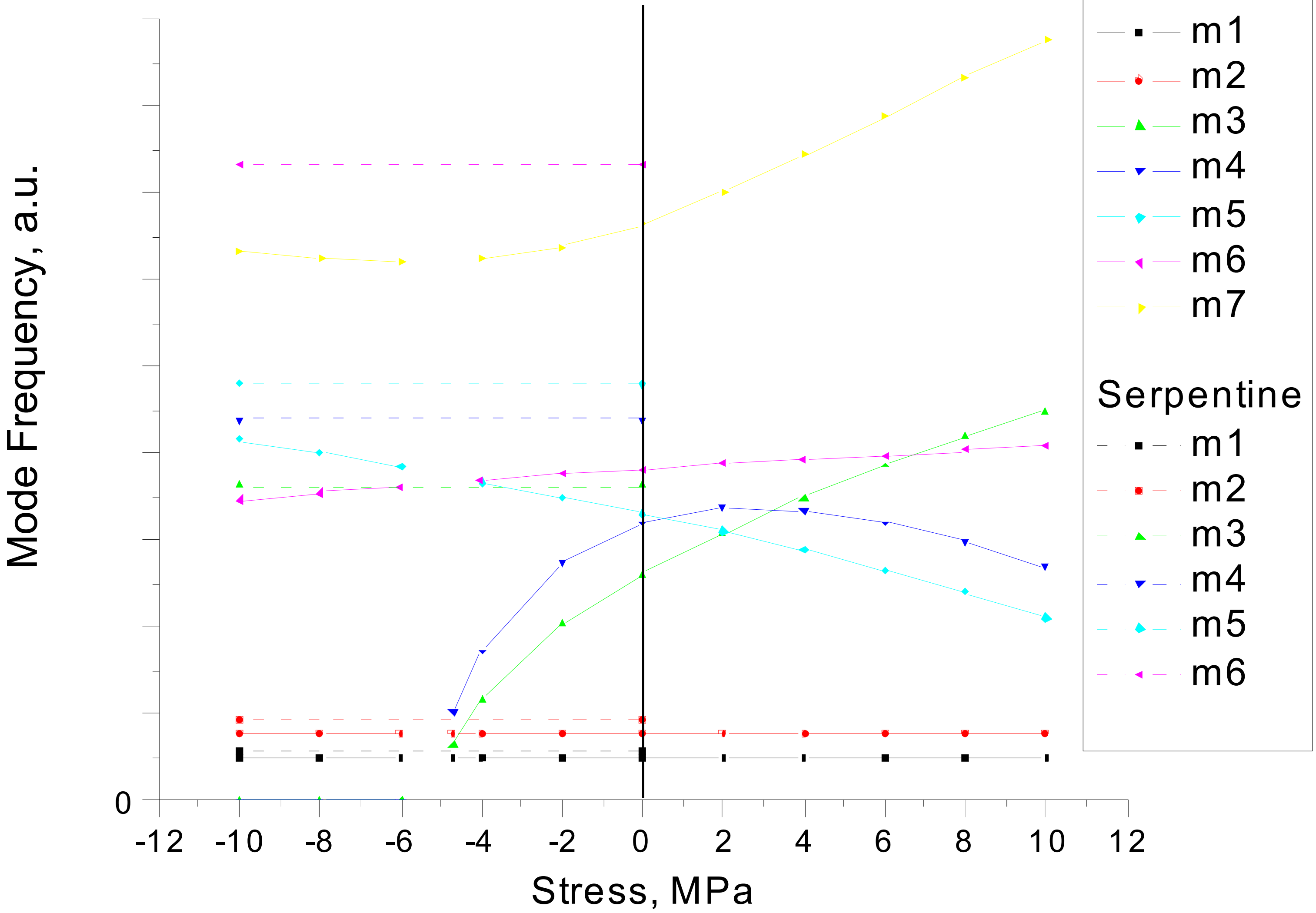
How do mode frequencies depend on stress ?

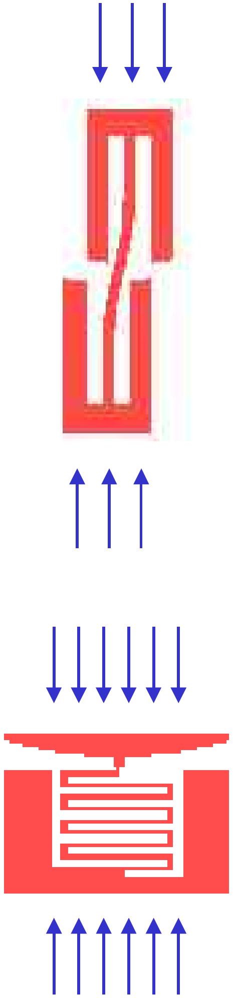


Resonance Frequency → 0 : Buckling

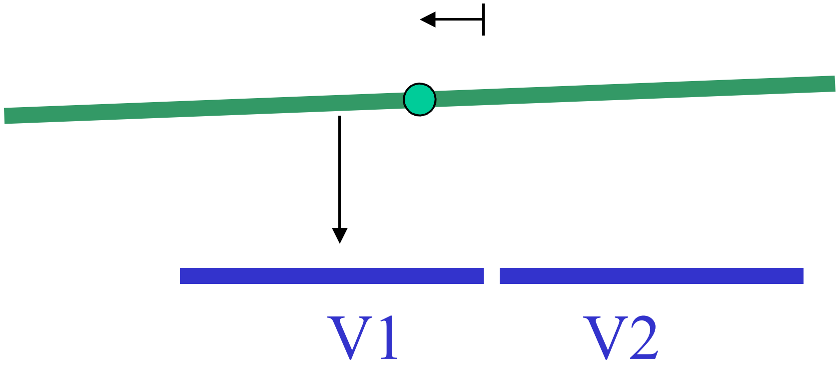


Strain-relieving Spring Is Linear

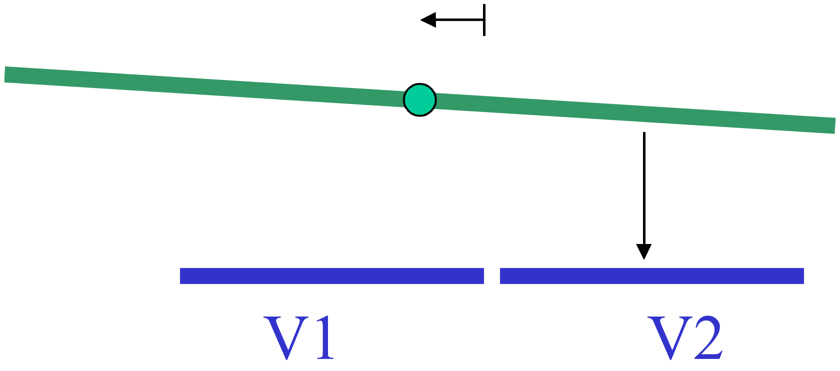




Buckled to V1

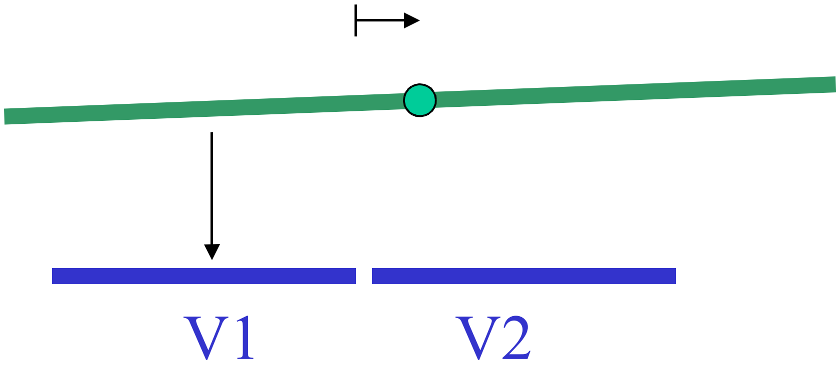


V1 voltage has to *increase* to produce the same torque

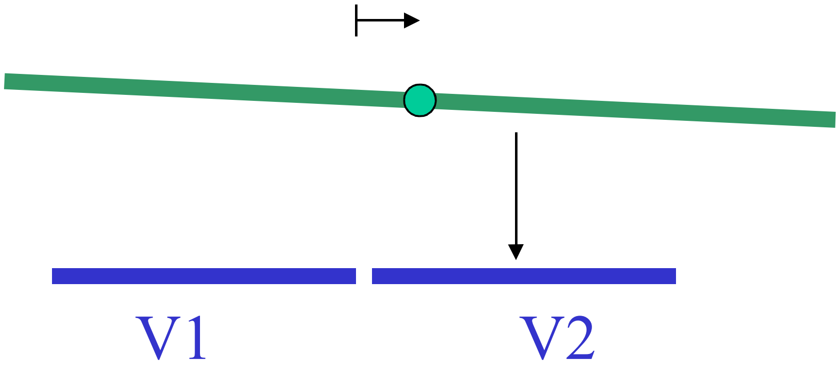


V2 voltage has to *decrease* to produce the same torque

Buckled to V2

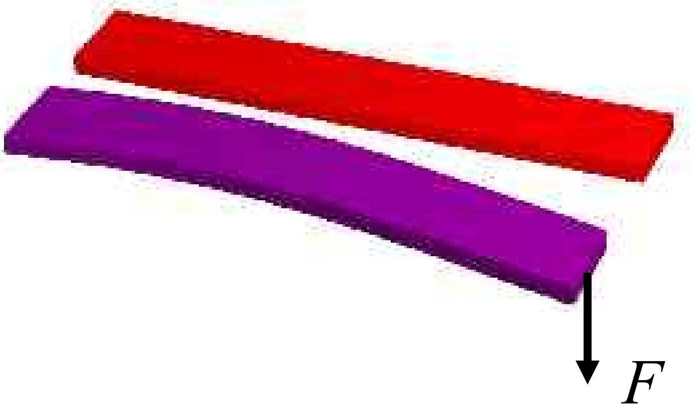


V1 voltage has to *decrease* to produce the same torque



V2 voltage has to *increase* to produce the same torque

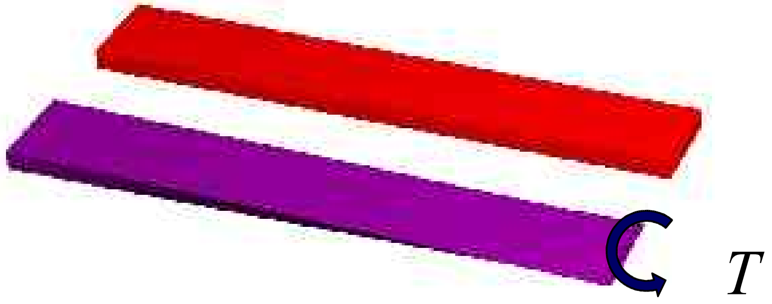
Beam Deformations



$$z(x)=-F\cdot\frac{x^2(3L-x)}{6EI};\quad z(L)=-F\cdot\frac{L^3}{3EI}$$

$$I=\frac{wt^3}{12}$$

L **length** E **Young's modulus**
a **width** G **shear modulus**
b **thickness**

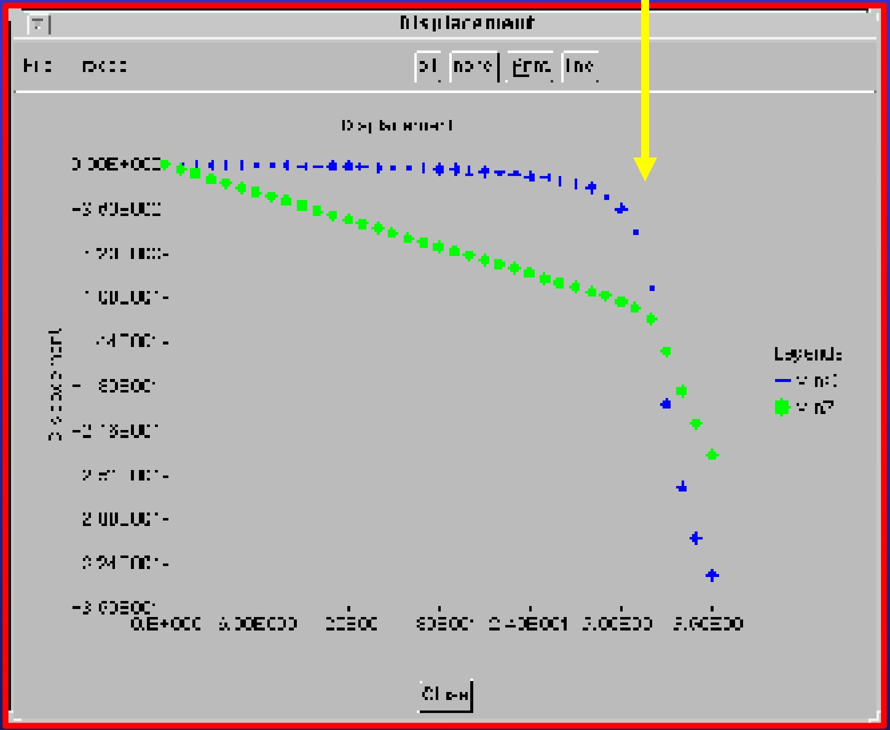


$$(x)=T\cdot\frac{x}{CG};\quad (L)=T\cdot\frac{L}{CG}$$

$$C=\frac{wt^3}{3}\quad for\quad t\ll w$$

Nonlinear mechanics

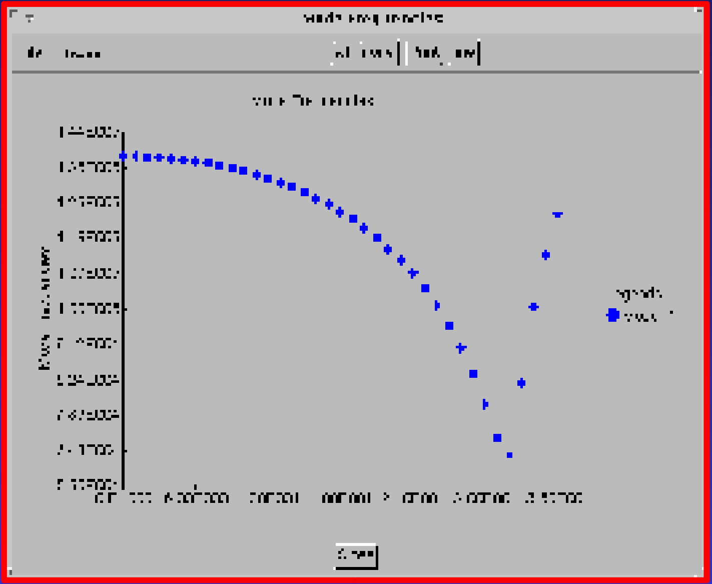
Instability!



$$F_{cr} = \frac{4.01}{L^2}\sqrt{EGIC} = 31\,\mu N$$

(Landau, Lifshitz, “Theory of elasticity”)


Velocity Magnitude



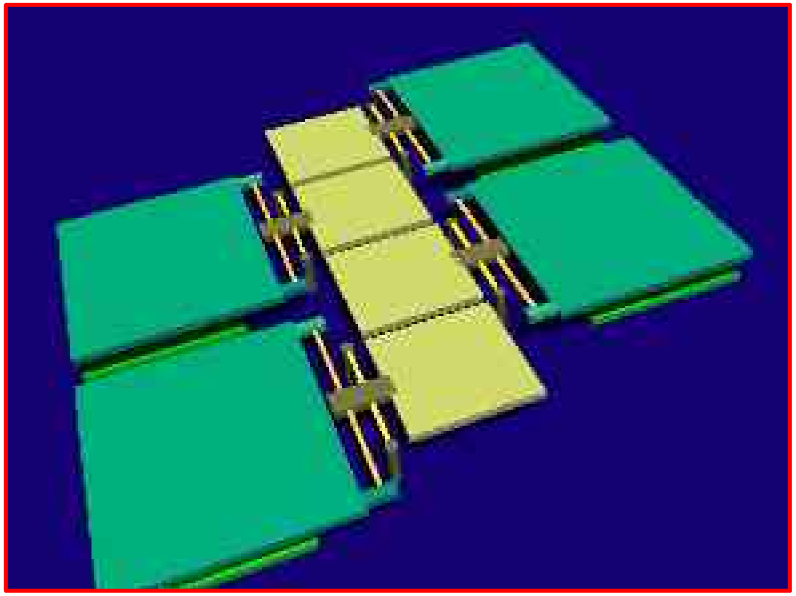

Velocity Magnitude


Velocity Magnitude

Double Hinge Tilting Mirror

- 10 degrees of continuous tilt
- 30 x 50 um mirrors
- moderate V < 100V
- high speed, f > 10kHz

- high fill factor (close-packed)
- no electromechanical crosstalk
- surface-micromachined



Angle amplification enables a more efficient actuation regime

Micromechanical transmission mechanism

Angle Amplification

$$\boxed{\sin(\theta) = \frac{L}{d}\sin(\alpha)}$$

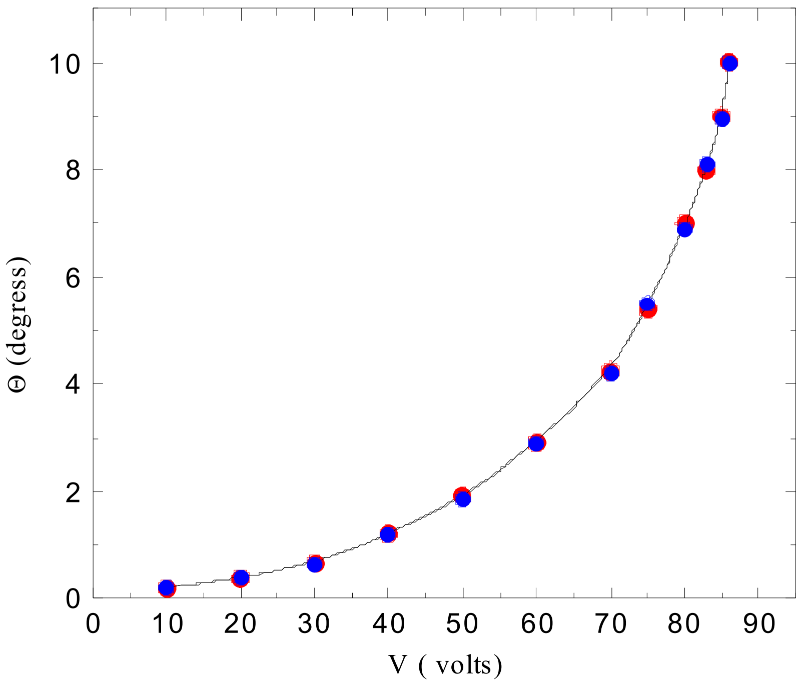
For an actuator consisting of plates, maximum output work is typically:

$$\boxed{W_{\max} \propto \frac{A}{g} V^{2}}$$

The *transmission mechanism* increases work produced by the actuator:

- **larger area can be used**
- **actuator gap can be decreased,**

while maintaining the required range of motion



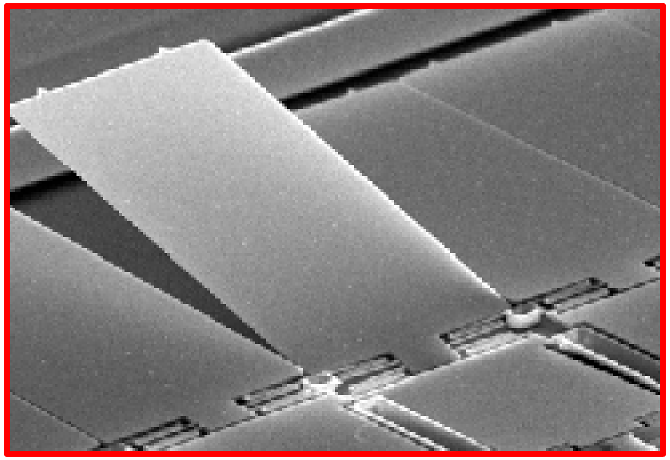
Transmission Mechanism Efficiency

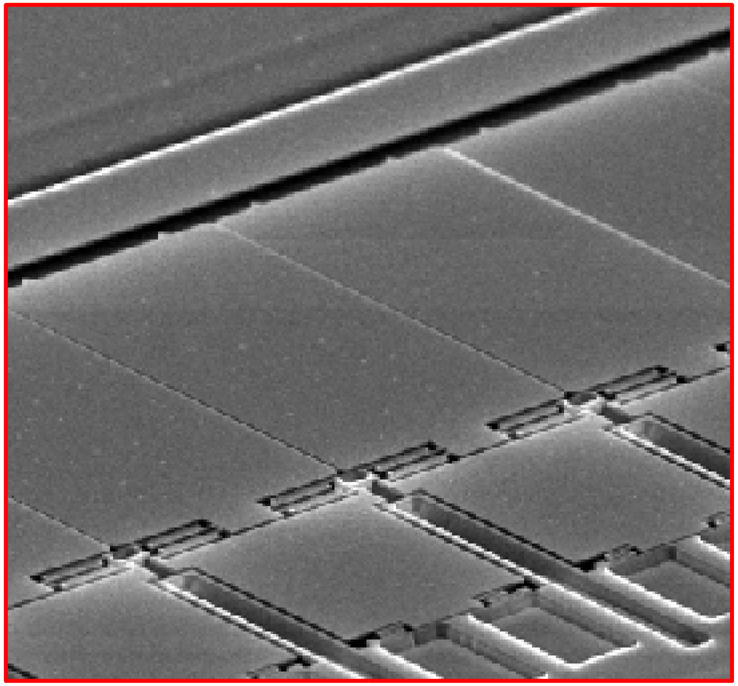
$$W_{electrostatic} = E^{required}_{mech} + E^{other}_{mech} = E^{torsional}_{mech} + E^{Z}_{mech}$$

$$E^{torsional}_{mech} = \frac{1}{2}\tau\theta \qquad {}^{2}$$

$$E^{Z}_{mech} = \frac{1}{2} K_Z \; z^2$$

$$\eta \qquad = \frac{E^{required}_{mech}}{W_{electrostatic}} \to {}^{T} \qquad / d^2 \ll K_Z$$





To maximize efficiency, need to increase stiffness to unwanted deformations:

<u>nonlinear</u> -

- **mechanical contact - friction**
- **straight torsion rod - stress sensitivity**

<u>linear</u> -

- **high aspect ratio spring**
  - submicron lithography

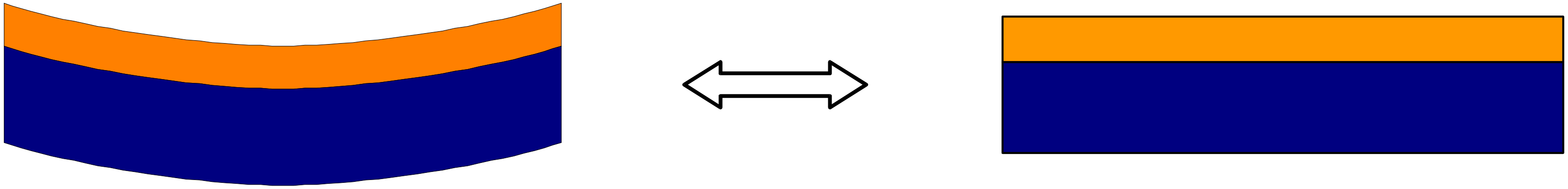
Stress Induced Mirror Deformation Issues

Residual stress in surface micromachining poly-Si is well-controlled
Proper low-stress metallization materials are used

Polysilicon = SOI
(for curvature issues)

Correct choice of reflector Si thickness:
curvature - thickness - mass - speed (f) - spring stiffness - voltage

Deviation from desired shape less than
$\lambda/20$

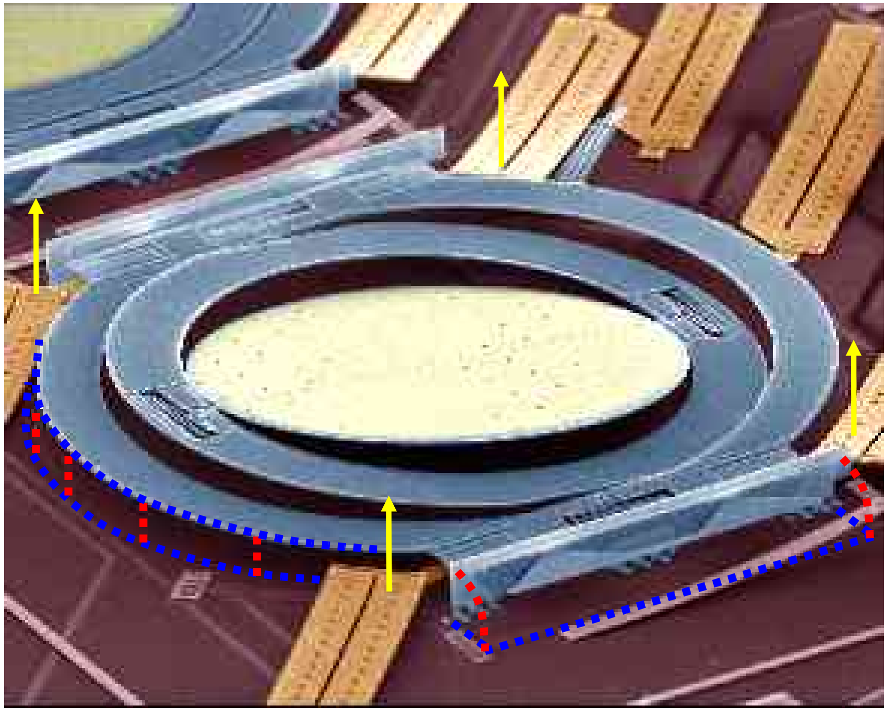


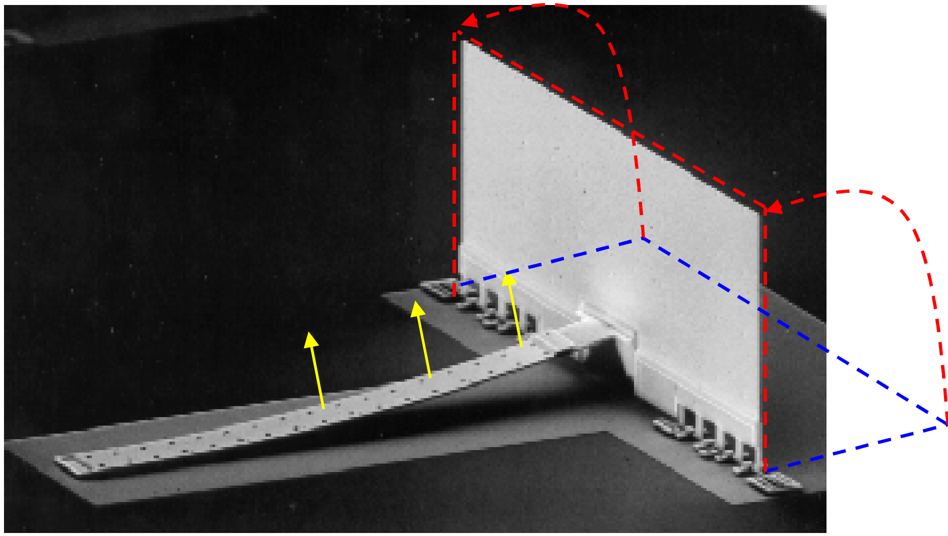
"**Stress-induced curvature engineering in surface-micromachined devices,**" V. A. Aksyuk, F. Pardo, D. J. Bishop, **SPIE Symposium on Design, Test, and Microfabriction of MEMS and MOEM, 30 March-1 April, 1999, Paris**

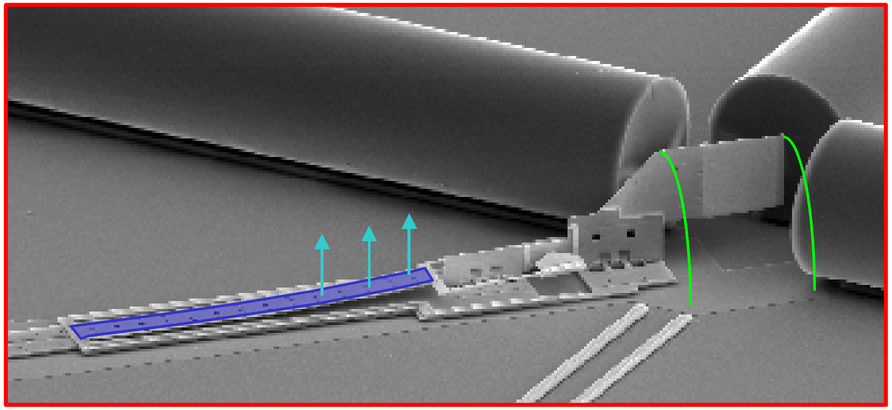
Lucent Technologies
Bell Labs Innovations

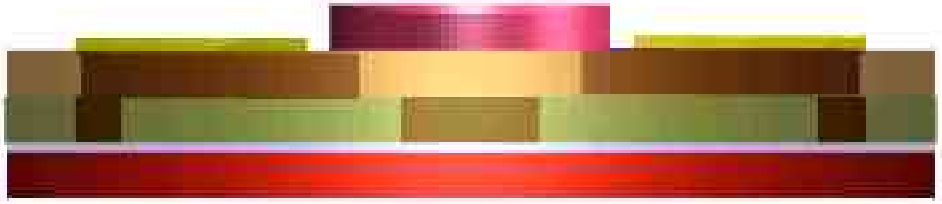
Self-assembly During Release

Makes Complex Structures Practical





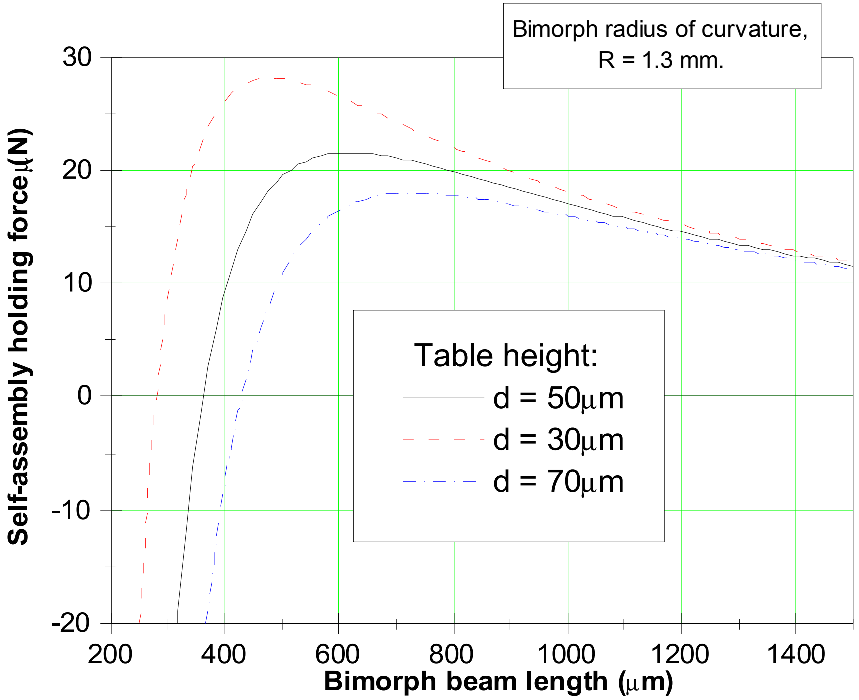




V.A. Aksyuk et. al. Proc. SPIE v.3680 1999

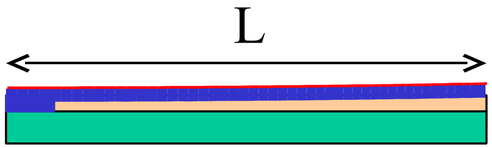
Self-assembly Force Calculation

W=100um

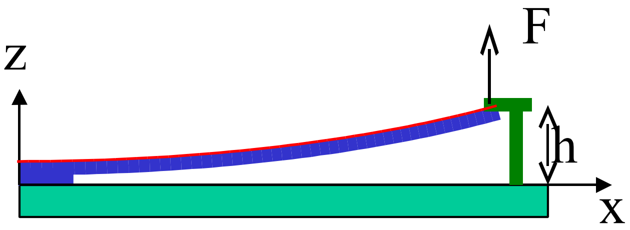


$$z(x)=\frac{x^2}{2R}-\frac{Fx^2(3L-x)}{6EI};\quad h=z(L)\quad\Rightarrow\quad F=3EI\frac{\frac{L^2}{2R}-h}{L^3}$$

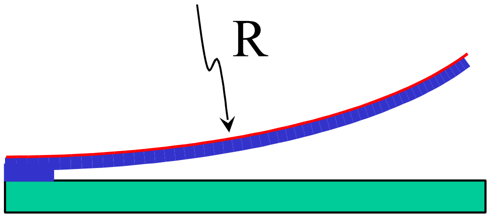
Before release



After release



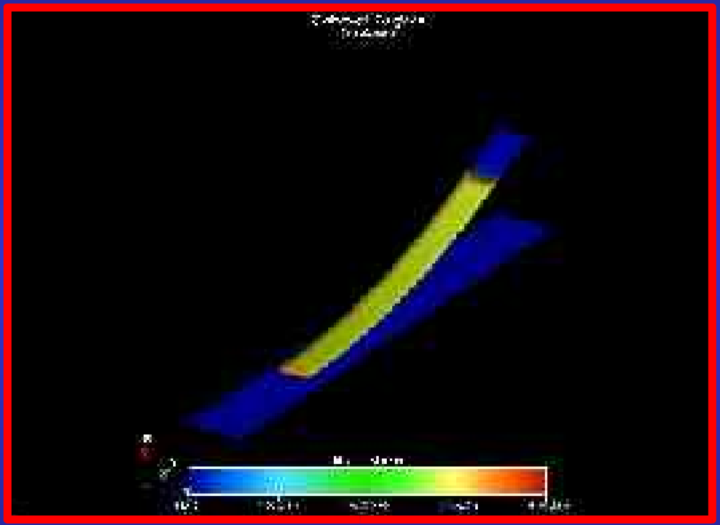
Free-standing shape

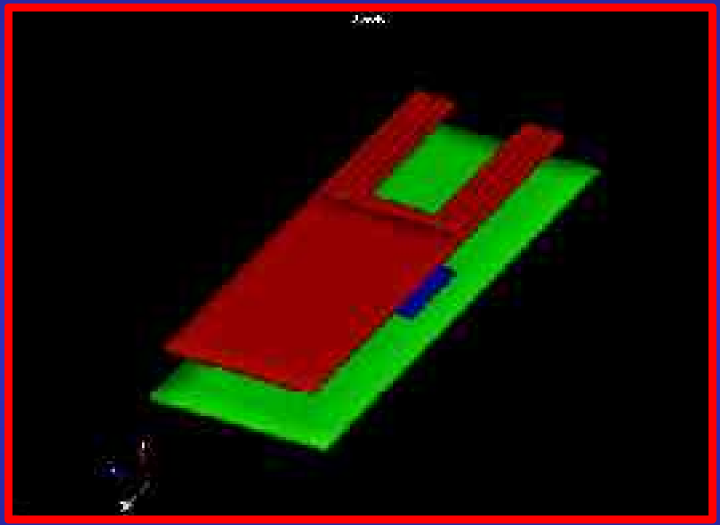


Self-assembly Using Residual Stress Is Robust and Reliable

- Holding force produced by mirror assembly arms exceeds 70μN, compared to:
  - Maximum electrostatic force (*Vmax* on all four electrodes) 10μN
  - 500g mechanical shock 15μN
- 256-mirror array chips are released with all mirrors assembled and functional.
- Uniform and accurate - lithographically defined final position.
- Batch fabrication, wet process.
- No external probes, leads or power are required.
- Was adapted to a variety of devices.

Party Favor device
- fully coupled problem





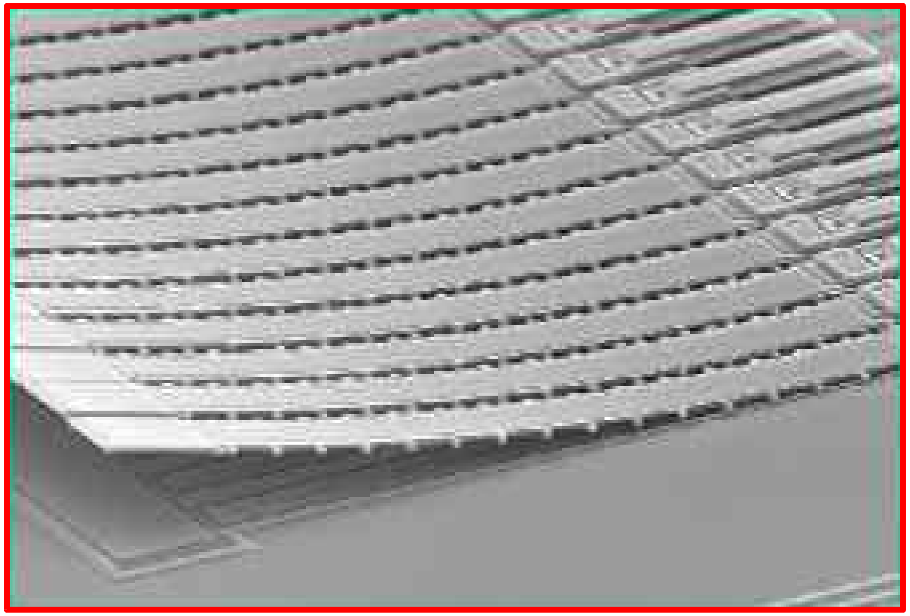
- Exact beam shape not known
- Electrostatics depends on beam shape

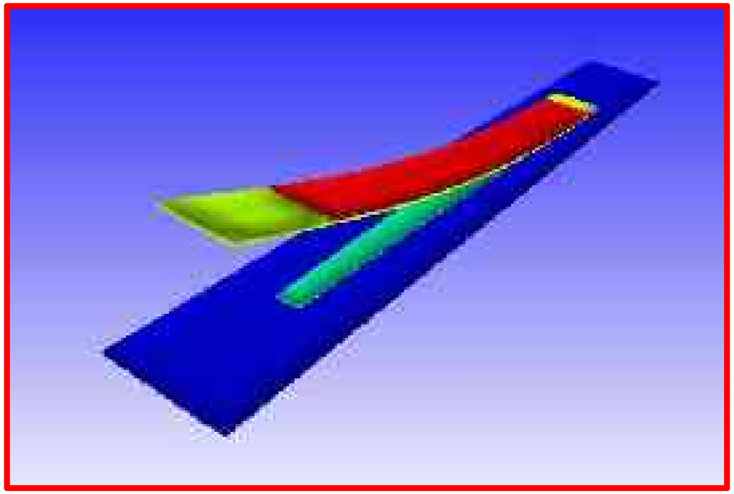
Have to use coupled analysis

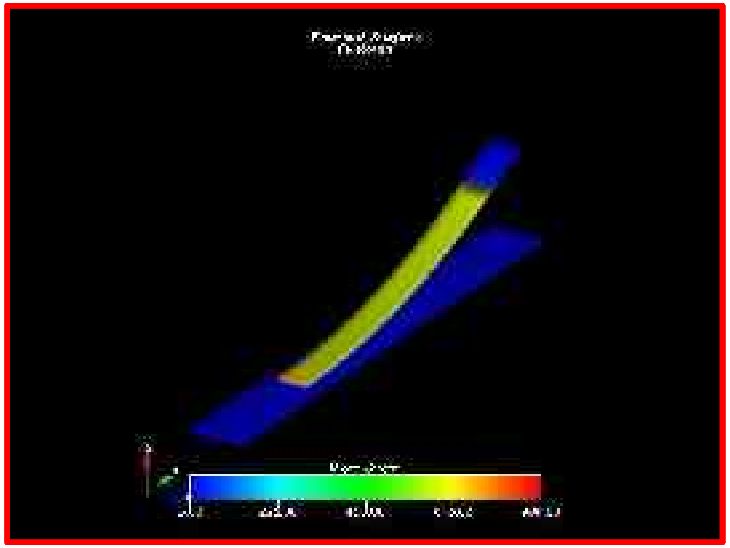
- Plate does not deform
- Springs do not contribute to electrostatics

Not a fully coupled problem

"Party Favor" Actuators







- Stress-engineered shape
- Deforming actuator plate
- "Zip-lock" operation with mechanical contact
- No fine-lithography features required

<u>Large deflections and forces</u> can be achieved at moderate or low voltages.

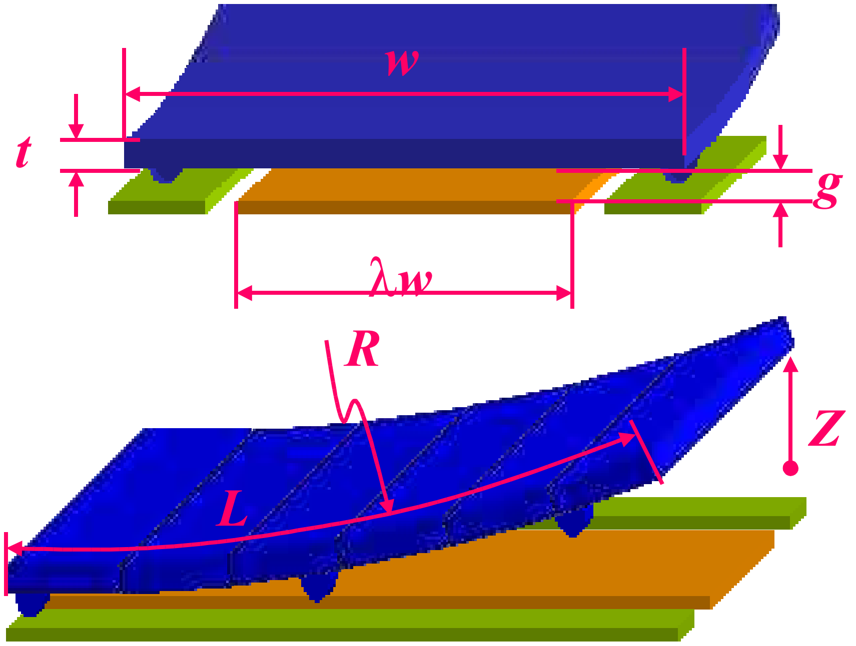
Will be uncurling if: $\Delta U_{elastic} < \Delta U_{elec}(V)$

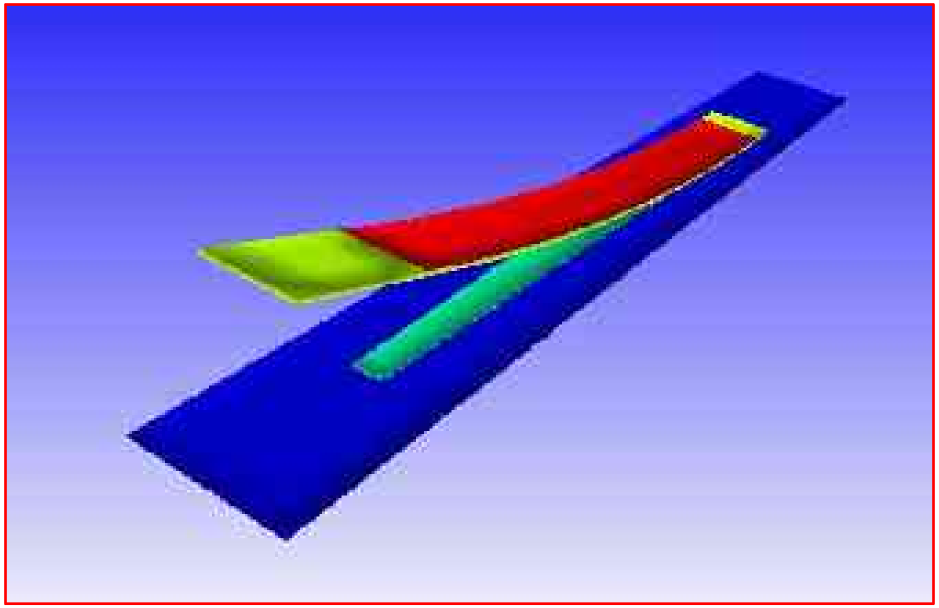
To uncurl a length of the beam: $\Delta U_{elastic} = \dfrac{Et^3 w\,\Delta L}{24R^2}$

"Near-field" estimate:

$$\Delta U_{elec} = \frac{V^2}{2}\Delta C \approx \frac{V^2}{2}\Delta C_{closed} = \frac{\varepsilon_0 \lambda w\,\Delta L}{g}\frac{V^2}{2}$$

Threshold voltage: $V^2 \approx \dfrac{1}{\varepsilon_0}\dfrac{Et^3}{12R^2}\dfrac{g}{\lambda}$



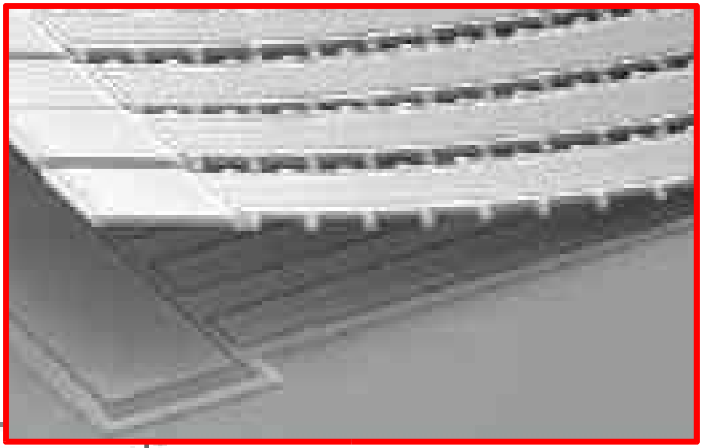


OUTPUT WORK: $W_{\max} \propto \dfrac{L\lambda w}{g}V^2$

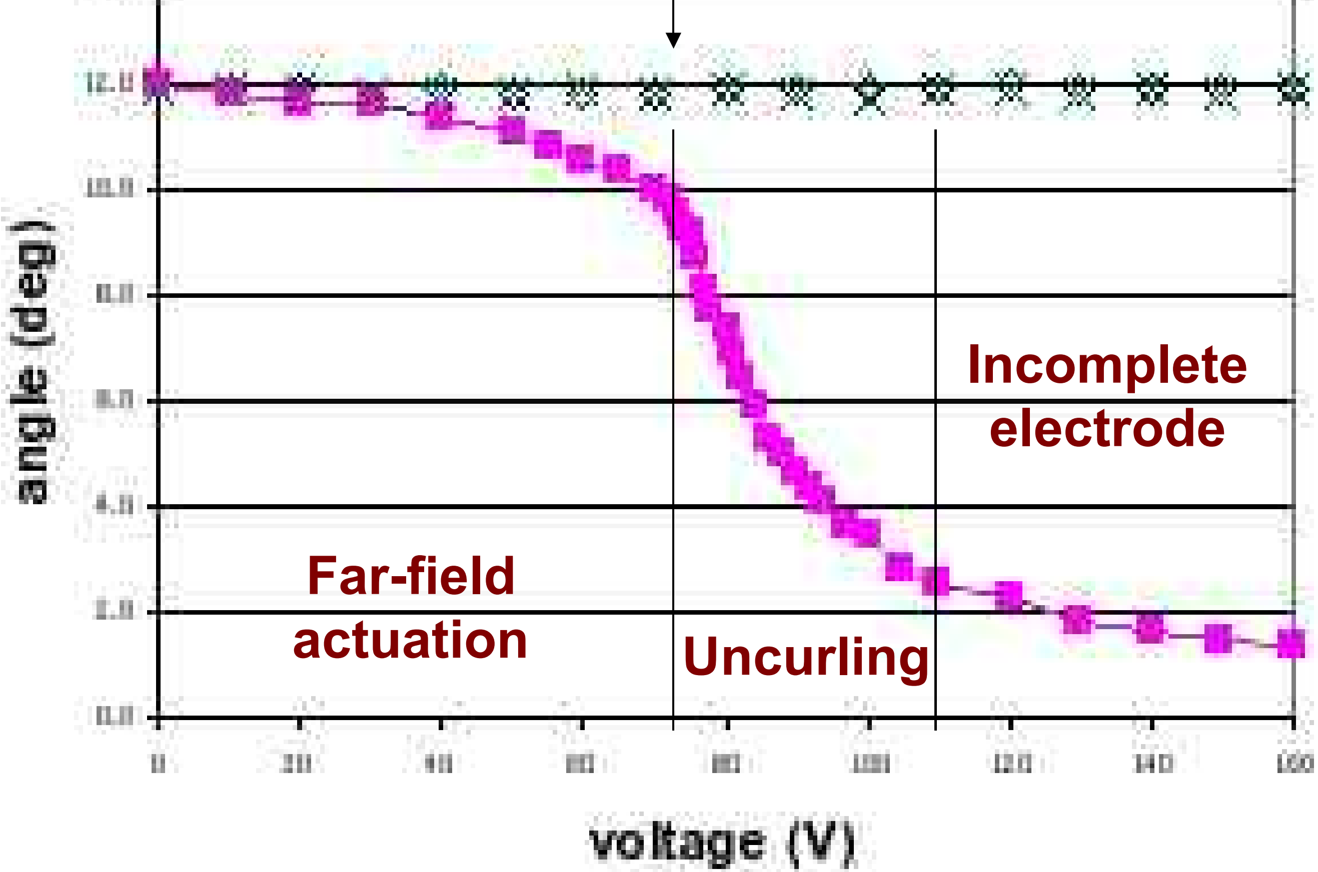
BUT:

- Maximum displacement Z is *unlimited*
- Gap g is *independent* of Z
- Decreasing g lowers the voltage, while *maintaining* the output force and displacement

Device Performance



$V_{threshold}$

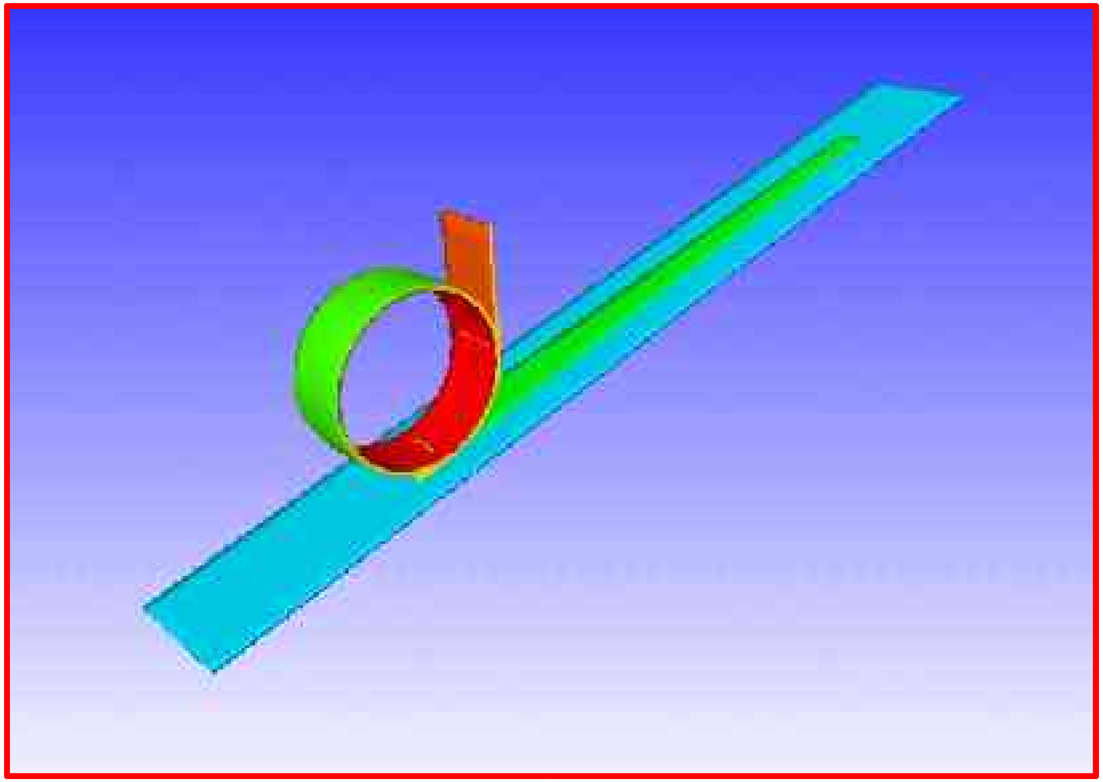


Far-field actuation

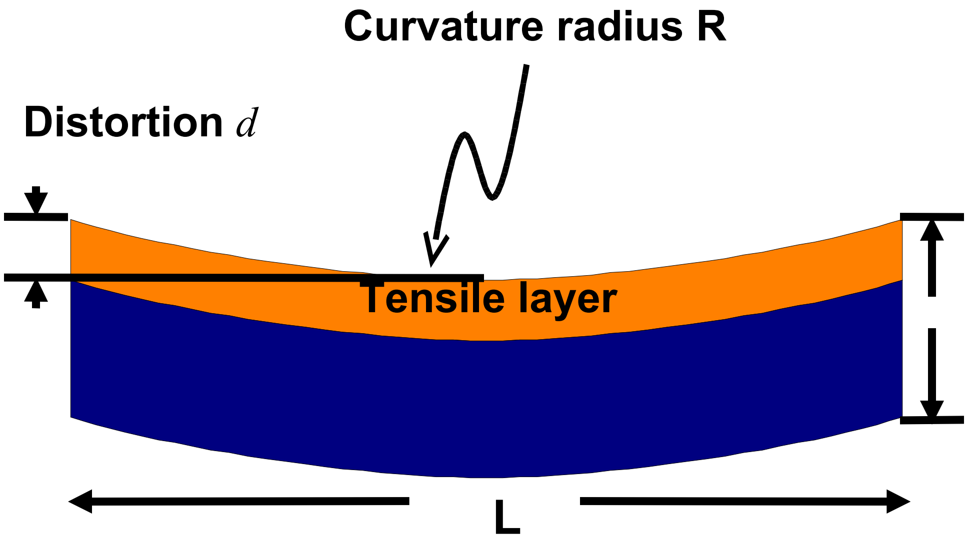
Uncurling

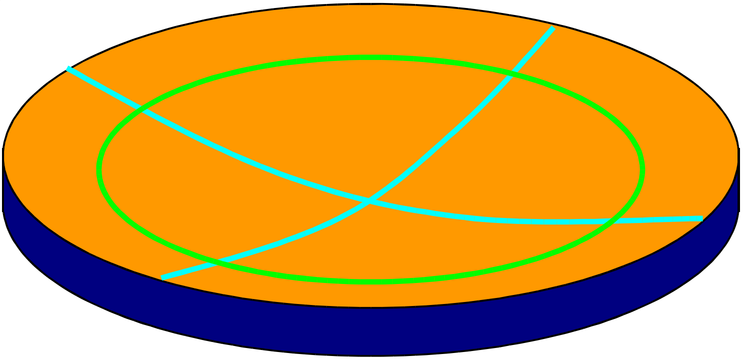
Incomplete electrode

Too Much Stress !



Residual Stress Induced Mirror Deformation



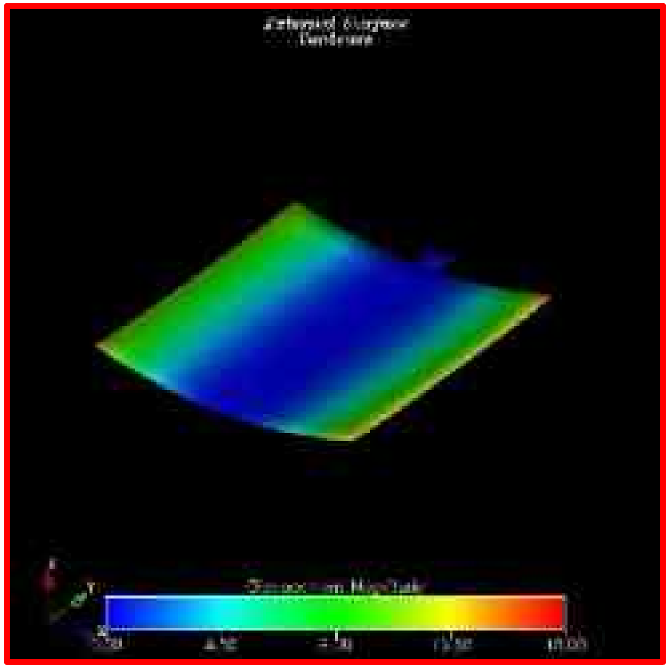


Deformation ***spherical*** for $D \geq d$

For larger deformations, there must be in-plane tension or compression due to geometry.

But what happens if the stress is very high?

Spontaneous Symmetry Breaking



If stress is high, deformation changes from spherical to *cylindrical.*
A square plate becomes *bi-stable* !

A bi-stable actuator *does not require power* to maintain either state.
States can be *switched* electrostatically, similar to the Party Favor device.

Acknowledgements

MEMS devices: design, process, testing, reliability

S. Arney, H. Bair, C. Bolle, B. Barber, D. Carr, H. B. Chan, C. Chang, A. Gasparyan, R. George, L. Gomez, S. Goyal, D. Greywall, M. Haueis, T. Kroupenkine, V. Lifton, D. Lopez, M. Paczkowski, F. Pardo, A. Ramirez, R. Ruel, H. Shea, M. E. Simon, J. Vuillemin, J. Walker

Subsystem and System: optics, packaging, physical design, electronics, software, training & test

N. Basavanhally, R. Boie, C. Doerr, J. Ford, R. Frahm, D. Fuchs, J. Gates, R. Giles, J. Kim, P. Kolodner, J.S. Kraus, B. Kumar, C. P. Lichtenwalner, D.F. Lieuwen, Y. Low, D. Marom, D.T. Neilson, C. Nijander, C. J. Nuzman, R. Pafcheck, A. R. Papazian, D. Ramsey, R. Ryf, R. Scotti, L. Stulz, H. Tang, A. Weiss, J. Weld

NJ Nanotechnology Consortium (and formerly Si Fabrication Research Lab): MEMS processing, process development

G. R. Bogart, E. Ferry, F. P. Klemens, J. F. Miner, R. Cirelli, S. Rogers, J. E. Bower, R. C. Keller, W. Mansfield, C-S.Pai, W. Lai, K. Teffeau, H. T. Soh, J. A. Taylor, A. Kornblit, T.C. Lee and J. Q. Liu

Leadership and support

S. Arney, J. Gates, R. Giles, D. Bishop

MEMS Hinge technology

Out of plane mechanisms: Fold up structures