Microelectromechanical Systems (MEMS) Actuators

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INTRODUCTION

Actuators

- Thermal
  - Two beam heated cantilever
  - Polyimide on Heaters
  - Bimetalic
  - heaters on diaphragms
- Electrostatic
  - Capacitor Plate Drive
  - Comb Drive
- Electromagnetic
  - Diaphragm
- Peizoelectric
  - ZnO

OUTLINE

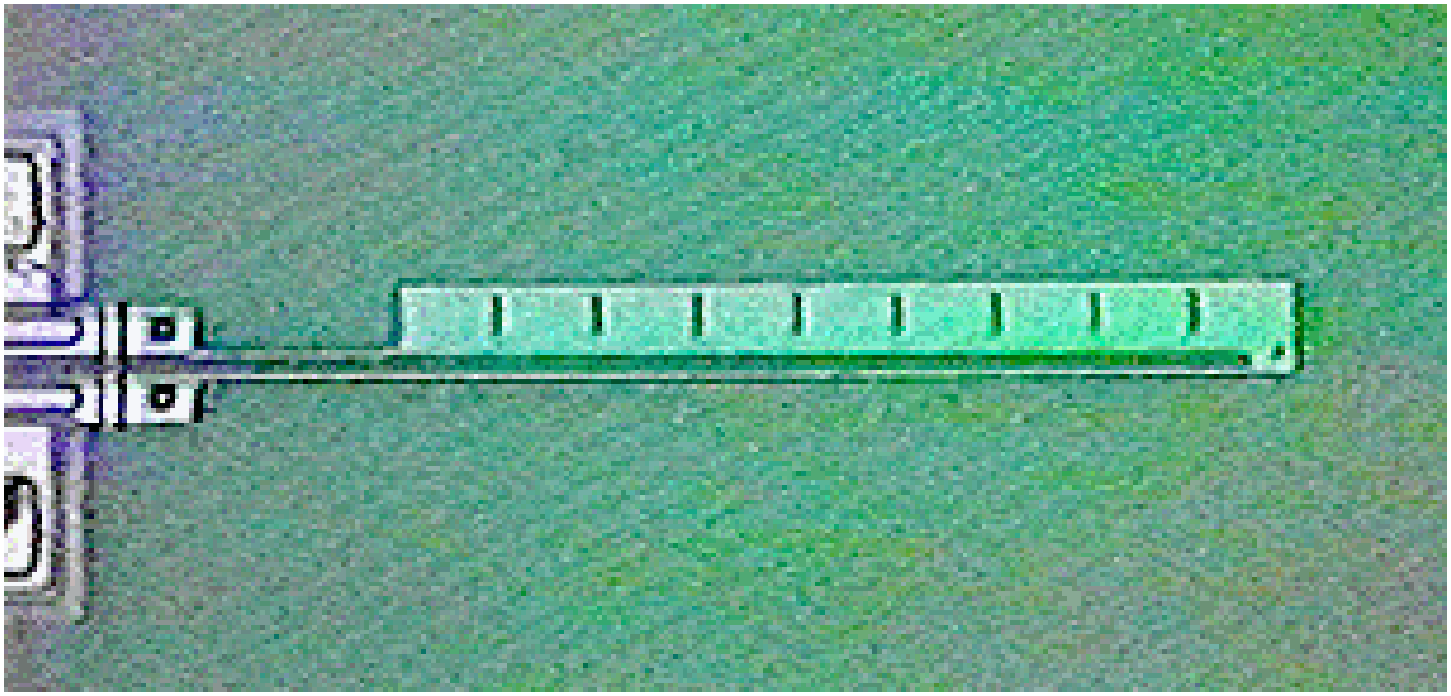
Polycrystalline Silicon Thermal Actuators
Heated Polyimide Mirrors
Polyimide Thermal Actuators
    A Walking Silicon Micro-Robot
Electrostatic Force
Electrostatic Impact-Drive Microactuator
    Shuffle Motor
Electrostatic Comb Drive
Diaphragms
Magnetic Actuators on a Diaphragm
Heaters on a Diaphragm

POLYCRYSTALLINE SILICON THERMAL ACTUATORS

Polycrystalline Silicon Thermal Actuators Integrated with Photodetector Position Sensors

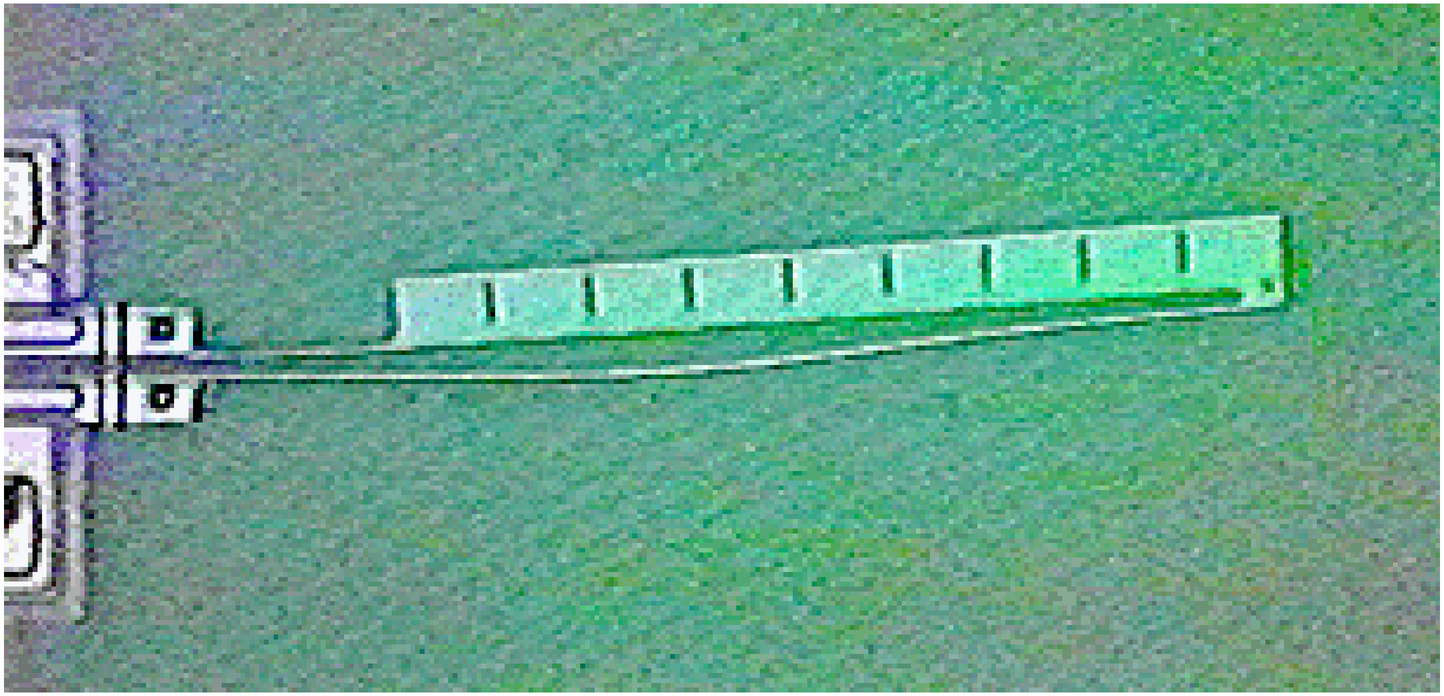
Kevin Munger

POLYCRYSTALLINE SILICON THERMAL ACTUATORS



No current flow

POLYCRYSTALLINE SILICON THERMAL ACTUATORS



Current flow

THERMAL PROPERTIES

	MP °C	Coefficient of Thermal Expansion ppm/°C	Thermal Conductivity w/cmK	Specific Heat cal/gm°C
Diamond	3825	1.0	20	0.169
Single Crystal Silicon	1412	2.33	1.5	0.167
Poly Silicon	1412	2.33	1.5	0.167
Silicon Dioxide	1700	0.55	0.014	
Silicon Nitride	1900	0.8	0.185	
Aluminum	660	22	2.36	0.215
Nickel	1453	13.5	0.90	0.107
Chrome	1890	5.1	0.90	0.03
Copper	1357	16.1	3.98	0.092
Gold	1062	14.2	3.19	0.031
Tungsten	3370	4.5	1.78	0.031
Titanium	1660	8.9	0.17	0.043
Tantalum	2996	6.5	0.54	0.033
Air			0.00026	0.24
Water	0		0.0061	1.00

1 watt = 0.239 cal/sec

THERMAL EXPANSION

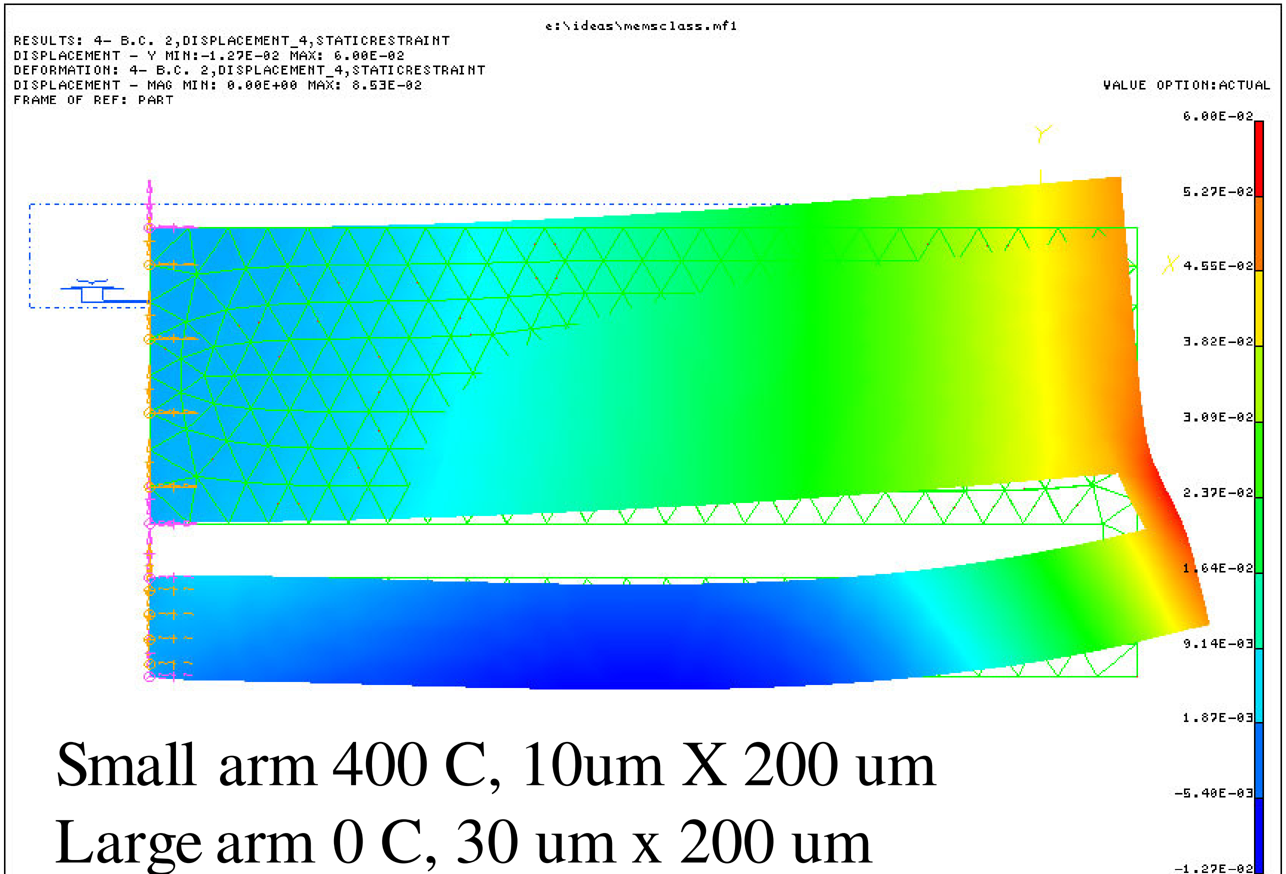
1. How much will a 500 um long bar of aluminum expand if it is heated 200 C above ambient?

ΔL/L = 22 ppm/C
= 22 x 200 = 4400 ppm = 4400E-6
ΔL = 4400E-6 x 500 um = 2.2 um

2. If the hot arm on a 200µm actuator is 400C hotter than the cold arm how much longer will it be ?

ΔL/L = 2.33 ppm/C
= 2.33 x 400 = 932 ppm = 932E-6
ΔL = 932E-6 x 200 um = 0.186 um

FINITE ELEMENT ANALYSIS OF THERMAL BENDING



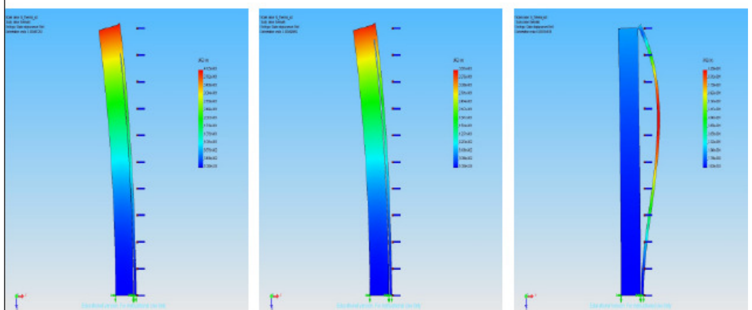
Small arm 400 C, 10um X 200 um

Large arm 0 C, 30 um x 200 um

Maximum Displacement = 0.12 um

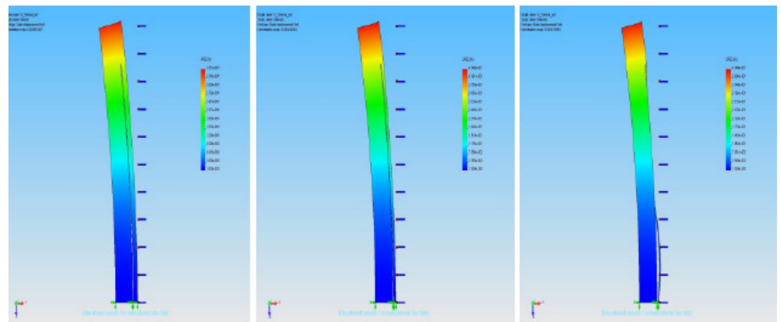
SIMULATION

Varying Connection Width Lx



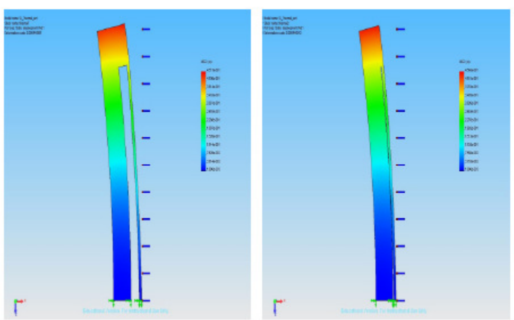
10_25_200 10_25_100 10_10_10

Varying small-arm width



10_50 10_25 10_10

Increasing gap width

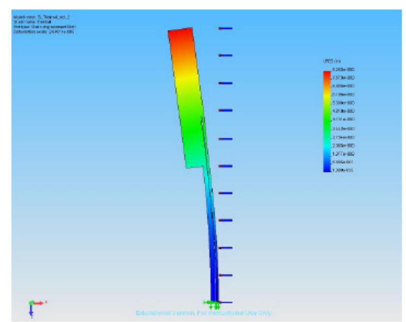


100_25_300 10_25_300

Future Work

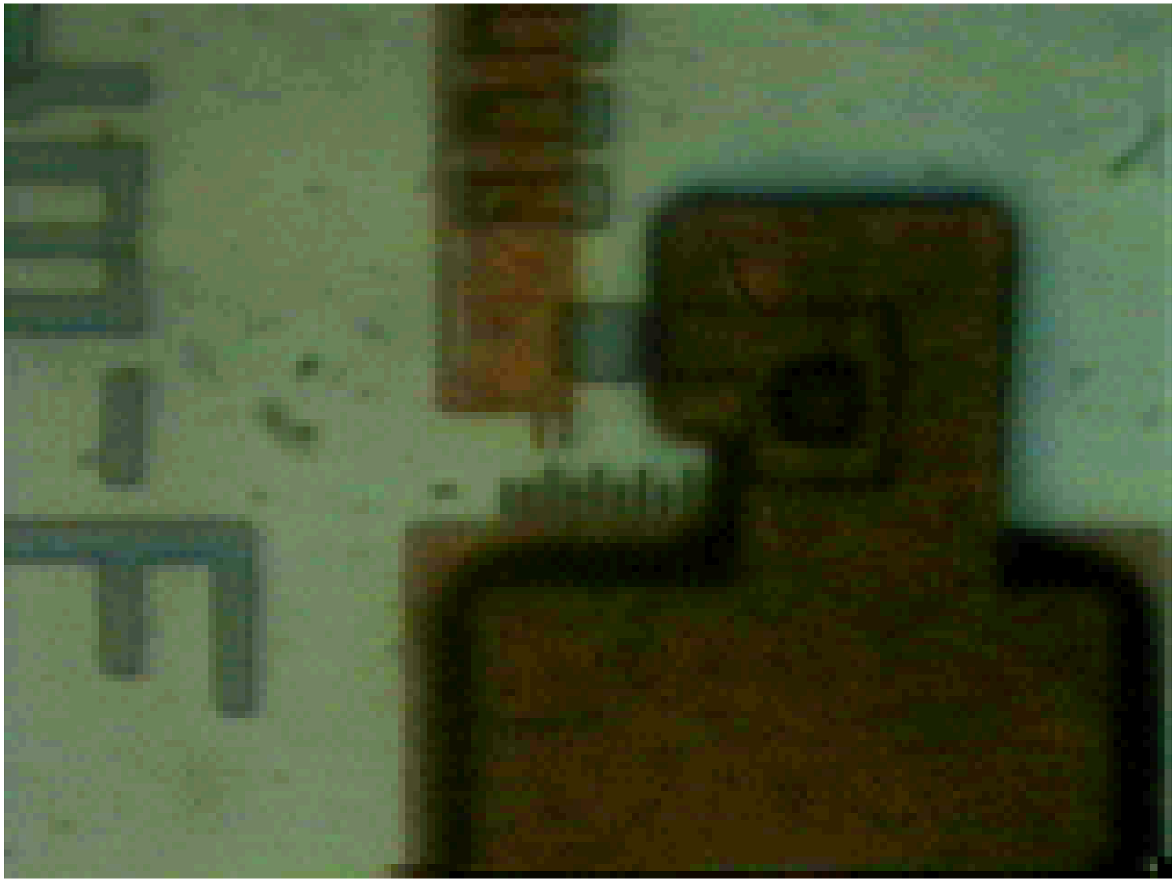
•Simulate structure that resembles the real design better (max displacement increases to 301µm vs. the 205µm of previous structure)

•Vary parameters and apply DOE techniques to investigate optimal parameters for max displacement.



Ws=25um, Lx=300um, Wg=10um
Max displacement=301.4µm

THERMAL ACTUATOR MOVIE



POLYCRYSTALLINE SILICON THERMAL ACTUATORS

Summary

These devices give large mechanical motion on the order of several to few 10's of micrometers

These devices are analog

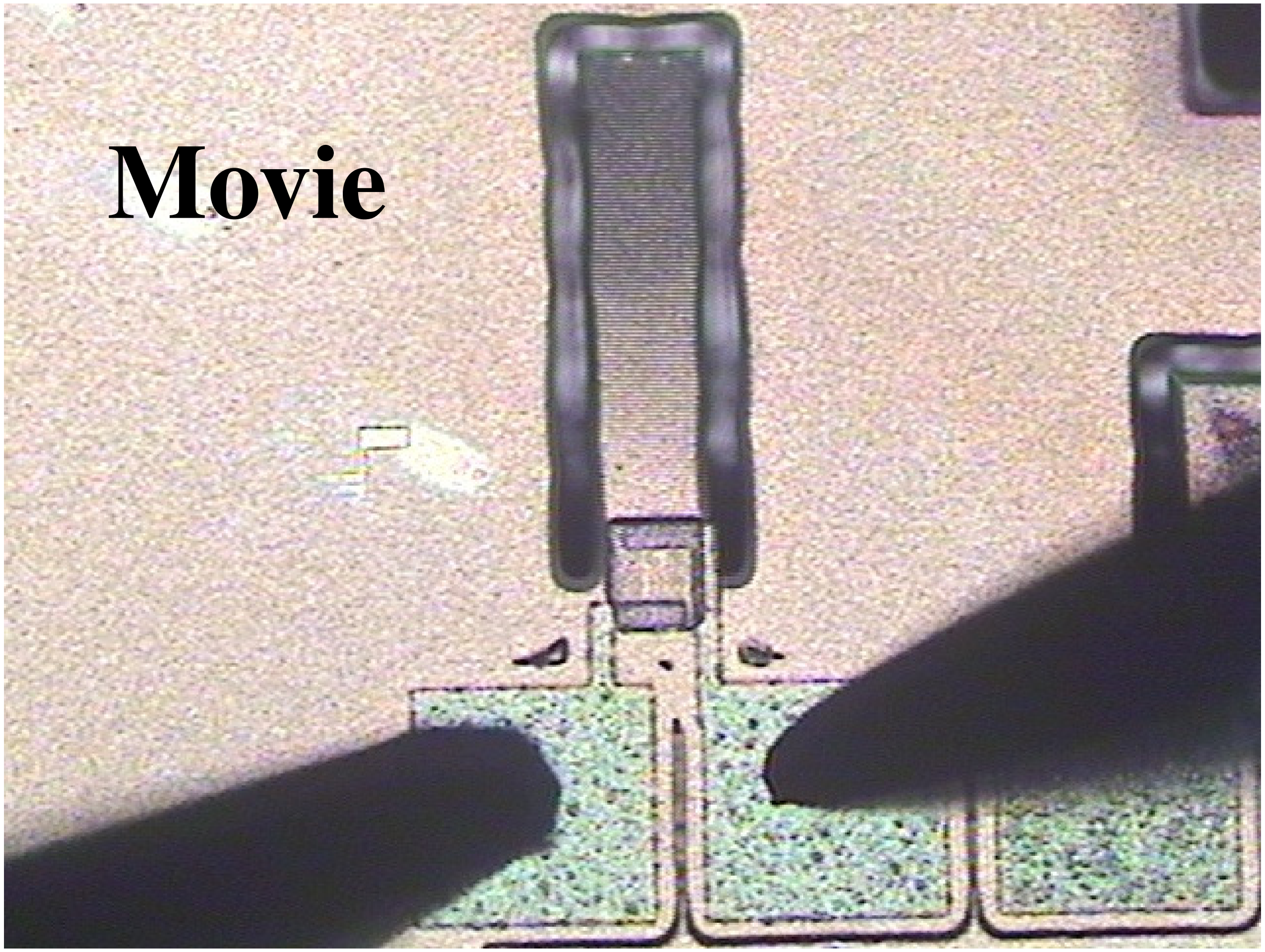
Integrated with analog photodiode position detection can give feedback for accurate position

Cycle fatigue seems to be infinite

COEFFICIENTS OF THERMAL EXPANSION

	Thermal Expansion
Silicone Elastomers	275-300 ppm/°C
Unfilled Epoxies	100-200
Filled Epoxies	50-125
Epoxy, glass laminates	100-200
Epoxy, glass laminate, xy axis	12-16
Aluminum	20-25
Copper	15-20
Alumina Ceramic	6.3
Type 400 Steels	6.3-5.6
Glass Fabric	5.1
Borosilicate Glass	5.0
Silicon	2.4
Inconel	2.4
Nickel-iron alloy (30 Ni - 61 Fe)	1.22
Quartz	0.3

POLYIMIDE ON HEATER



Rochester Institute of Technology
Microelectronic Engineering

A WALKING SILICON MICRO-ROBOT

Presented at
The 10th Int Conference on Solid-State Sensors and Actuators (Transducers'99), Sendai, Japan, June 7-10, 1999, pp 1202-1205.

A WALKING SILICON MICRO-ROBOT

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ABSTRACT

The first walking batch fabricated silicon micro-robot able to carry loads has been developed and investigated. The robot consists of arrays of movable robust silicon legs having a length of 0.5 or 1 mm. Motion is obtained by thermal actuation of robust polyimide joint actuators using electrical heating. Successful walking experiments have been performed with the 15x5 mm^2 sized micro-robot. Walking speeds up to 6 mm/s with high load capacity has been achieved. The robot could carry a maximum external load of 2500 mg on its back (> 30 times the dead-weight of the robot).

A WALKING SILICON MICRO-ROBOT

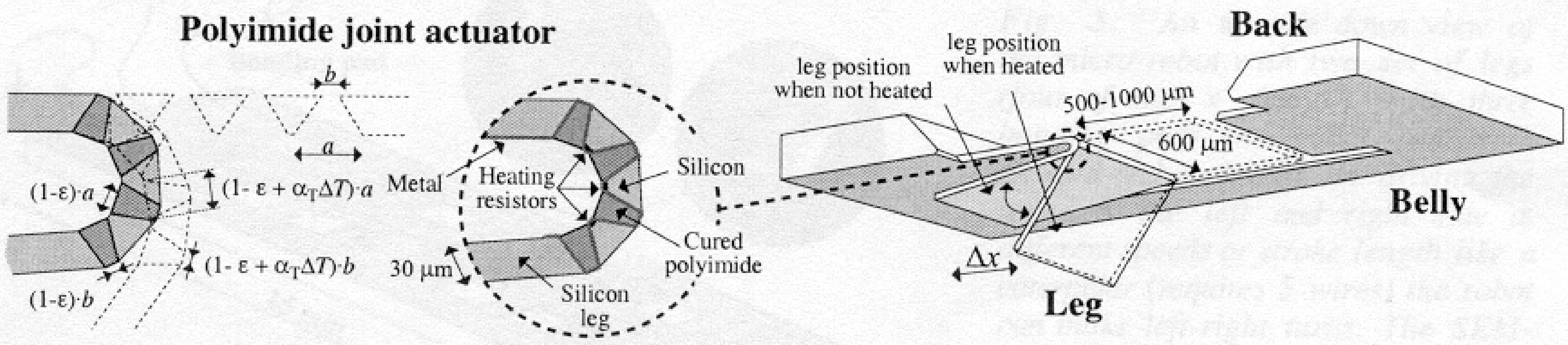

Fig. 1. Design and actuation principle for the leg movements based on a four V-groove joint. By heating the joint a horizontal displacement, Δx, is obtained due to larger absolute thermal expansion of the polyimide at the top of the V-groove than at the bottom ($\alpha_T \cdot \Delta T \cdot a > \alpha_T \cdot \Delta T \cdot b$).

http://www.s3.kth.se/mst/staff/thorbjorne.html

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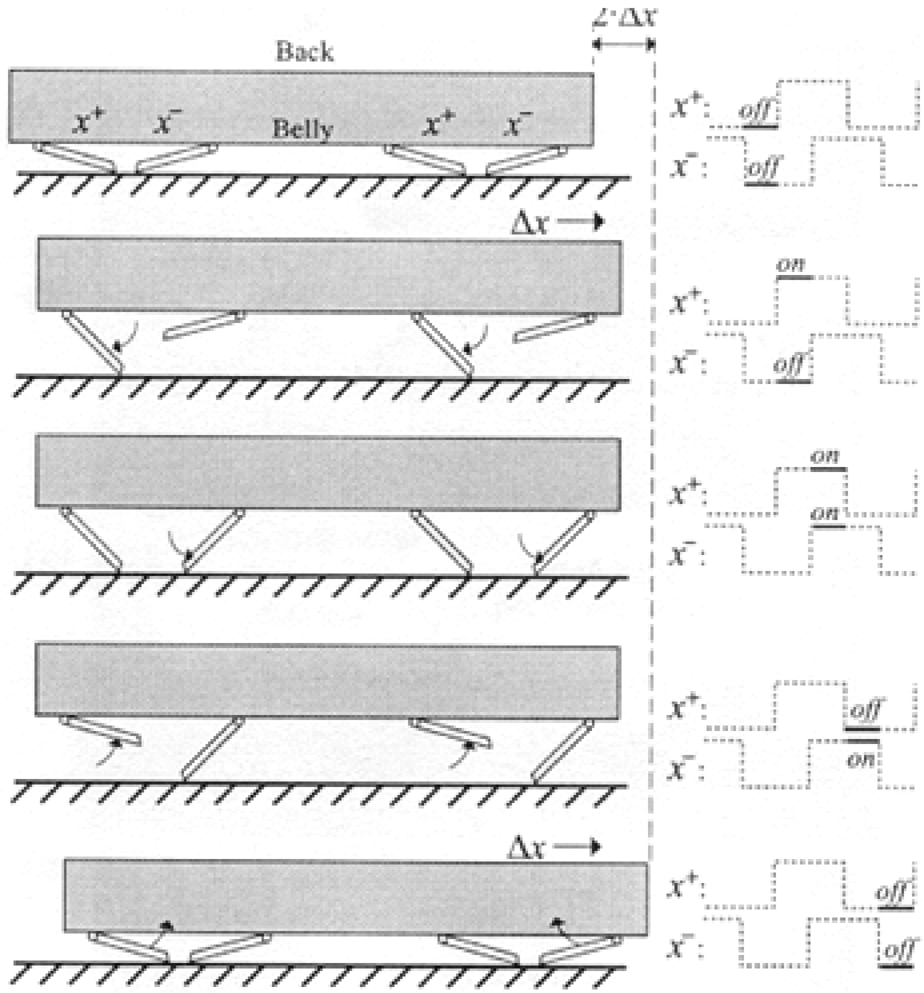
A WALKING SILICON MICRO-ROBOT

Fig. 2. Operation principle for the asynchronous driven micro-robot. A displacement equal to 2·Δx is obtained during one period due to the fixed phase difference of 90 degrees between the two sets of legs (x^+ and x^-). A 180 degrees phase-shift between x^+ and x^- will results in walking in the opposite direction.



A WALKING SILICON MICRO-ROBOT

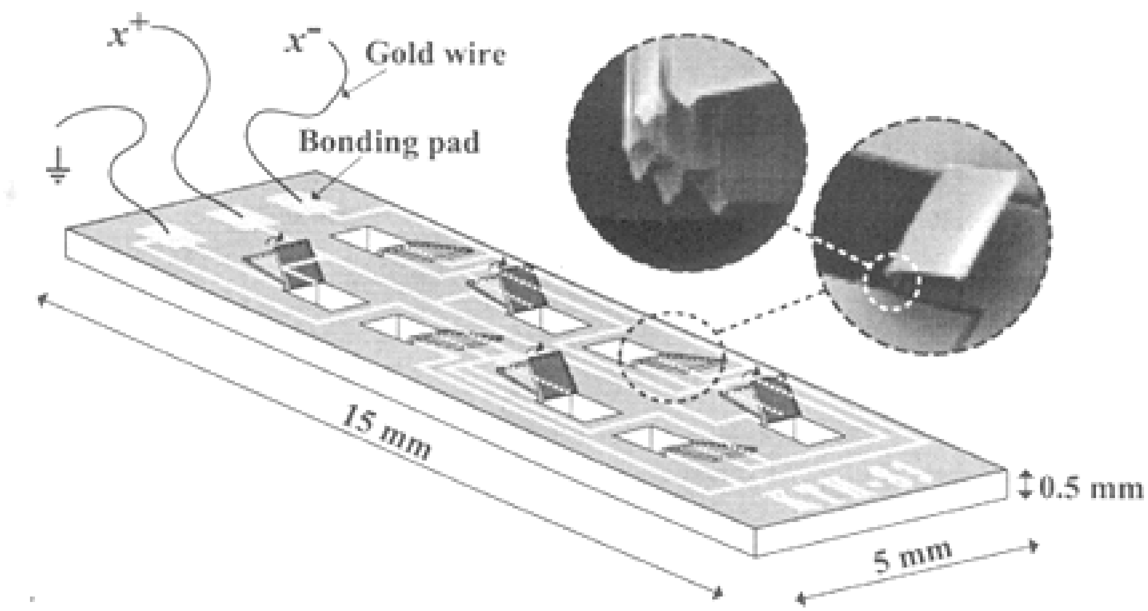


Fig. 3. An up-side down view of the micro-robot with two set of legs (four of each x^+ and x^-). With three bonding pads the robot can walk forward and backward. By driving the legs on the left and right side at different speeds or stroke length like a caterpillar (requires 5 wires) the robot can make left-right turns. The SEM-photos show silicon leg with a length of 500 µm and a close-up of a five V-groove polyimide joint.

A WALKING SILICON MICRO-ROBOT

FABRICATION

The fabrication process is schematically shown in Fig. 4 [10, 14]. The key steps are: (*a*) forming the integrated heater using LPCVD-deposited poly-silicon encapsulated in low-stressed silicon nitride and anisotropic KOH etching of 30 μm deep V-grooves. (*b*) local silicon dioxide (LOCOS) growth, forming via holes to the heaters, patterning the 1.5 μm thick aluminium conductors deposited by sputtering. (*c*) spinning and patterning the polyimide in the V-grooves, a backside 500 μm KOH silicon etch. (*d*) dicing the robot (from the back-side), a BHF oxide etch and solvent cleaning to release the 30 μm thick silicon legs and the protecting wafer, finally a polyimide curing in an oven to erect the legs.

Several different versions of the micro-robot have been fabricated:

- Polyimide joint actuator variants: with 3 and 4 V-grooves
- Leg variants: 2x6 with a length of 500 μm and 2x4 with a length of 1000 μm
- Steering variants: two groups of four or six legs (3 bonding pads for back and forth) and four groups of two or three legs (5 bonding pads for back and forth + right and left)
- Two DOF-legs (both knee and ankle joint) for walking up/down steps or on rough surfaces.

Fig. 3. An up-side down view of

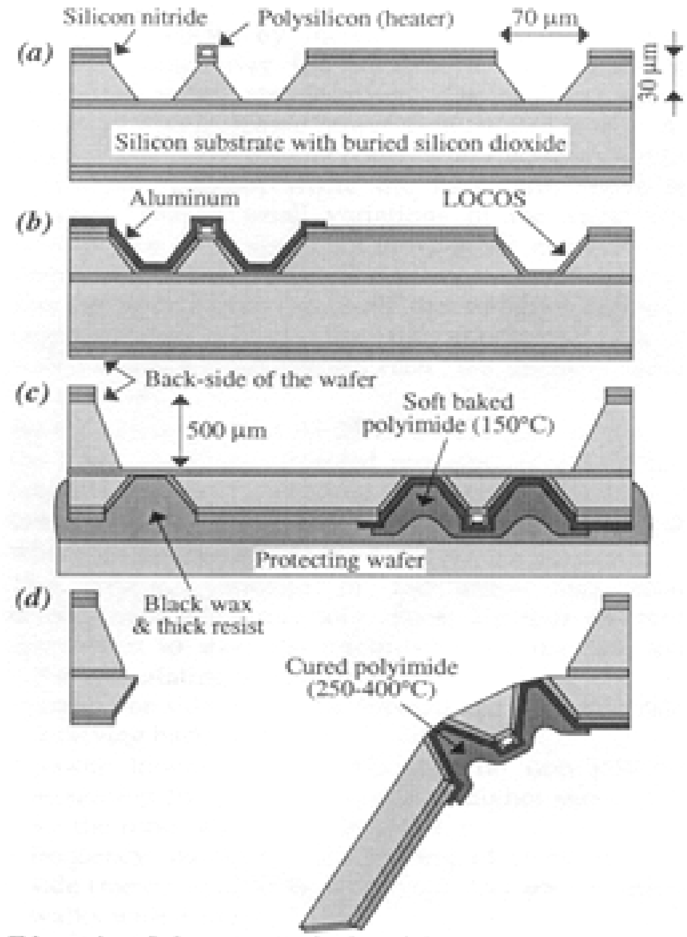


Fig. 4. Schematic of the fabrication process based on SOI-wafers.

A WALKING SILICON MICRO-ROBOT

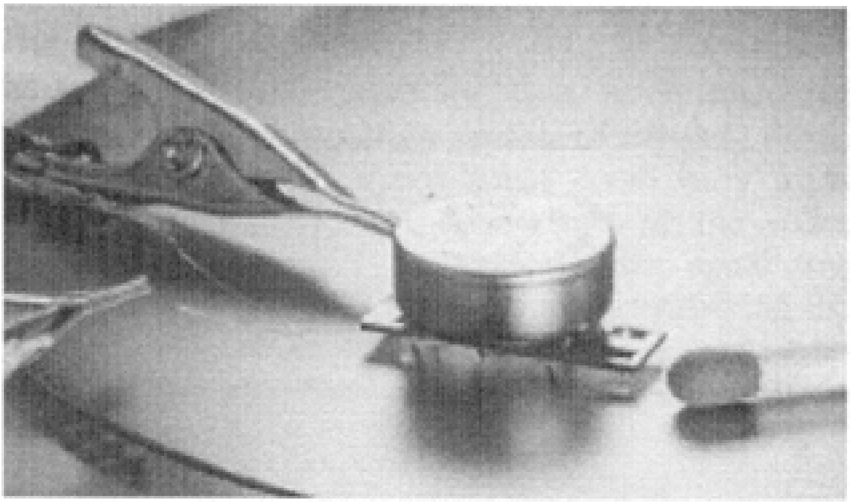


Fig. 5. The micro-robot during a load test. The load of 2500 mg is equivalent to maximum 625 mg/leg (or more than 30 times the weight of robot itself). The power supply is maintained through three 30 μm thin and 5 to 10 cm long bonding wires of gold.

Table 1. Characteristic measurements of the polyimide joint actuators.

Curing temp, T / shrinkage, ε	350 °C / 40% (3 V-grooves) 280 °C / 30% (4 V-grooves)
Life-time	> $2\cdot10^8$ load cycles
Stroke length, Δx / power consumption, P	< 340 μm / < 175 mW (for 1 mm leg with 4 V-grooves)
Cut-off frequency, f_c	3 – 4 Hz (-3 dB)
Force / displacement (before plastic deform.)	50-100 mN / 250-400 μm

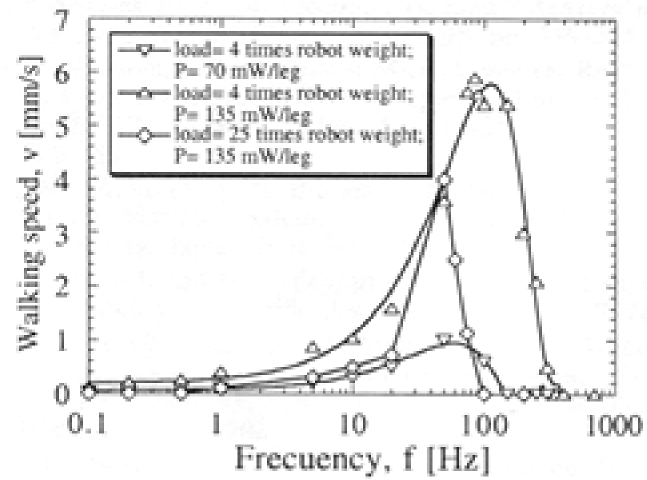
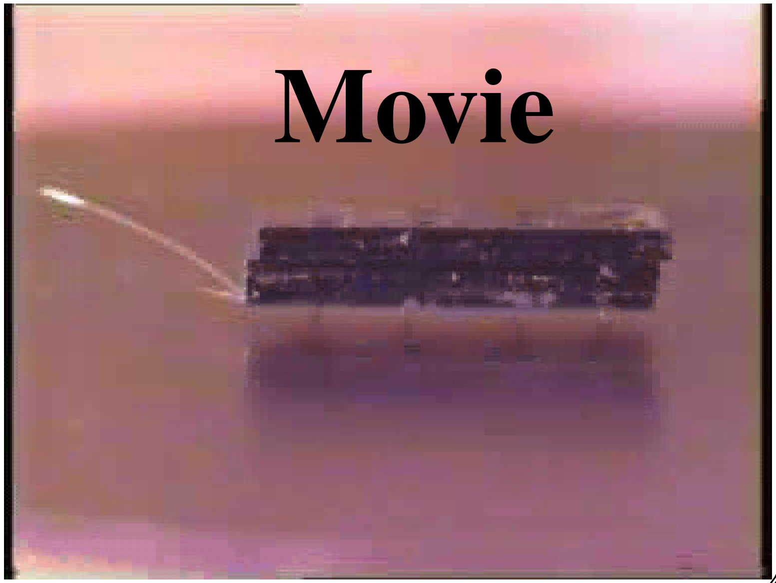


Fig. 6. Walking speed as a function of frequency for different loads and power.

A WALKING SILICON MICRO-ROBOT

CONCLUSION

This paper has presented the first batch fabricated walking silicon micro-robot capable of carrying loads. The polyimide joint based robot could carry loads more than 30 times the dead-weight of the robot itself. The maximum measured walking speed was 6 mm/s with potential to improve by modifying the steering. The challenge for the future is to create tele-operated and autonomous micro-robots on a single silicon chip.



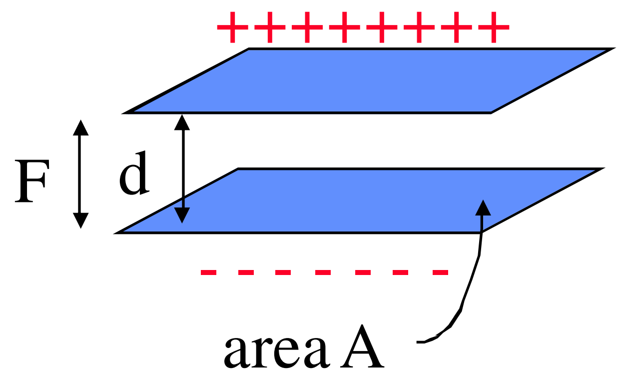
CAPACITIVE ELECTROSTATIC FORCE

Energy stored in a parallel plate capacitor W with area A and space between plates of d

$$W = \frac{1}{2} QV = \frac{1}{2} CV^2$$

since Q = CV

The energy stored in a capacitor can be equated to the force times distance between the plates



$$W = Fd \quad \text{or} \quad F = W/d$$

$$C = \frac{\varepsilon_o \varepsilon_r A}{d}$$

$$F = \frac{\varepsilon_o \varepsilon_r A V^2}{2d^2}$$

ε_o = permitivitty of free space = 8.85e-12 Farads/m

ε_r = relative permitivitty (for air ε_r = 1)

ELECTROSTATIC FORCE EXAMPLE

Example: 100 µm by 100 µm parallel plates
space = 1 µm, voltage = 10 V

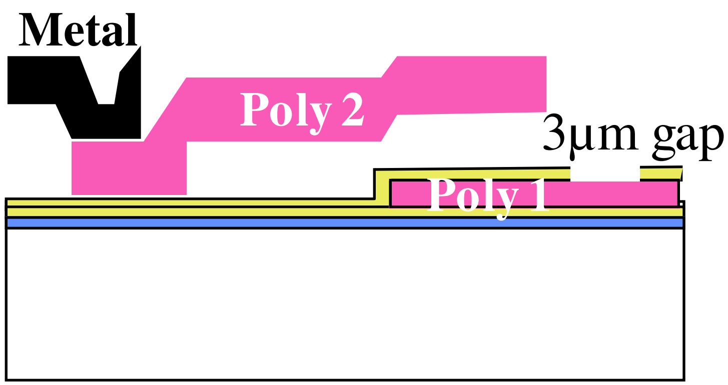
Find the force of attraction between the two plates

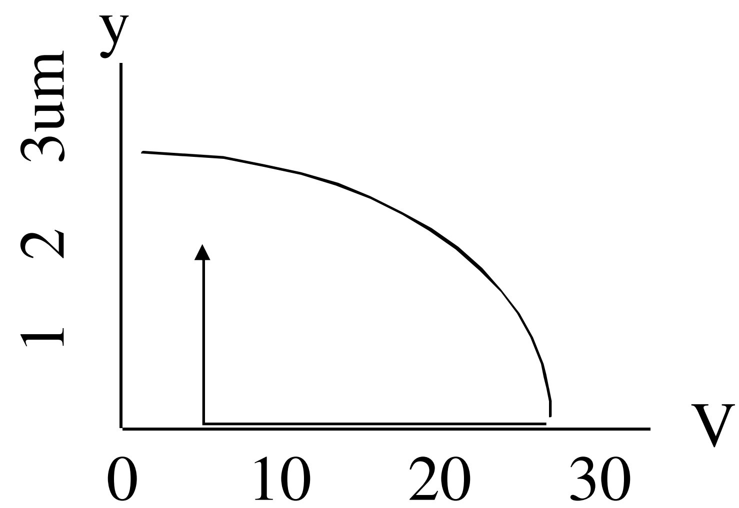
$$F = \frac{\varepsilon_o \varepsilon_r A V^2}{2d^2}$$

$$F = \frac{(8.85e\text{-}12)(1)(100e\text{-}6)(100e\text{-}6)(10)^2}{2(1e\text{-}6)^2}$$

F = 4.42e-6 newtons

MEMS CANTILEVER WITH ELECTROSTATIC ACTUATOR

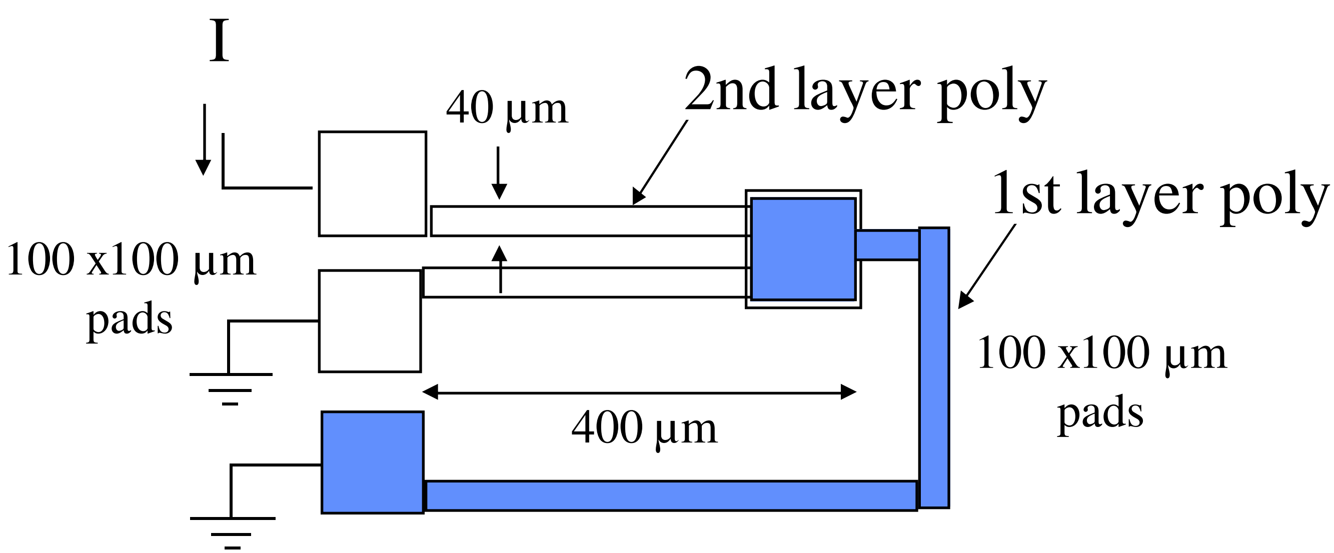




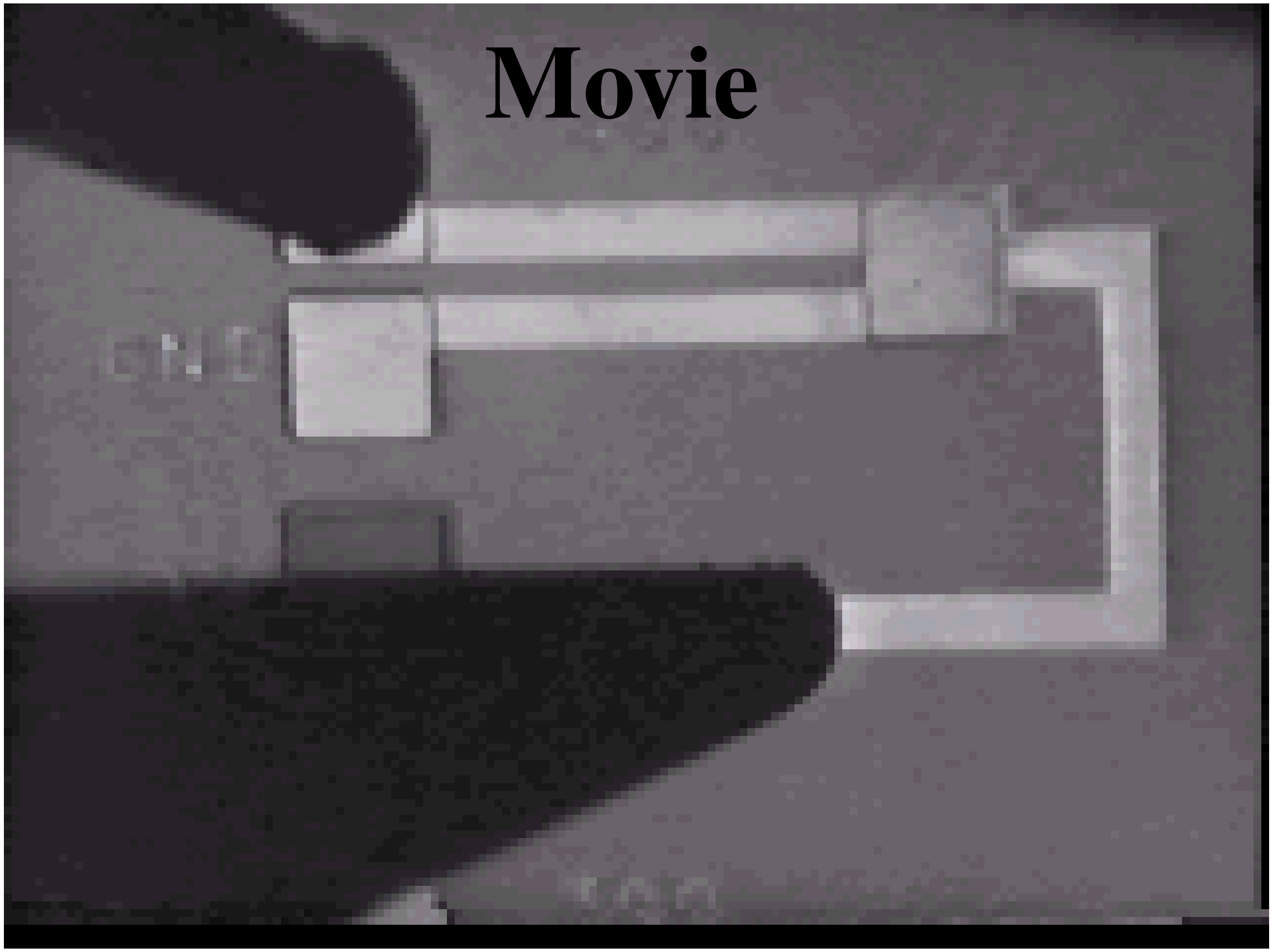
As the voltage is increased the electrostatic force starts to pull down the cantilever. The spring constant opposes the force but at the same time the gap is decreased and the force increases. The electrostatic force increases with $1/d^2$ so eventually a point is reached where it is larger than the spring force and the cantilever snaps down all the way. The voltage has to be reduced almost to zero to release the cantilever.

MEMS CANTILEVER WITH ELECTROSTATIC ACTUATOR

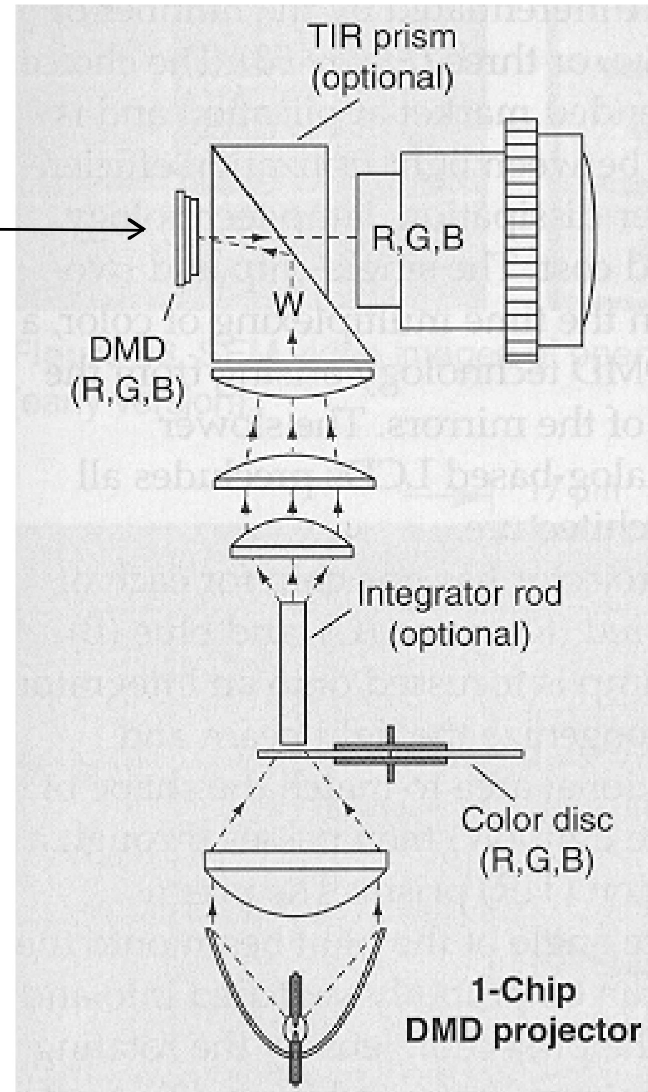
Example: Plot the displacement versus current assuming poly sheet resistance of 200 ohms/sq, a piezoresistance coefficient of 1e-10 cm/dyne, d=1.5 µm, h=2µm and other appropriate assumptions.



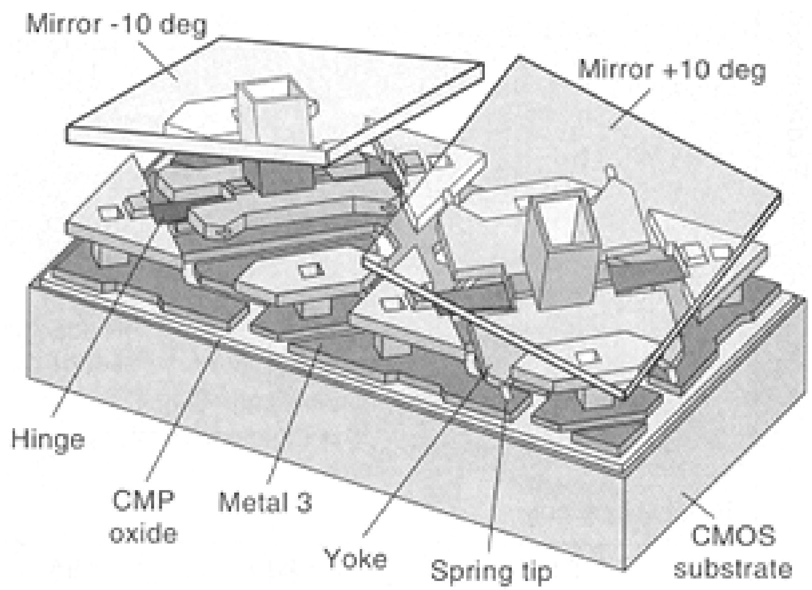
ELECTROSTATIC FORCE MOVIE

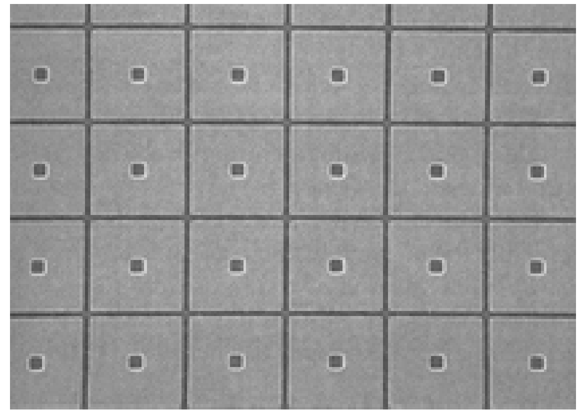


DIGITAL LIGHT PROJECTION SYSTEM



TI DLP - ELECTROSTATIC MIRRORS





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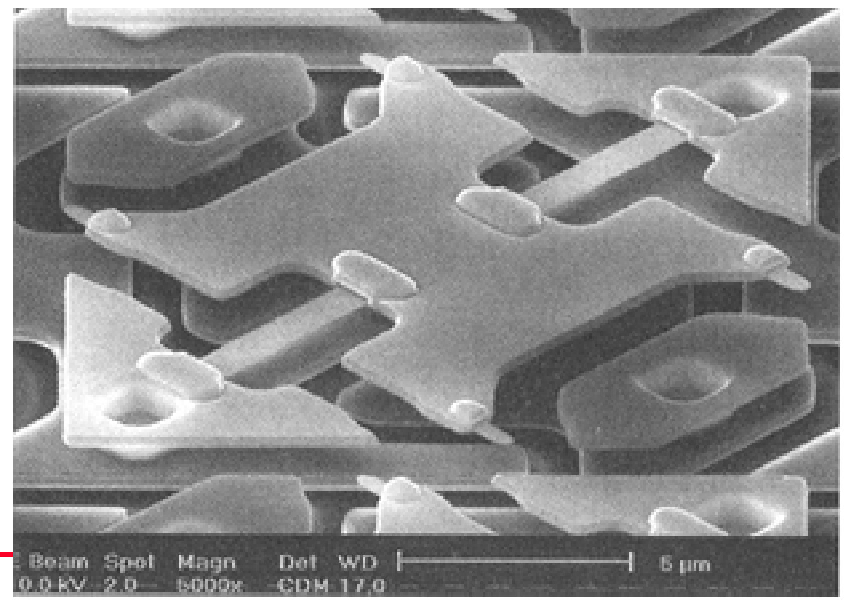
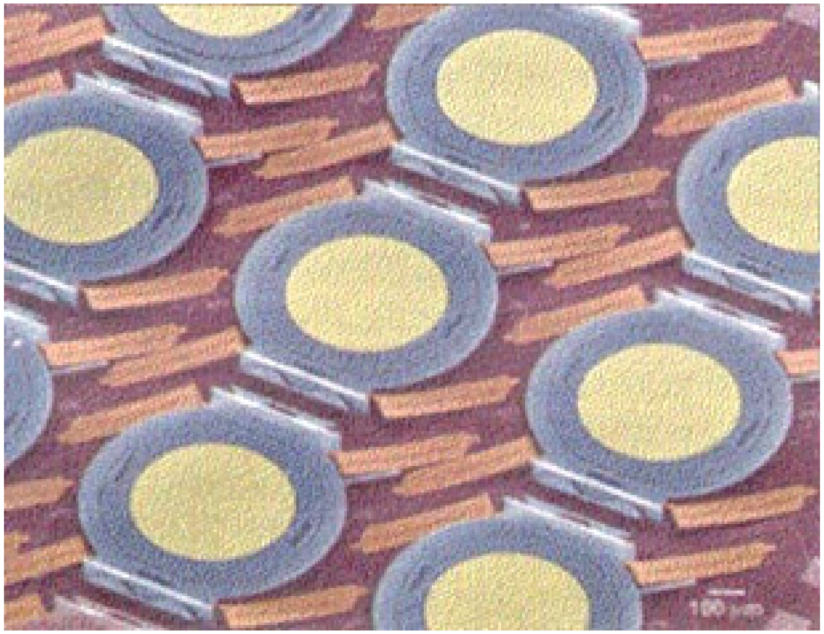
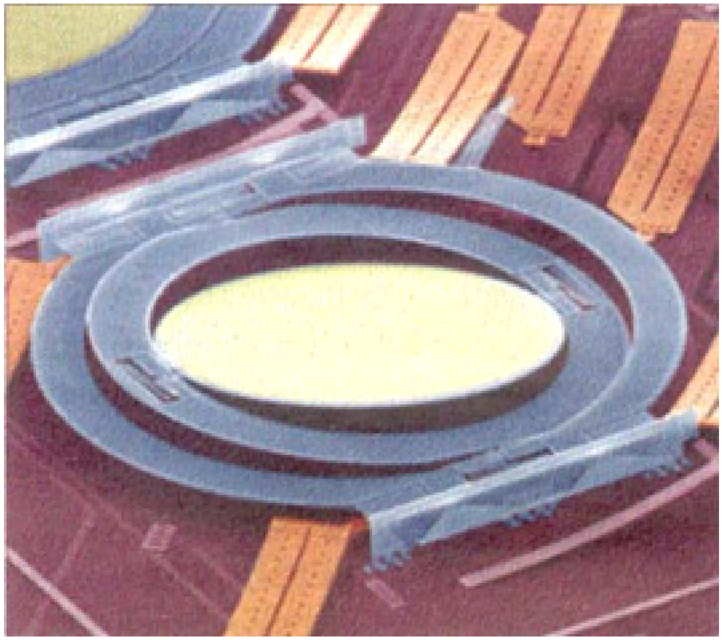
Torrisonal Mirrors Can Tilt Along One Axis



ELECTROSTATIC MIRROR

MOEMs - Micro Optical Electro Mechanical Systems

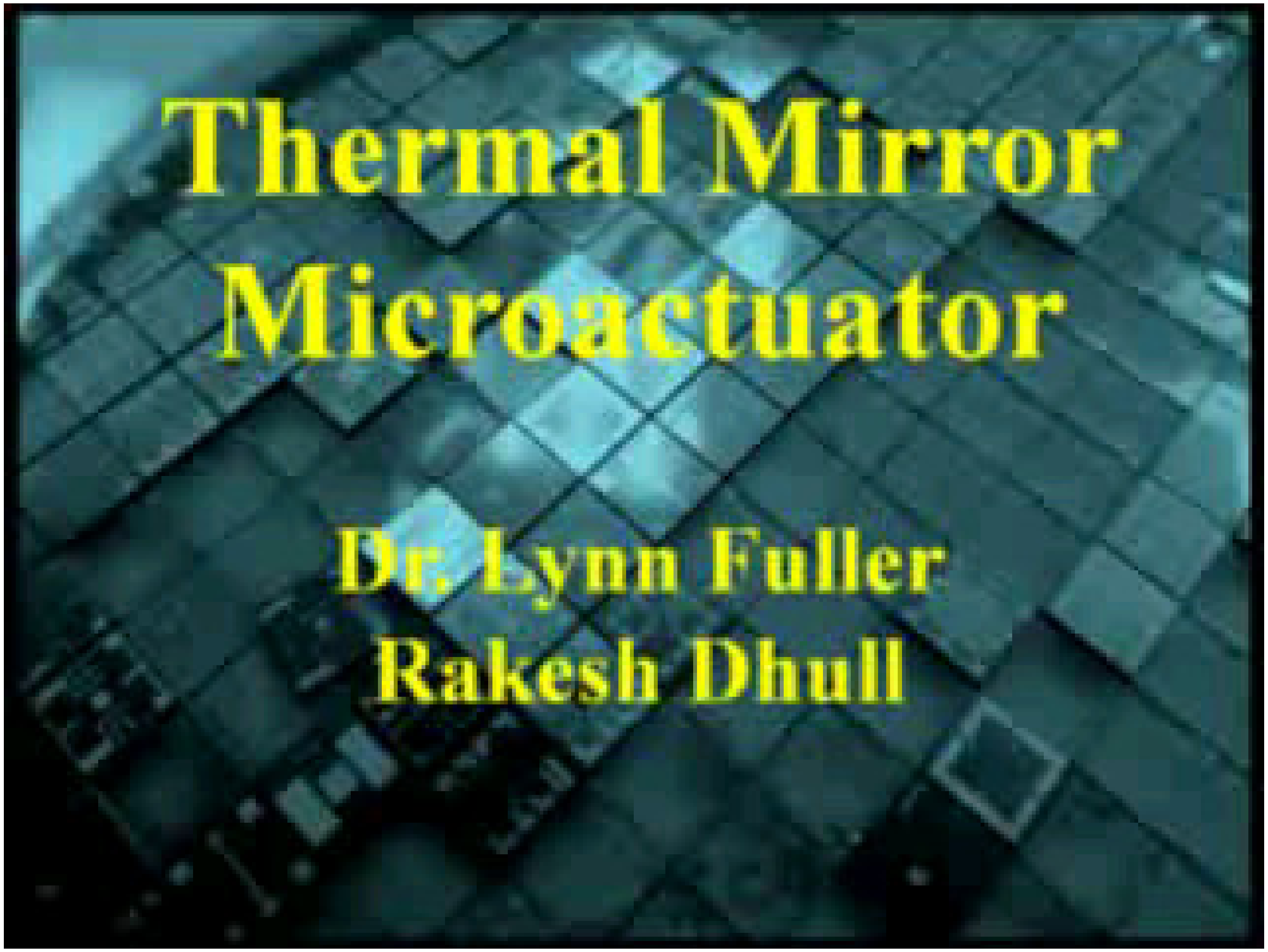




Lucent Technologies–Lambda Router (256 mirror fiber optic multiplexer)

Nested Torrisonal Mirrors Can Tilt Along Three Axis

THERMALLY ACTUATED MICRO MIRROR



ELECTROSTATIC IMPACT-DRIVE MICROACTUATOR

Electrostatic Impact-Drive Microactuator

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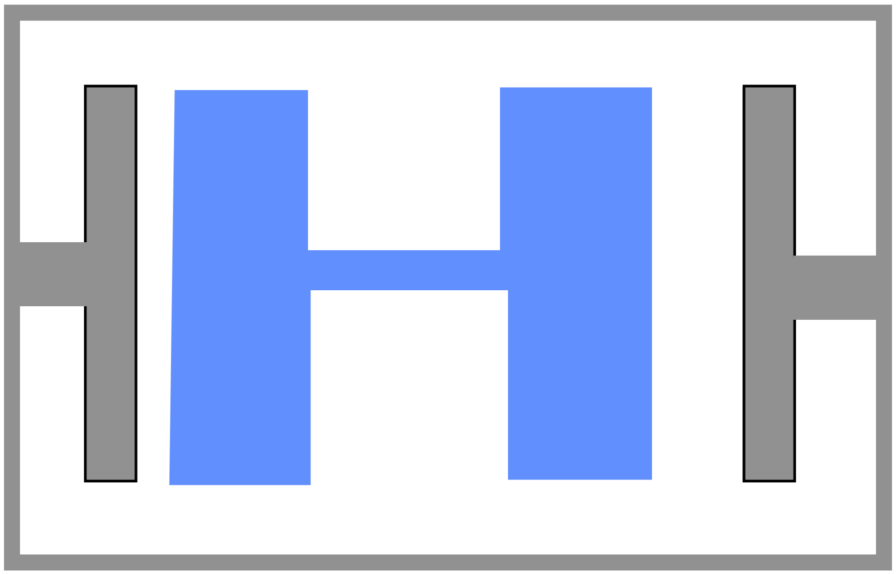
ABSTRACT

A fully packagable micromachined actuator was developed for generating precise but unlimited displacement. A suspended silicon mass is encapsulated between glass plates and driven by electrostatic force. By hitting a stopper, it generates impact force to drive the whole actuator in a small step (~10nm). It is a micromachined and electrostatic version of the impact-drive actuator.

ELECTROSTATIC IMPACT-DRIVE MICROACTUATOR



ELECTROSTATIC IMPACT-DRIVE MICROACTUATOR

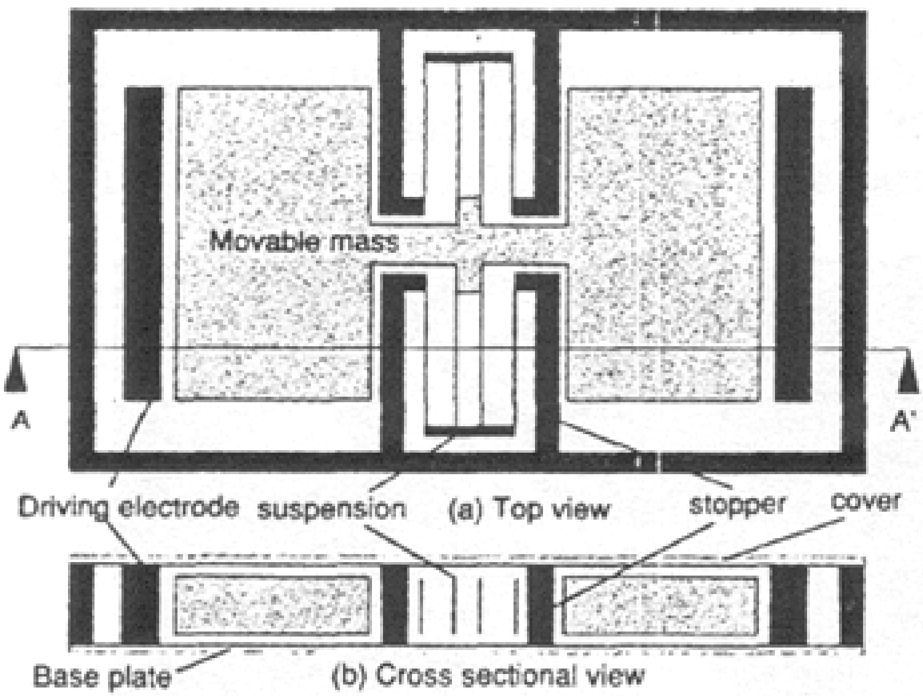


Figure 1: Structure of impact actuator

1. Actuator can generate high power
2. Maintain a position precisely
3. Move a long distance.

ELECTROSTATIC IMPACT-DRIVE MICROACTUATOR

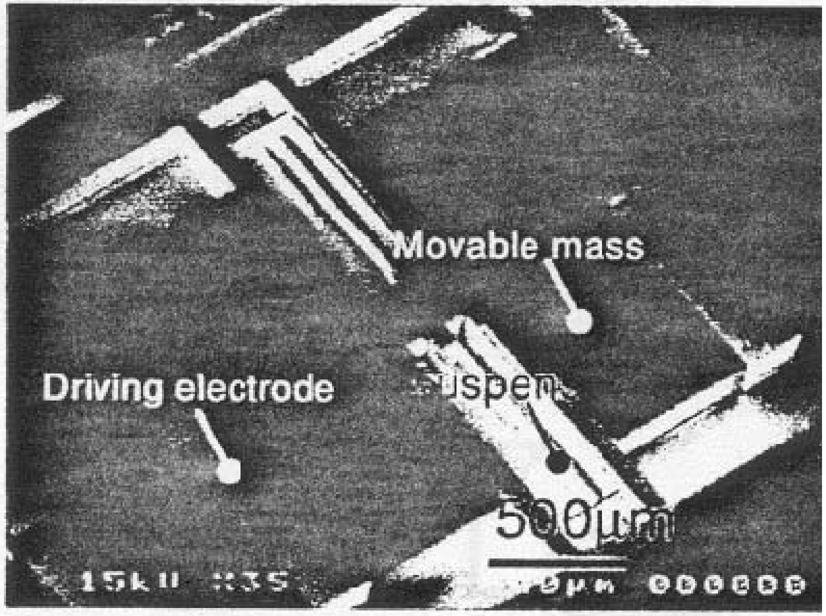


Figure 4: SEM view of the actuator

FABRICATION PROCESS

Figure 3 shows the fabrication process. We made the actuator from a silicon wafer by using dry bulk micromachining.

(a) First, we apply an aluminum layer on the 255µm-thick silicon wafer and patterned aluminum to define an external wall and fixed electrodes. The same pattern was formed on the backside by photolithography for fixed parts like anchor and driving electrode.

(b) We perform ICP-RIE from the backside of the wafer and define the recess to release the movable structure. In this time, fixed parts are not etched.

(c) After photoresist removal by O_2 plasma ashing, the wafer is bonded on a Pyrex glass by anodic bonding.

(d) The second lithography on the front side defines the mass and suspensions.

(e) After dicing the wafer into individual samples, ICP-RIE is performed from the front side.

(f) We remove the photoresist mask and perform ICP-RIE again. (delay-masking process [3]) Movable parts can be released from top glass.

(g) Finally, a glass is bonded on top of the sample to encapsulate the structures completely.

ELECTROSTATIC IMPACT-DRIVE MICROACTUATOR

Testing

Figure shows test results for 1Hz actuation, each impact gives 20 nm displacement

Lifetime looks good. Test for 1 month, 550 million collisions, no visible problems

Energy was supplied to actuator by wireless RF transmision

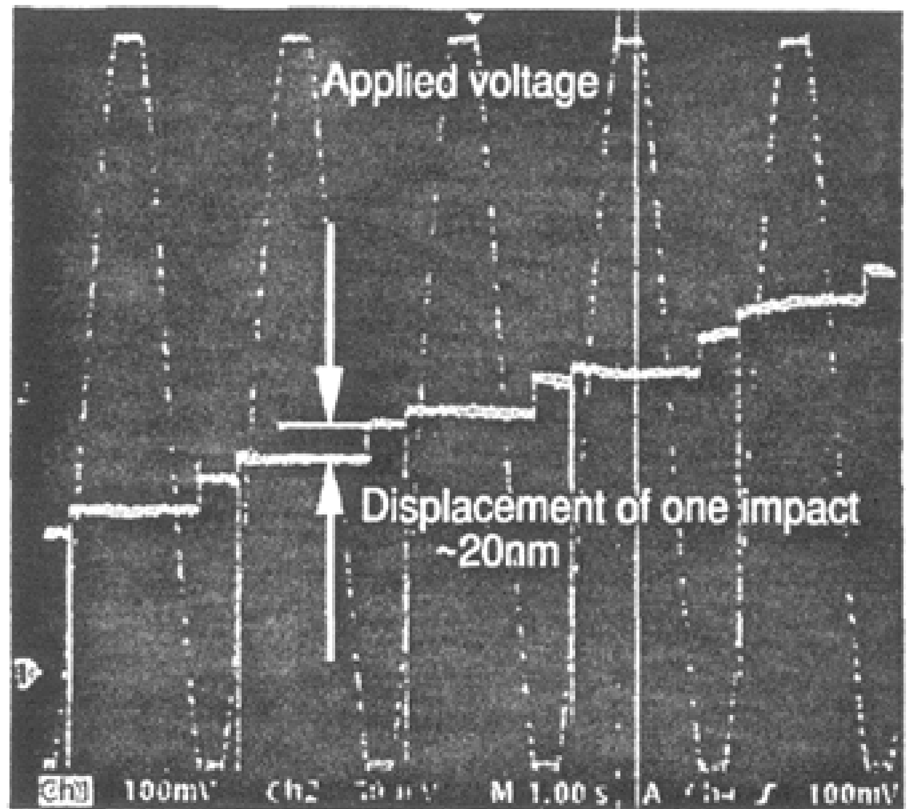


Figure 7: Displacement of one impact

ELECTROSTATIC IMPACT-DRIVE MICROACTUATOR

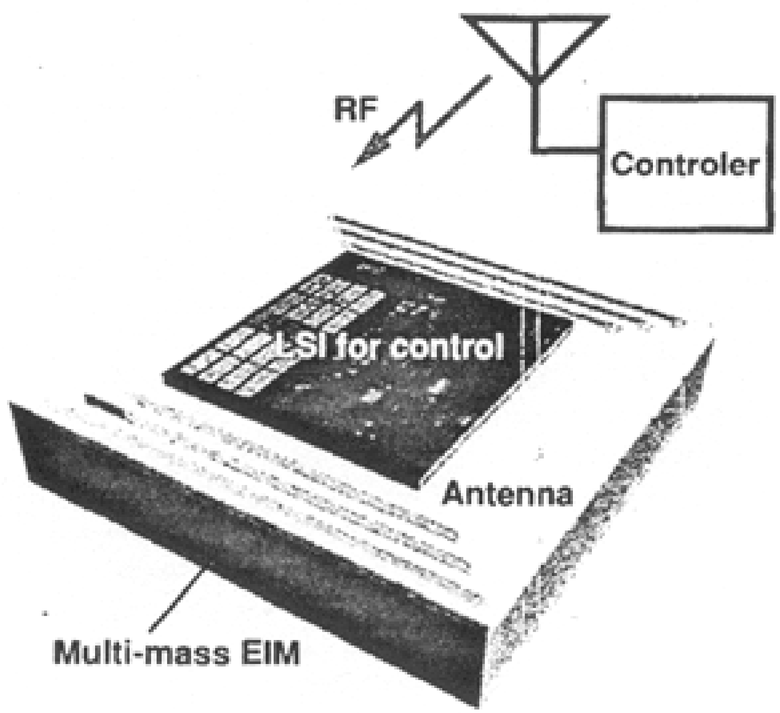


Figure 9: Wireless energy supply system

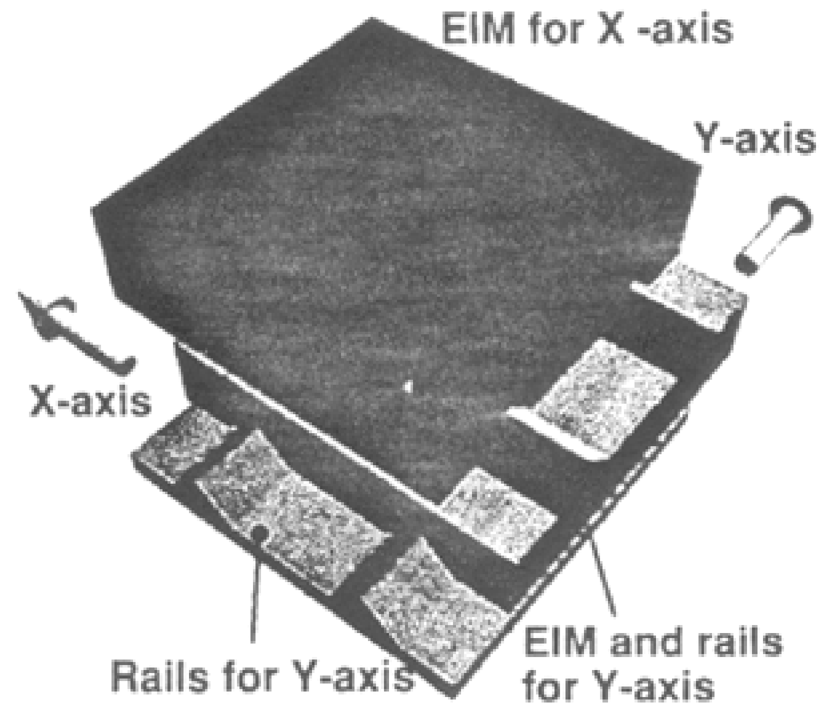


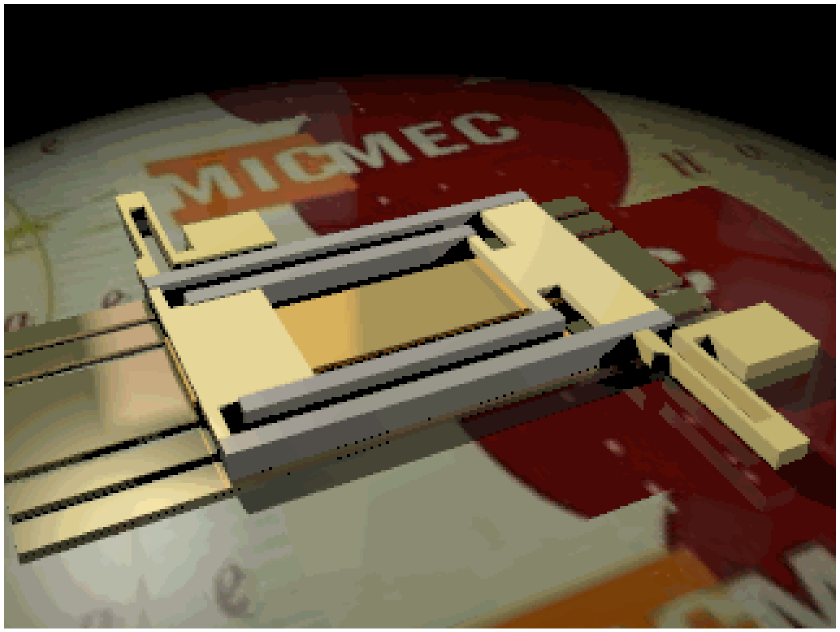
Figure 10: Micro X-Y stage

ELECTROSTATIC IMPACT-DRIVE MICROACTUATOR

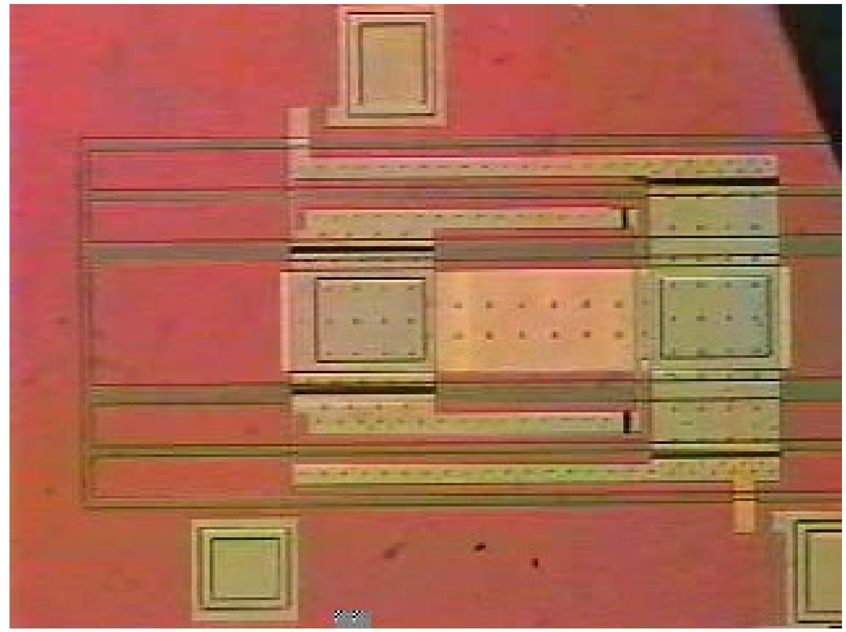
Conclusion

A New type of actuator is described
Diven by electrostatic force
~15 nm per impact at 100 Volts
Speed of 2.7 um/sec at 200 Hz
Life greater than 550 million impacts

SHUFFLE MOTOR MOVIES



Movie

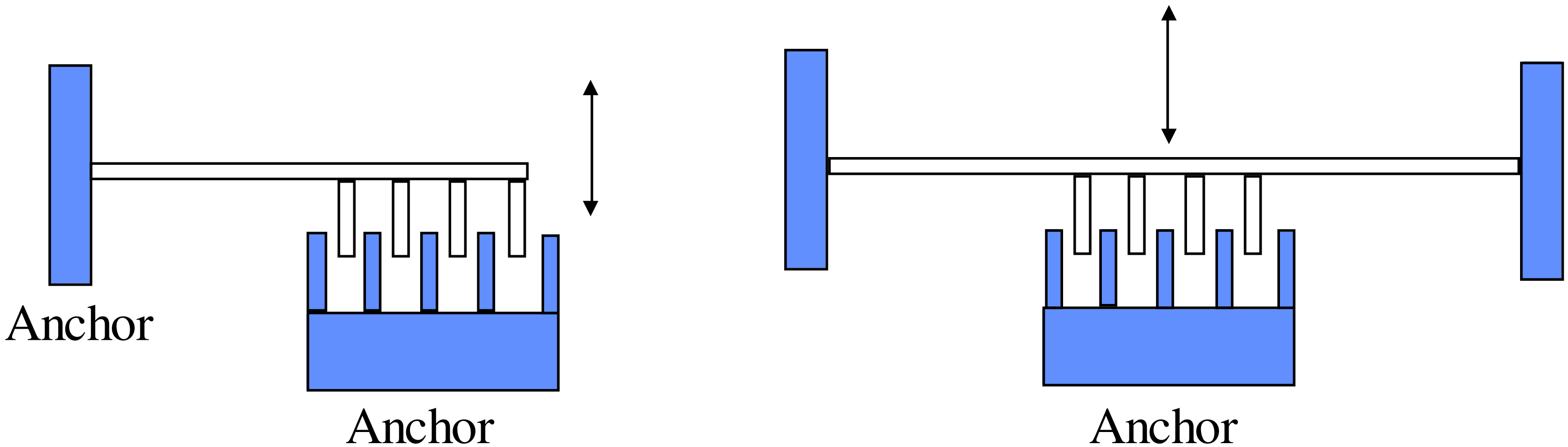


Movie

What actuation mechanism is this?

GAP COMB DRIVE MICROACTUATORS

Electrostatic movement parallel to wafer surface

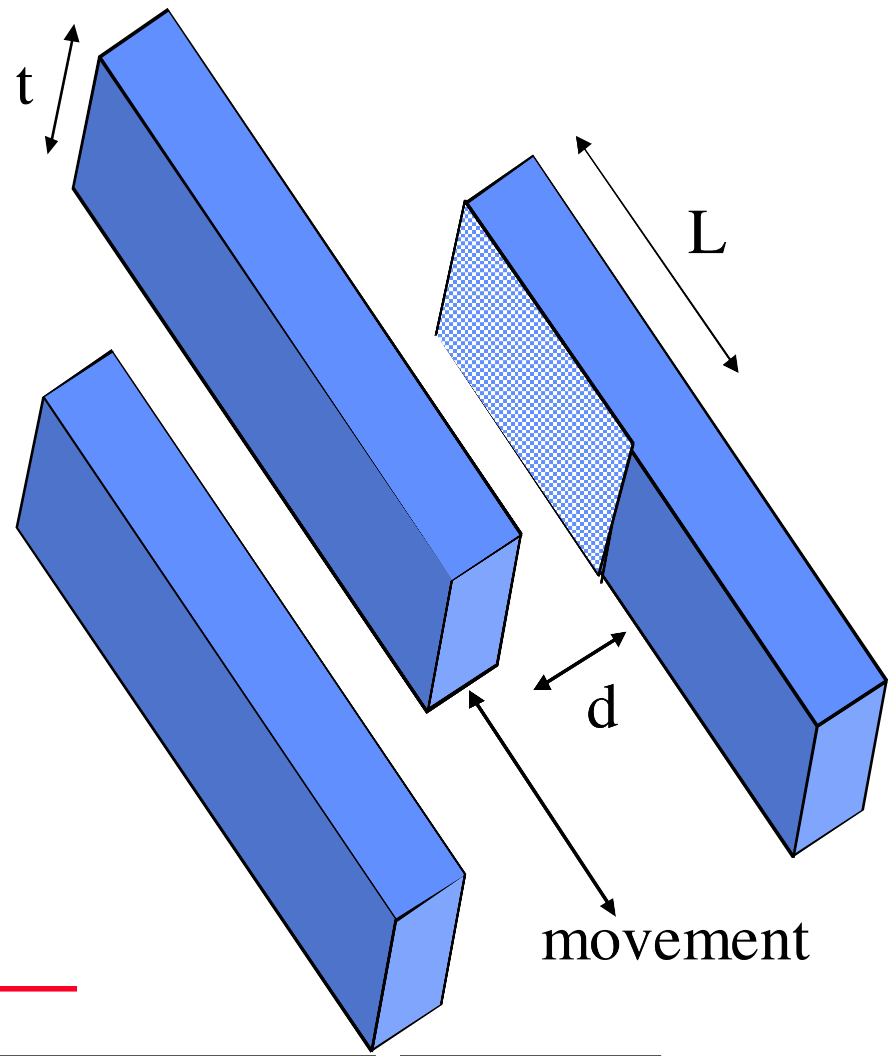


From Jay Zhao

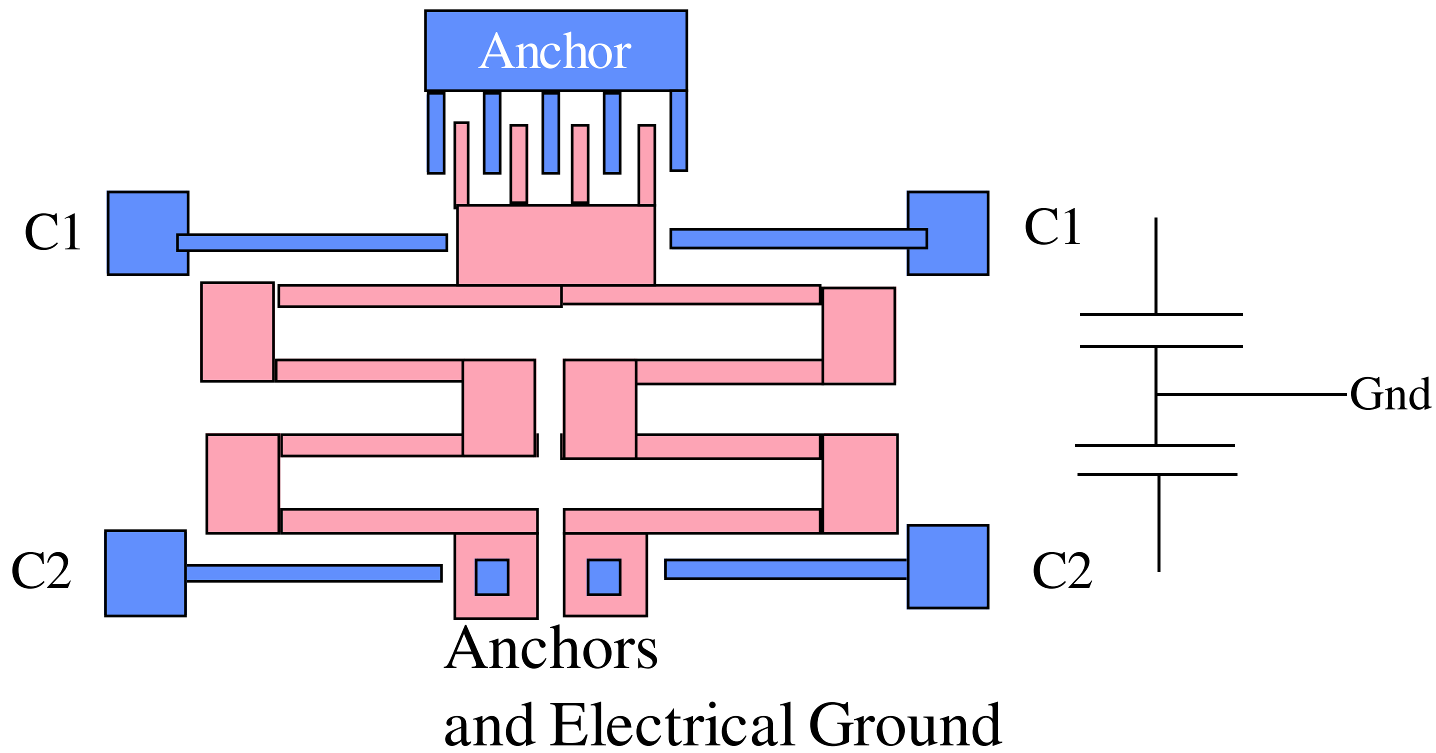
CALCULATION OF DISPLACEMENT VS VOLTAGE

$$C = \varepsilon r \, \varepsilon o \; t \; L/d$$

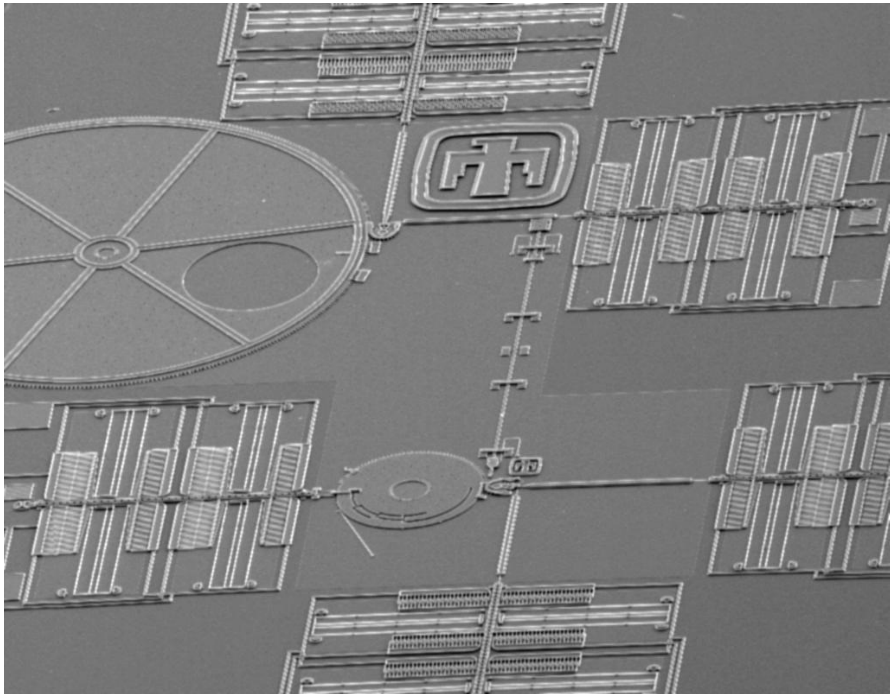
$$F = \varepsilon r \, \varepsilon o \; t \; V^2 / 2 \, d$$

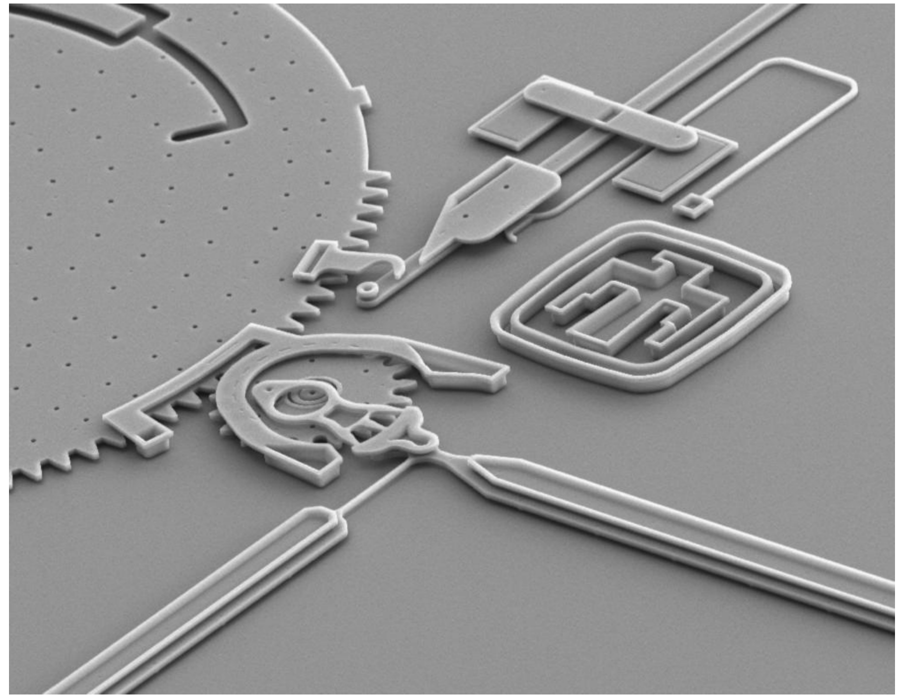


COMBINED SPRING ELECTROSTATIC DRIVE AND CAPACITIVE OR PIEZORESISTIVE READ OUT



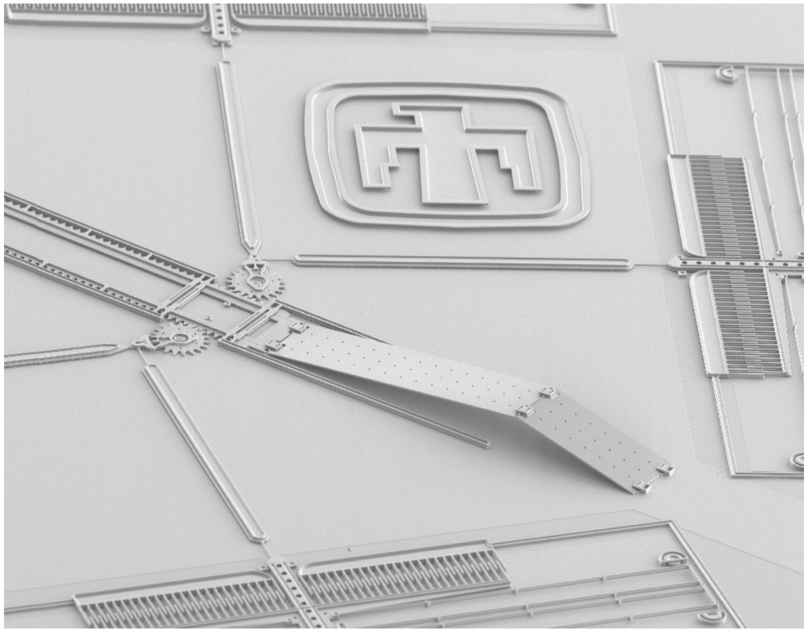
PICTURES & MOVIES OF ELECTROSTATIC COMB DRIVE





Movies at www.sandia.gov

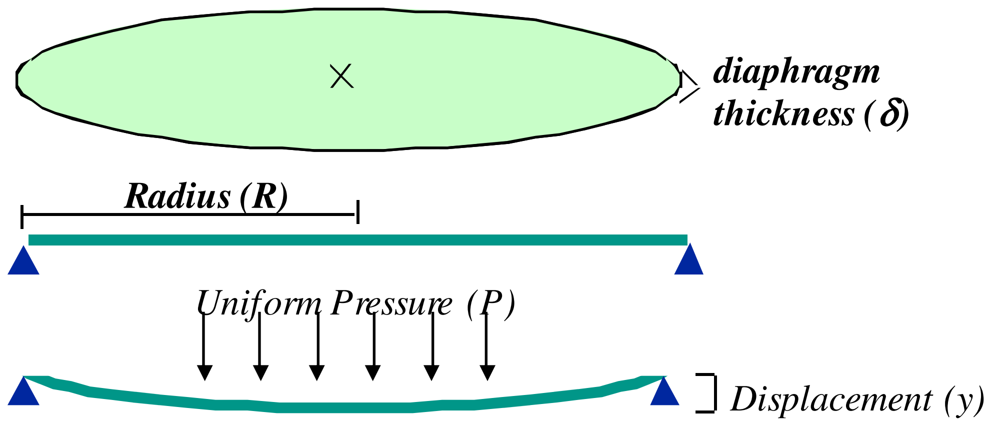
PICTURES & MOVIES OF ELECTROSTATIC COMB DRIVE



Movies at www.sandia.gov

DIAPHRAGM

Diaphragm: Displacement



Equation for deflection at center of diaphragm

$$y = \frac{3PR^4[(1/\nu)^2-1]}{16E(1/\nu)^2\delta^3} = \frac{(249.979)PR^4[(1/\nu)^2-1]}{E(1/\nu)^2\delta^3}$$

E = Young's Modulus, **ν** = Poisson's Ratio

for Aluminum **ν** =0.35

*The second equation corrects all units assuming that pressure is mmHg, radius and diaphragm is μm, Young's Modulus is dynes/cm^2, and the calculated displacement found is μm.

MECHANICAL PROPERTIES

	Density	Youngs Modulus	Yield	Ultimate Strength	Knoop Hardness	Poisson's Ratio
	gm/cm^3	10^{12}dyne/cm^2		10^{10} dyne/cm^2		Kgm/mm^2
Single Crystal Silicon	2.33	1.9	12	15	850	0.28
Poly Silicon	2.33	1.5	12	18	850	0.28
Silicon Dioxide	2.19	0.73	8.4	16	570	0.3
Silicon Nitride	3.44	3.85	14	28	3486	0.3
Aluminum	2.7	0.68	17		150	0.334
Nickel	8.9	2.07	59	310	112	0.31
Chrome	7.19	2.54		83	170	0.3
Copper	8.96	1.20	33	209		0.308
Gold	19.3	0.78		103		0.44
Tungsten	19.3	4.1	4	98	350	0.28
Titanium	4.5	1.05	140	220	100	0.34
Tantalum	16.6	1.86		35	124	0.35

10 dyne/cm^2 = 1 newton/m^2

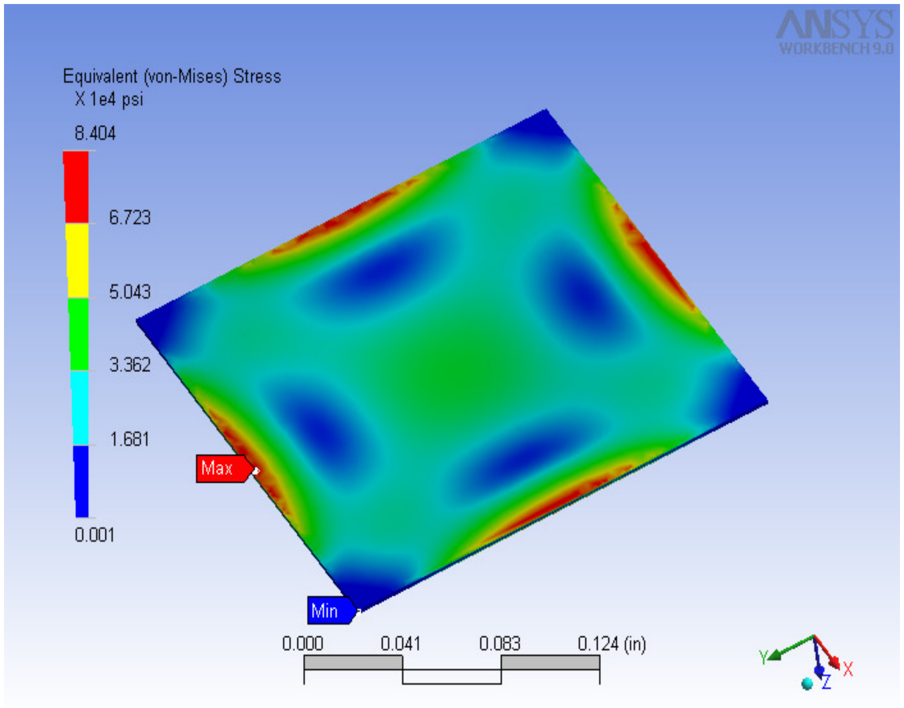
Metals Handbook

CALCULATOR FOR DIAPHRAGM DEFLECTIONS

Rochester Institute of Technology					5-Apr-06
Dr. Lynn Fuller	Microelectronic Engineering, 82 Lomb Memorial Dr., Rochester, NY 14623				
Deflection Ymax = 0.0151 P $L^4(1-Nu^2)/EH^3$		Ymax =	0.17	µm	
	P = Pressure	P =	15	lbs/in2	
	L = Length of side of square diaphragm	L =	1000	µm	
	E = Youngs Modulus	E =	1.90E+11	N/m2	
	Nu = Poissons Ratio	Nu =	0.32		
	H = Diaphragm Thickness	H =	35	µm	
		P =	1.03E+05	Pascal	
Stress = 0.3 P $(L/H)^2$ (at center of each edge)		Stress =	2.53E+07	Pascal	
	P = Pressure	Yield Strength =	1.20E+10	Pascal	
	L = Square Diaphragm Side Length				
	H = Diaphragm Thickness				
Capacitance = eoer Area/d		C =	7.97E-11	F	
	eo = Permitivitty of free space = 8.85E-14 F/cm				
	er = relative permitivitty = 1 for air	Area =	9.00E-02	cm2	
	Area = area of plates x number of plates	N =	1		
	d = distance between plates	d =	1	µm	
		If round plates, Diameter =	0	µm	
		If square plates, Side =	3000	µm	

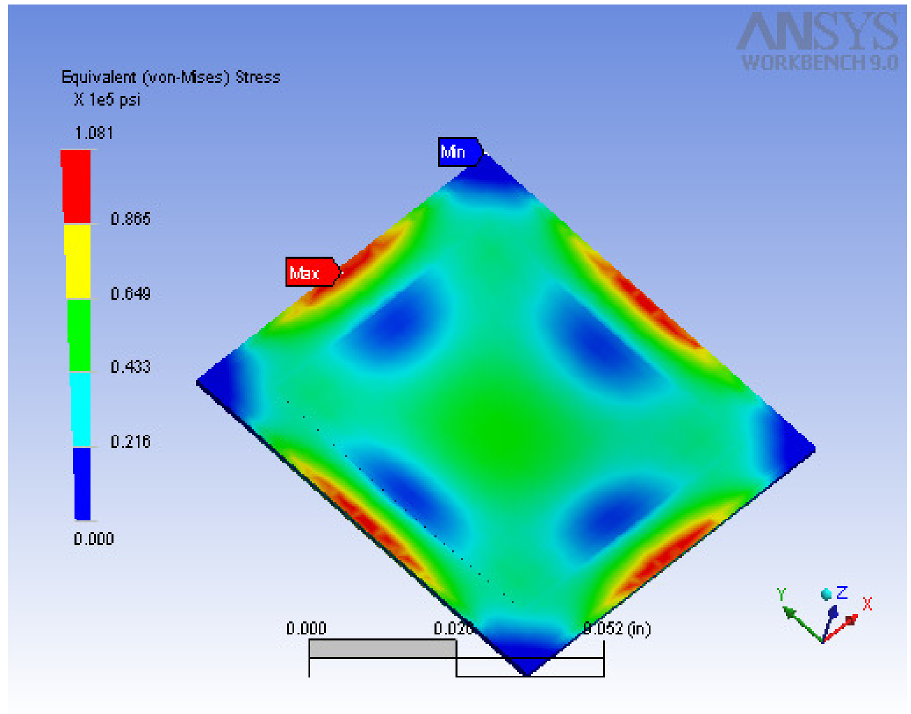
ANSYS FINITE ELEMENT ANALYSIS

Regular Si Diaphragm



Corrugated Diaphragm

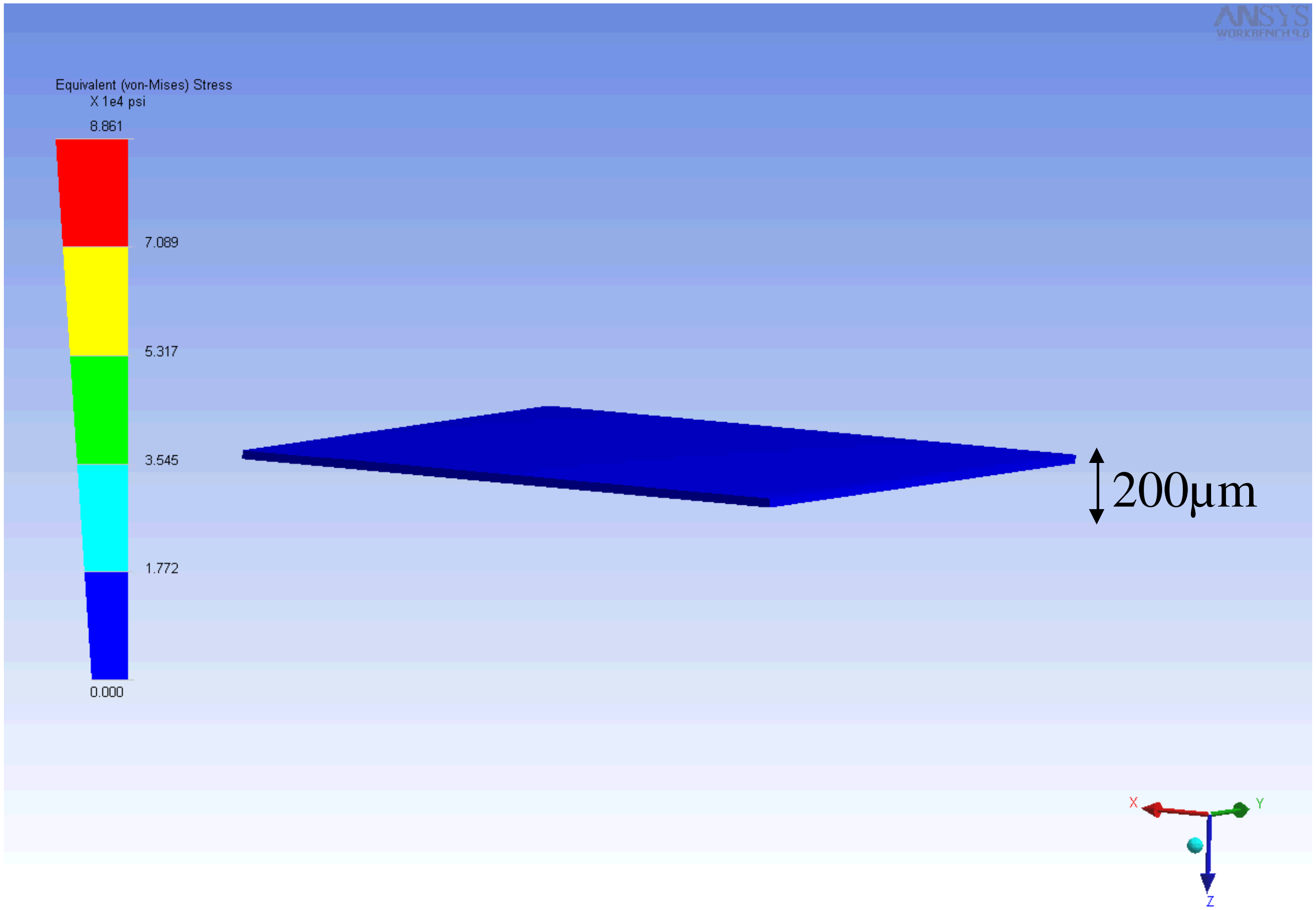
Layer 2: 1.5mm x 1.5mm Polysilicon 1µm thick



2mm x 2mm diaphragm 30µm thick, 50 psi applied

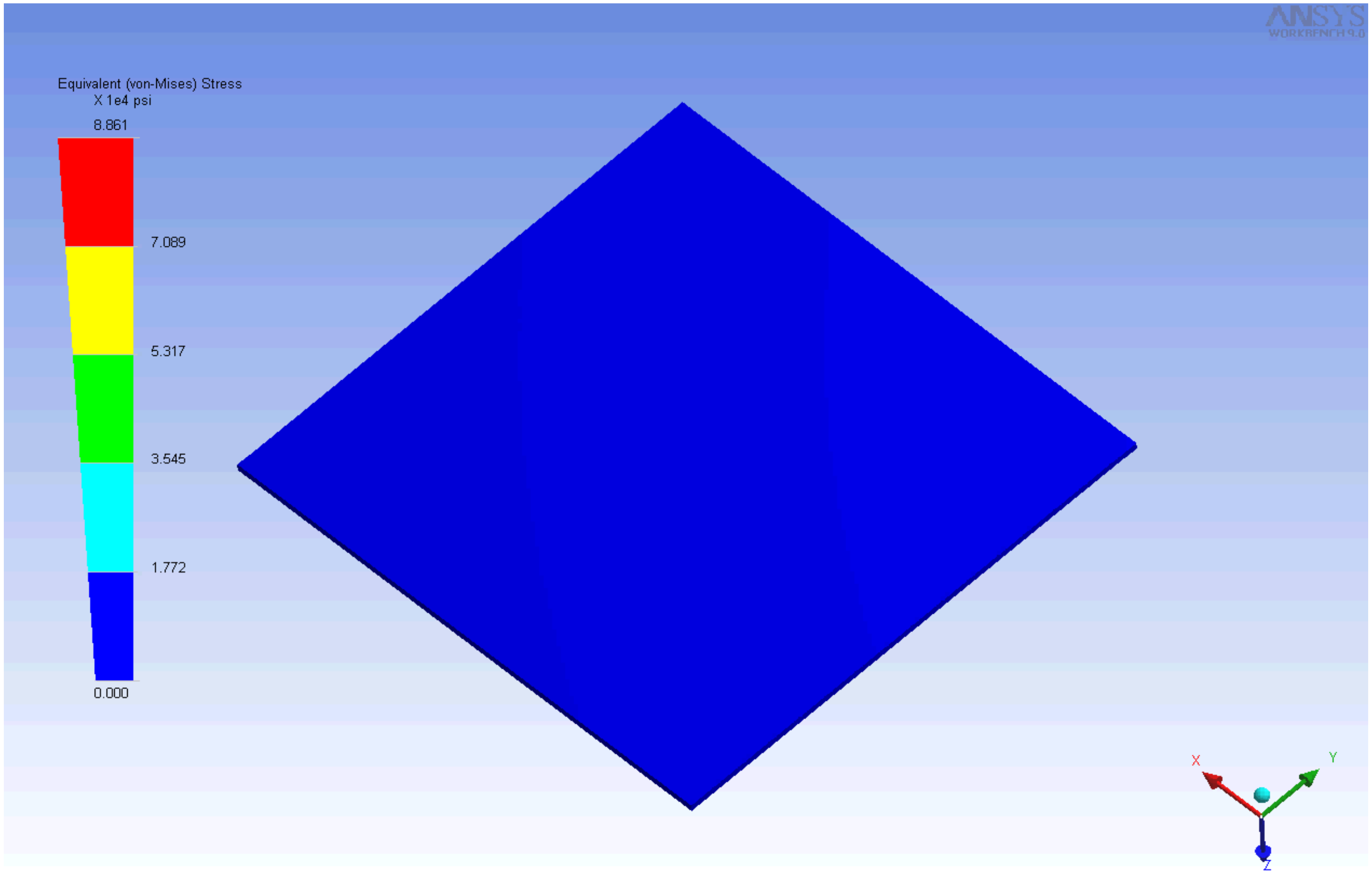
Rob Manley, 2005

DIAPHRAGM DEFORMATION MOVIE



Rob Manley, 2005

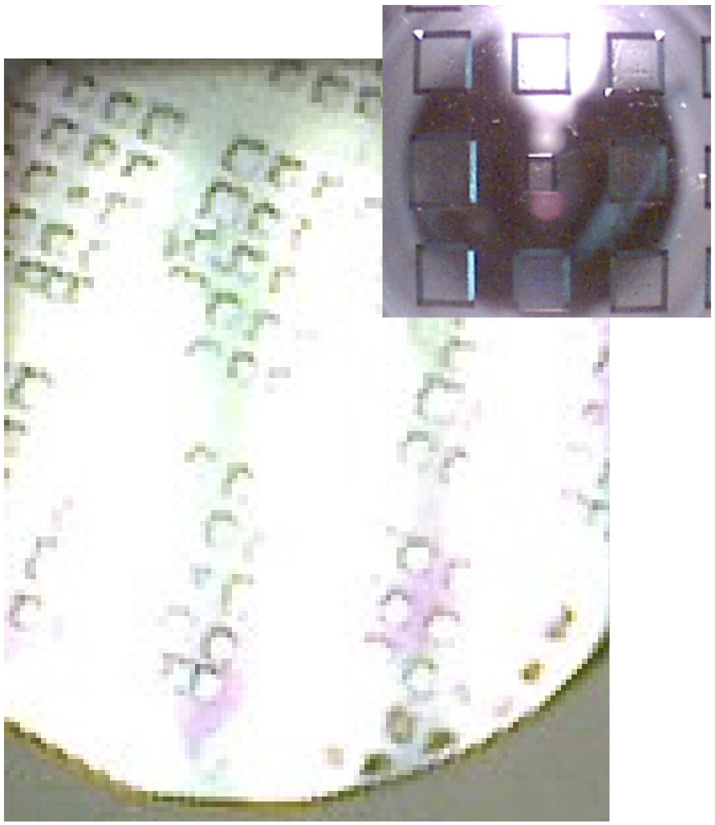
DIAPHRAGM STRESS MOVIE



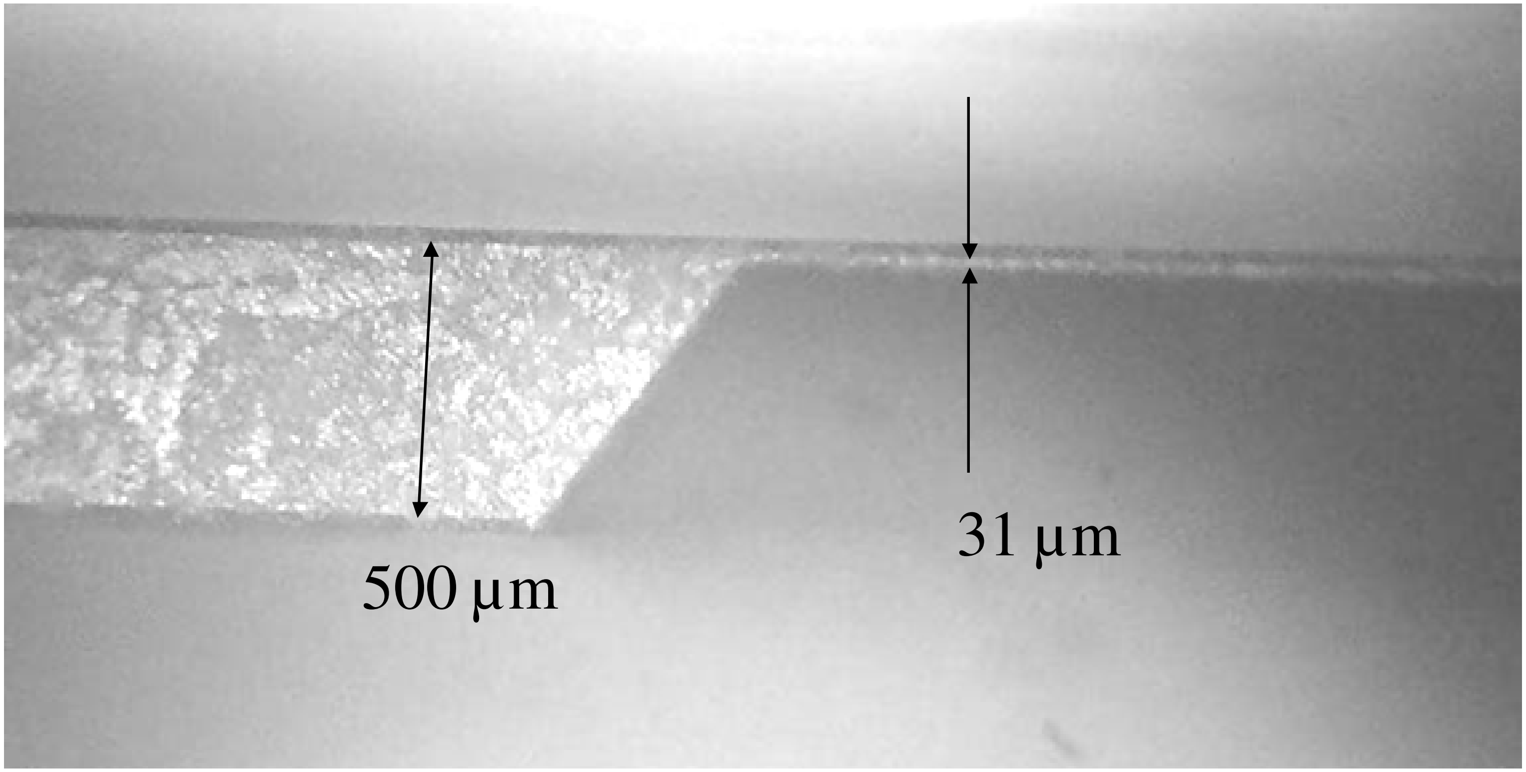
Rob Manley, 2005

PICTURES OF WAFER AFTER KOH ETCH

50 µm in 57 min ~.877 µm/min

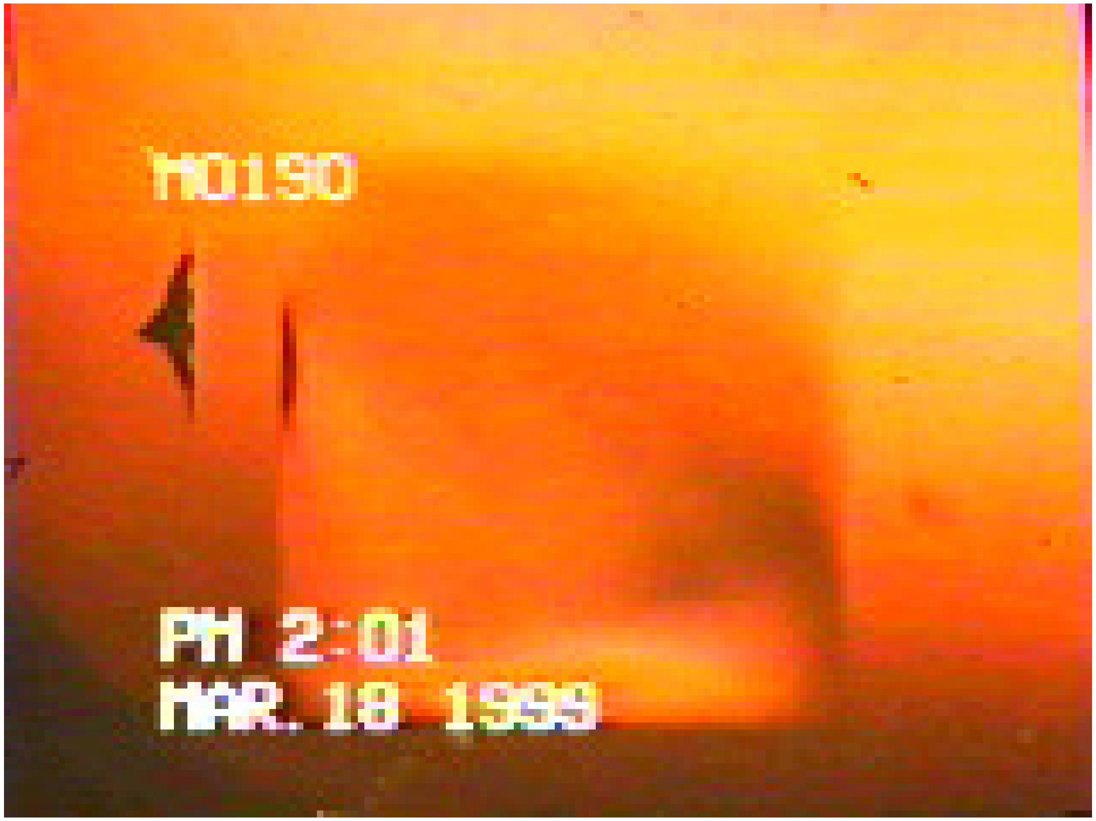


HEIGHT MEASUREMENT USING OPTICAL MICROSCOPE



20% KOH Etch, @ 72 C, 10 Hrs.

SQUARE DIAPHRAGM MOVIE



MAGNETIC TORSIONAL MIRROR

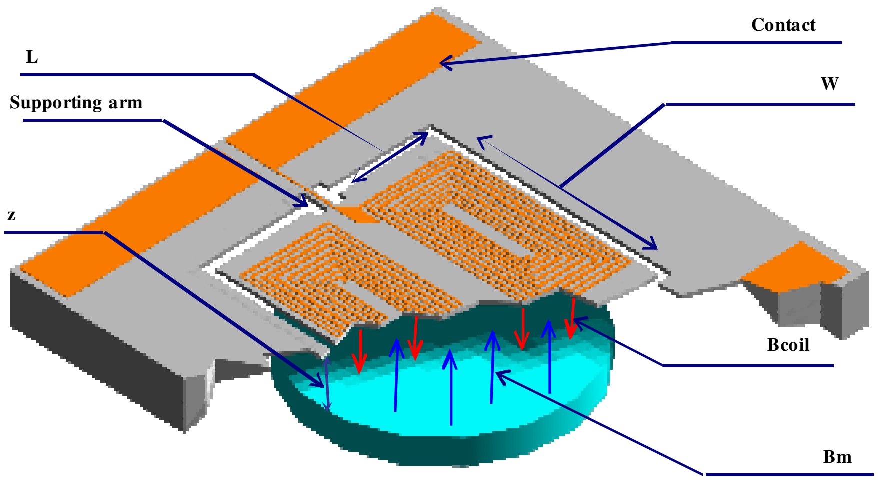


Figure 2: Cross sectional view labels with variables.

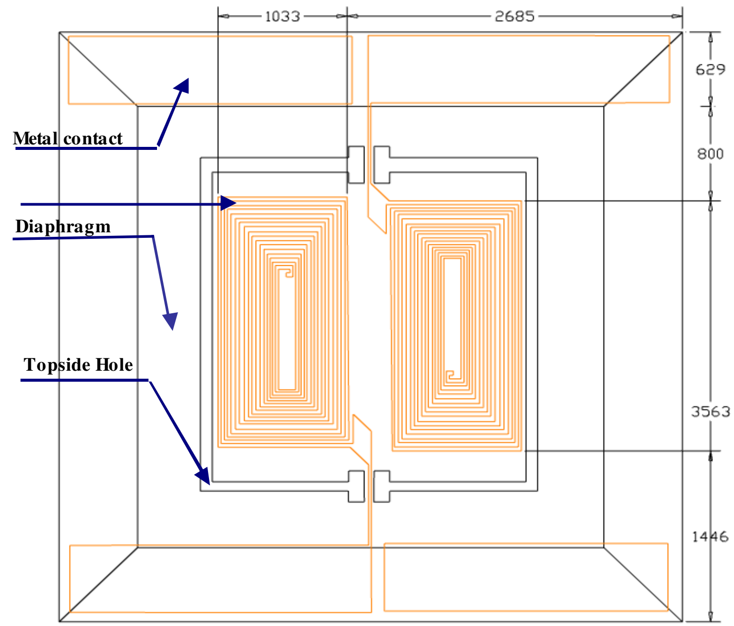


Figure 1: Top down CAD design of single axis Torsional Mirror

$$F = \frac{(m_m m_{coil})}{\mu_o z} = \frac{\frac{\mu_0}{4\pi}\left(\frac{2\pi R^2 I}{(z^2 + R^2)^{3/2}}\right)(LW)\ B_m}{\mu_o z}$$

Paper by Eric Harvey

MAGNETIC DEVICES

Magnetic flux density of a permanent magnet B is given by the manufacturer in units of weber/sq.meter or Tesla. (some of the magnets we use in MEMS are 2mm in diameter and have B=0.5 Tesla)

Magnetic flux density **B** in the center of a coil

$$B_{coil} = N * B_{loop}$$

where

$$B_{loop} = \frac{\mu_0}{4\pi}\left(\frac{2\pi R^2 I}{\left(z^2 + R^2\right)^{3/2}}\right)$$

The magnetic pole strength is m (webers) = B A where A is the pole area

The force between two poles is Force = $\frac{m1\ m2}{\mu o\ z}$

$\mu o = 4\pi x10^{-7}\ w^2/Nm^2$

http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magfie.html

MAGNETIC DEVICES

Force on a straight conductor in a uniform magnetic field.

F = I **L** X **B**

Force on a coil with current I in a uniform magnetic field

$$F = \frac{(m_m m_{coil})}{\mu_o z} = \frac{\frac{\mu_0}{4\pi}\left(\frac{2\pi R^2 I}{(z^2+R^2)^{3/2}}\right)(LW)\ B_m}{\mu_o z}$$

CALCULATOR FOR DIAPHRAGM DEFLECTIONS

Pressure Force = Pressure x Area	Fpress =	1.03E-01	N
Electromagnetic Force = I L B	Fmagnetic =	1.88E-03	N
Assuming a constant field strength B from a	Rmax of Coil =	1000	µm
permanent magnet then, Lorentz Force = I L B	Rmin of Coil =	500	µm
where I is the current in a coil of length L,	Number of turns (N) =	40	turns
L =~ 2 pi Rave x N, Rave = (Rmax+Rmin)/2	Length of coil (L) =	1.88E-01	m
	Current (I) =	0.02	amperes
	Magnet Field Strength (B) =	0.5	Tesla
Electromagnetic Force =			
	distance between magnet and coil, d =	300	µm
	radius of coil, Rc =	750	µm
	radius of magnet =	2000	µm
	Fmagnetic =	3.70E+00	N

$$F = \frac{3d}{2(d^2 + Rc^2)^{5/2}} \left[\frac{N I \mu_0 \pi Rc^2 (B_m A_m)}{\mu_0 \pi} \right]$$

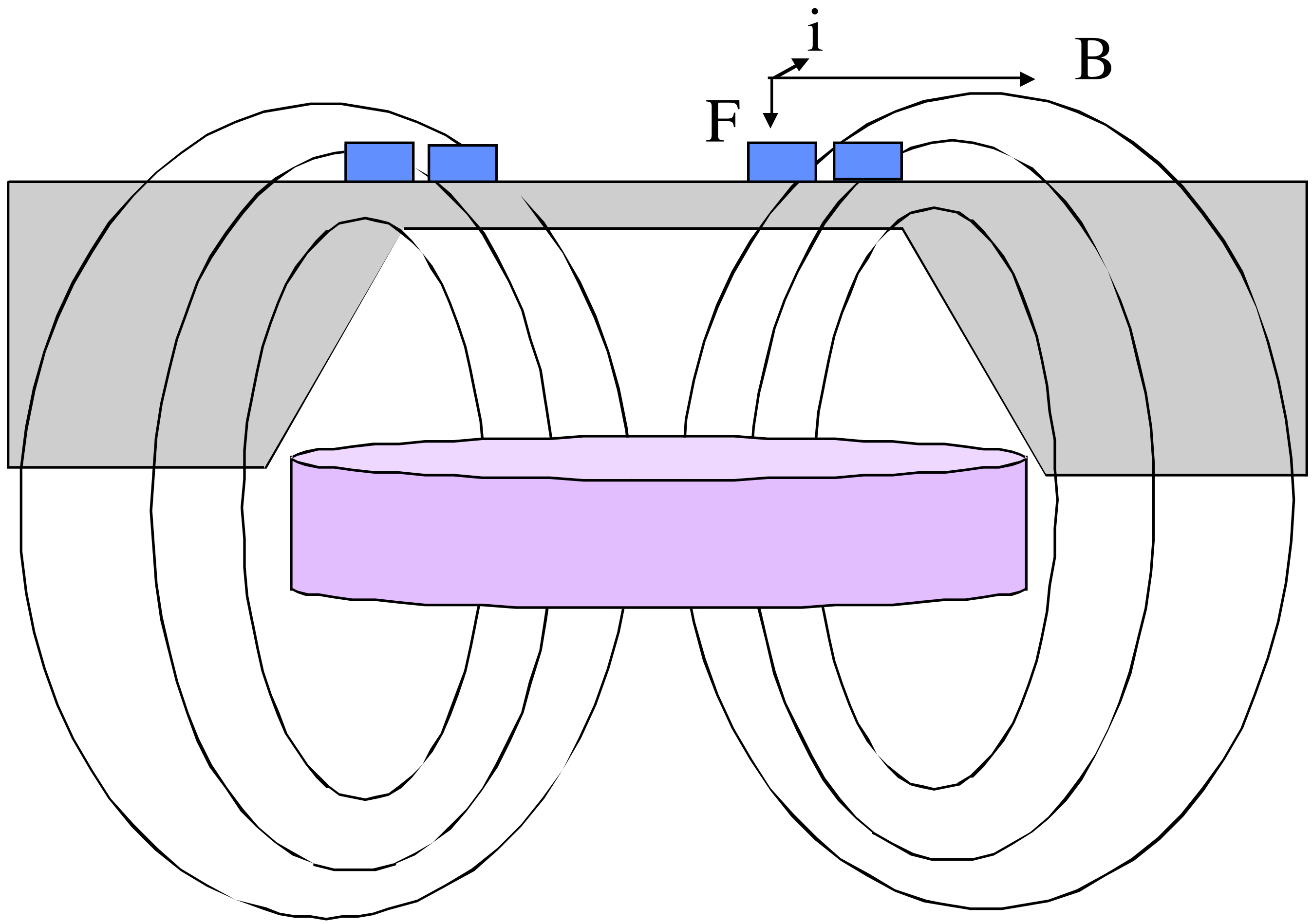
Where d is distance between coil and magnet
Rc is radius of coil
N is number of turns
I is current
Bm is magnet field strength
Am is magnet area

Cheng eq. 6-196

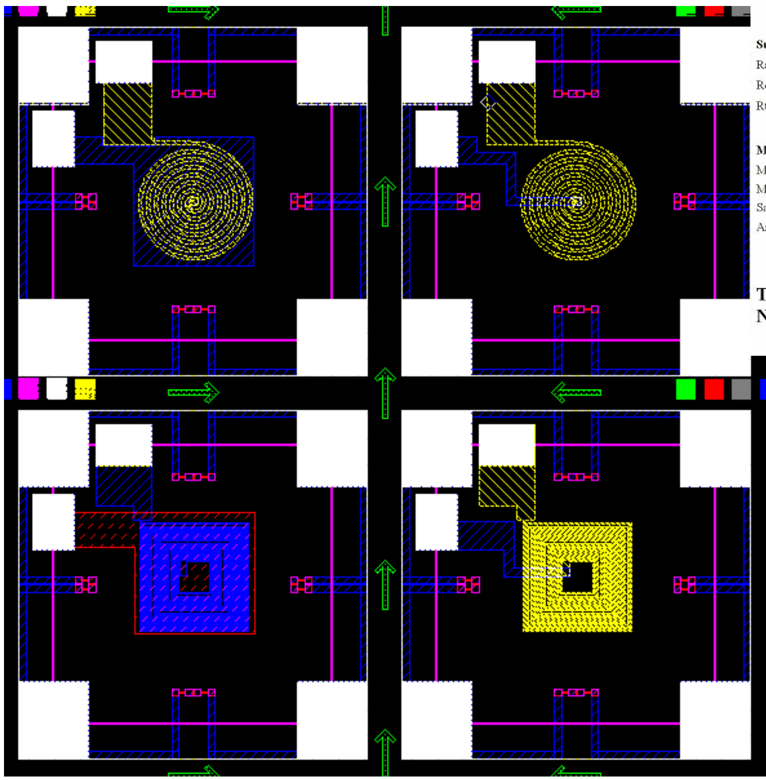
Materials Mechanical Properties — 10 dynes/cm2 = 1 N/m2 = 1 Pascal

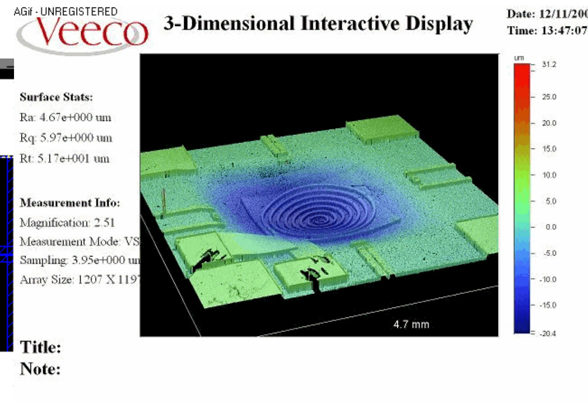
	Yield Strength	Youngs Modulus	Nu	
	xE10 dynes/cm2	xE12 dynes/cm2		Select only one
Si3N4	14	3.85	0.3	0
SiO2	8.4	0.73	0.3	0
Si	12	1.9	0.32	1

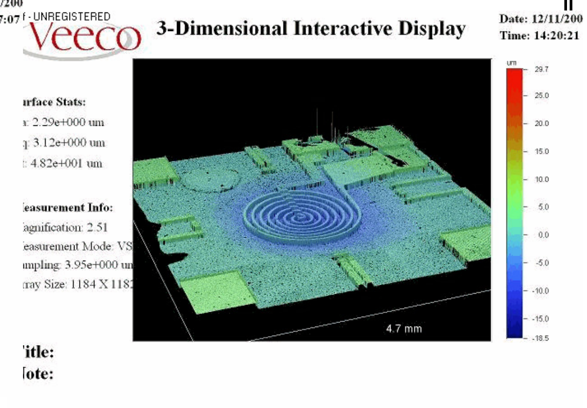
MAGNETIC FIELD

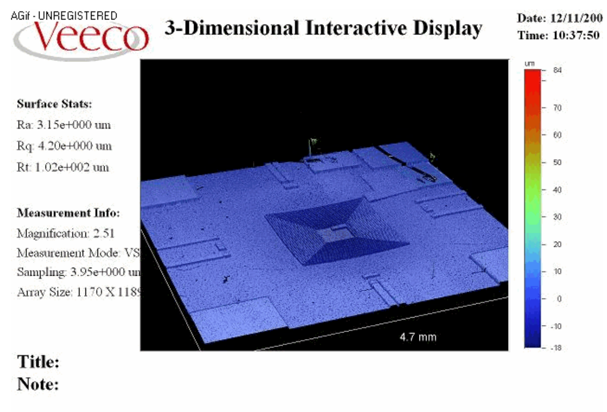


MEMS THERMAL ACTUATOR AND POSITION SENSOR



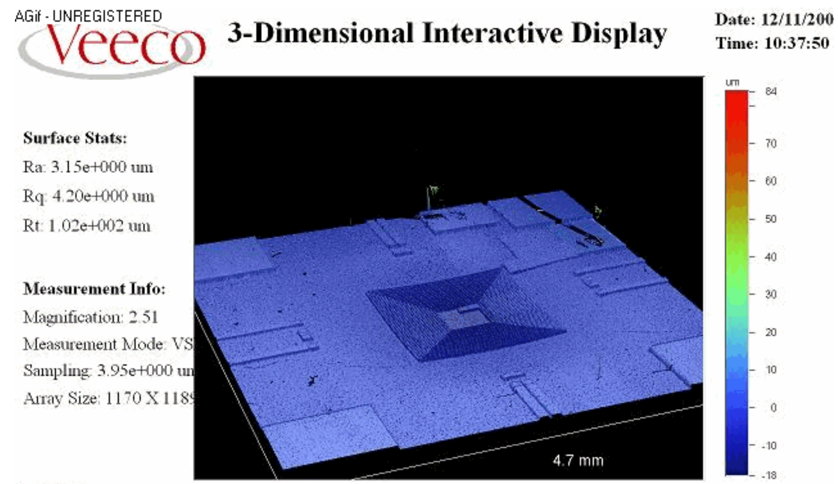




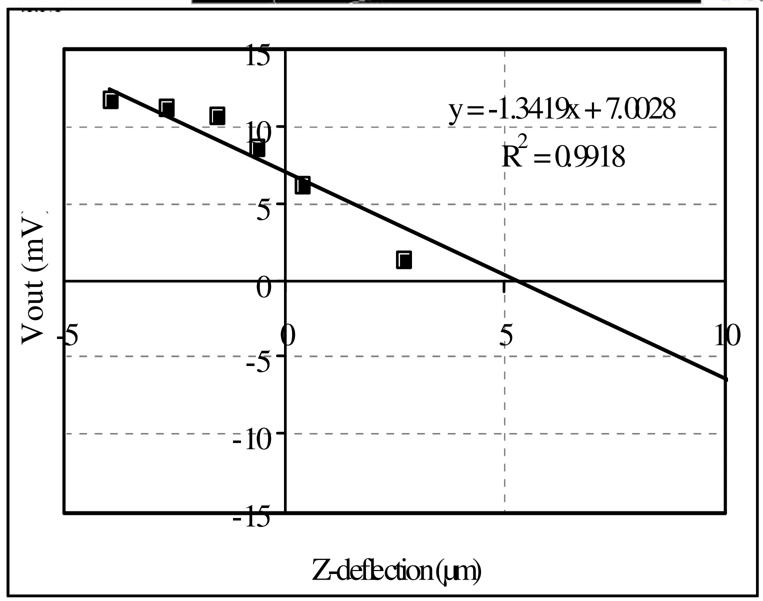


VERTICAL DISPLACEMENT

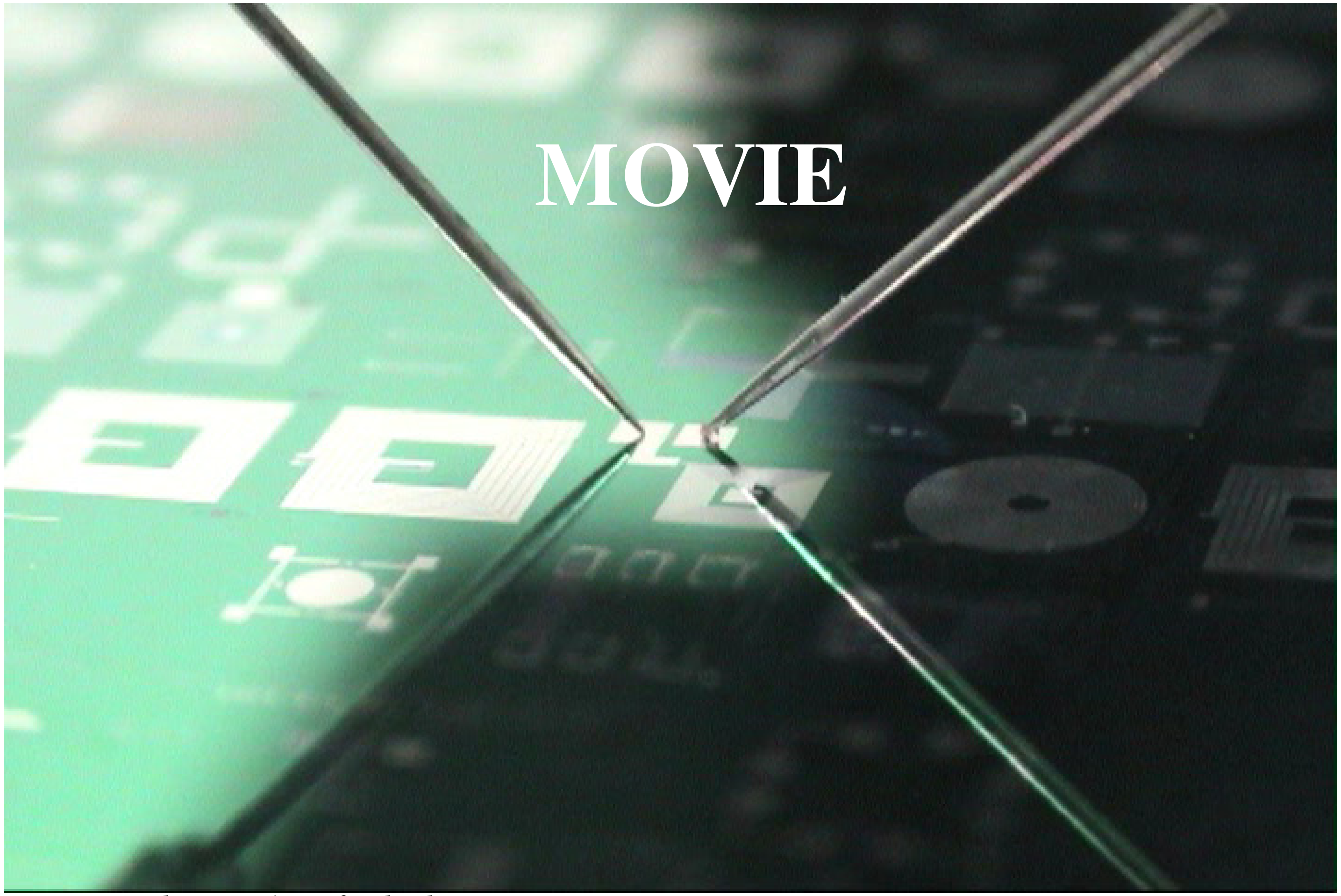
Iheat (mA)	Vout (mV)	Z-deflection (um) vecco
0	11.8	-4
20	11.3	-2.75
30	10.6	-1.6
40	8.7	-0.65
50	6.2	0.35
60	1.3	2.65
66	-17.4	17.5
70	-21.7	22.2



Veeco NT1100
Increase heater current
Measure z-displacement and Vout



MOVIE OF THERMAL DIAPHRAGM ACTUATION



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2. "Sensor Technology and Devices," Ristic, L.J., Artech House, London, 1994.
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5. "A walking Silicon Micro-Robot", Thorbjorn Ebefors, et.el., Department of signals, sensors and Systems, Royal Institute of technology, Stockholm, Sweden, 10th Int. conference on solid-State Sensors and Actuators, Sendai Japan, June 7-10, 1999.
6. MEMs Wing Technology for a battery-Powered Ornithopter, T. Nick Pornsin-sirirak, Caltech Micromachining Laboratory, Pasadena, CA, 91125, IEEE, 2000.

HOMEWORK - ACTUATORS

1. What makes the shuffle motors shown in this lecture move?

2. Go to www.sandia.gov and explore their Center for Integrated Nanotechnologies activity. Write a sentence about what you find.

3. Visit www-mtl.mit.edu/semisubway and visit "Laboratories", MEMS Clearing House, and MEMS Exchange. Write a sentence about what you find.