Microelectromechanical Systems (MEMS) Actuators

Dr. Lynn Fuller and Dr. Ivan Puchades

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MicroE Dept Webpage: http://www.rit.edu/kgcoe/microelectronic
INTRODUCTION

Actuators

Thermal
  Two beam heated cantilever
  Polyimide on Heaters
  Bimetalic
  heaters on diaphragms
Electrostatic
  Capacitor Plate Drive
  Comb Drive
Other
  Electromagnetic
  Peizoelectric
OUTLINE

Polycrystalline Silicon Thermal Actuators
Chevron Actuators
Heated Diaphragm Actuators
Heated Polyimide Cantilever Mirrors
Polyimide Thermal Actuators
  A Walking Silicon Micro-Robot
  Thermal Mirrors
Electrostatic Force
  Digital Light Projection
Electrostatic Impact-Drive Microactuator
  Shuffle Motor
Electrostatic Comb Drive
Magnetic Actuators on a Diaphragm
Polycrystalline Silicon Thermal Actuators Integrated with Photodetector Position Sensors

Kevin Munger
POLYCRYSTALLINE SILICON THERMAL ACTUATORS

No current flow
POLYCRYSTALLINE SILICON THERMAL ACTUATORS

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- $10$ dyne/cm² = 1 newton/m²
THERMAL EXPANSION

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

\[ \frac{\Delta L}{L} = 22 \text{ ppm/C} \]
\[ = 22 \times 200 = 4400 \text{ ppm} = 4400E^{-6} \]
\[ \Delta L = 4400E^{-6} \times 500 \text{ um} = 2.2 \text{ um} \]

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

\[ \frac{\Delta L}{L} = 2.4 \text{ ppm/C} \]
\[ = 2.4 \times 400 = 932 \text{ ppm} = 960E^{-6} \]
\[ \Delta L = 960E^{-6} \times 200 \text{ um} = 0.192 \text{ um} \]
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
**FEA 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 301 \( \mu \text{m} \) vs. the 205 \( \mu \text{m} \) of previous structure)
- Vary parameters and apply DOE techniques to investigate optimal parameters for max displacement.

**Future Work**

- \( W_s = 25 \mu \text{m}, L_x = 300 \mu \text{m}, W_g = 10 \mu \text{m} \)
- Max displacement = 301.4 \( \mu \text{m} \)

*Rochester Institute of Technology*
*Microronic Engineering*
December 2001
Kevin Munger joined IBM Burlington, VT

Maximum Deflection 9 µm at 30 µW
162,000 cycles, 6 msec.

Thermal Actuator with Integrated Photodiode
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
CHEVRON ACTUATOR

10° Angle

1000um

Thermal Expansion for Si is 2.33E-6/°C
Current flow causes heating and movement
CHEVRON ACTUATOR

10° Angle  1000um
MODIFIED BULK PROCESS FOR MEMS CLASS 2004-06
Diaphragm: Displacement

**Diaphragm**

Uniform Pressure (P)

Radius (R)

Displacement (y)

Diaphragm thickness (δ)

Equation for deflection at center of diaphragm

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

*The second equation corrects all units assuming that pressure is mmHg, radius and diaphragm is μm, Young’s Modulus is dynes/cm², and the calculated displacement found is μm.*

\(E = \text{Young’s Modulus, } \nu = \text{Poisson’s Ratio}\)

for Aluminum \(\nu = 0.35\)
### SELECTED MATERIAL PROPERTIES

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- $10$ dyne/cm$^2 = 1$ newton/m$^2$
### CALCULATOR FOR DIAPHRAGM DEFLECTIONS

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<th>Parameter</th>
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</tr>
</thead>
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<tr>
<td>Deflection Ymax = 0.0151 P L^4(1-Nu^2)/EH^3</td>
<td>Ymax = 0.17 µm</td>
</tr>
<tr>
<td>P = Pressure</td>
<td>P = 15 lbs/in2</td>
</tr>
<tr>
<td>L = Length of side of square diaphragm</td>
<td>L = 1000 µm</td>
</tr>
<tr>
<td>E = Youngs Modulus</td>
<td>E = 1.90E+11 N/m2</td>
</tr>
<tr>
<td>Nu = Poissons Ratio</td>
<td>Nu = 0.32</td>
</tr>
<tr>
<td>H = Diaphragm Thickness</td>
<td>H = 35 µm</td>
</tr>
<tr>
<td>P = 1.03E+05 Pascal</td>
<td>Stress = 2.53E+07 Pascal</td>
</tr>
<tr>
<td>Yield Strength = 1.20E+10 Pascal</td>
<td></td>
</tr>
<tr>
<td>Capacitance = eoe Area/d</td>
<td>C = 7.97E-11 F</td>
</tr>
<tr>
<td>eo = Permittivity of free space</td>
<td>eo = 8.85E-14 F/cm</td>
</tr>
<tr>
<td>er = relative permittivity = 1 for air</td>
<td>er = 1</td>
</tr>
<tr>
<td>Area = area of plates x number of plates</td>
<td>Area = 9.00E-02 cm²</td>
</tr>
<tr>
<td>d = distance between plates</td>
<td>d = 1 µm</td>
</tr>
<tr>
<td>If round plates, Diameter =</td>
<td>Diameter = 0 µm</td>
</tr>
<tr>
<td>If square plates, Side =</td>
<td>Side = 3000 µm</td>
</tr>
</tbody>
</table>
CALCULATOR FOR DIAPHRAGM DEFLECTIONS

Deflection for given pressure
Stress at edge of diaphragm
Electrostatic equivalent pressure
Magnetic equivalent pressure
Resonant frequency
Piezoresistive bridge calculations
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
PICTURES OF WAFER AFTER KOH ETCH

50 µm in 57 min ~ 0.877 µm/min
DIAPHRAGM THICKNESS USING OPTICAL MICROSCOPE

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

500 µm

31 µm
SQUARE DIAPHRAGM MOVIE
**THERMAL ACTUATED VERTICAL DISPLACEMENT**

<table>
<thead>
<tr>
<th>$I_{heat} (mA)$</th>
<th>$V_{out} (mV)$</th>
<th>$Z$-deflection (µm) vecco</th>
</tr>
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<tr>
<td>0</td>
<td>11.8</td>
<td>-4</td>
</tr>
<tr>
<td>20</td>
<td>11.3</td>
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<td>30</td>
<td>10.6</td>
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<td>40</td>
<td>8.7</td>
<td>-0.65</td>
</tr>
<tr>
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<tr>
<td>60</td>
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<td>2.65</td>
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<tr>
<td>66</td>
<td>-17.4</td>
<td>17.5</td>
</tr>
<tr>
<td>70</td>
<td>-21.7</td>
<td>22.2</td>
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**Veeco NT1100**

Increase heater current  
Measure $z$-displacement and $V_{out}$

$y = -1.3419x + 7.0028$  
$R^2 = 0.9918$
VISCOCITY SENSOR JOURNAL PUBLICATION AND PATENT
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$10$ dyne/cm² = 1 newton/m²
A WALKING SILICON MICRO-ROBOT

Thorbjörn Ebeffors*, Johan Ulfstedt Mattsson, Edvard Kälvesten and Göran Stemme

Department of Signals, Sensors and Systems (S3),
Royal Institute of Technology (KTH), SE-100 44 Stockholm, Sweden
*Phone: +46 8 7907785 Fax: +46 8 10085 *E-mail: Thorbjorn.Ebeffors@s3.kth.se

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 15×5 mm² 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

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

Professor Goran Stemme
Kungliga Tekniska Hogskolan
Stockholm, Sweden
Fig. 2. Operation principle for the asynchronous driven micro-robot. A displacement equal to $2 \cdot \Delta x$ 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 result in walking in the opposite direction.
**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 $\mu$m 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 aluminum 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...
**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 the 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.

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<tr>
<td>Curing temp. $T$ / shrinkage, $\varepsilon$</td>
<td>$350 , ^\circ\text{C} / 40%$ (3 V-grooves)</td>
</tr>
<tr>
<td></td>
<td>$280 , ^\circ\text{C} / 30%$ (4 V-grooves)</td>
</tr>
<tr>
<td>Life-time</td>
<td>$&gt; 2 \cdot 10^8$ load cycles</td>
</tr>
<tr>
<td>Stroke length, $\Delta x$ / power consumption, $P$</td>
<td>$&lt; 340 \mu\text{m} / &lt; 175 \text{mW}$ (for 1 mm leg with 4 V-grooves)</td>
</tr>
<tr>
<td>Cut-off frequency, $f_c$</td>
<td>$3 – 4 \text{Hz}$ ($-3 \text{dB}$)</td>
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<tr>
<td>Force / displacement (before plastic deform.)</td>
<td>$50-100 \text{mN} / 250-400 \mu\text{m}$</td>
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*Fig. 6.* Walking speed as a function of frequency for different loads and power.
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.
THERMALLY ACTUATED MICRO MIRROR

Thermal Mirror Microactuator

Dr. Lynn Fuller
Rakesh Dhull

Rochester Institute of Technology
Microelectronic Engineering
CAPACITIVE ELECTROSTATIC FORCE

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

$W = 0.5 \, QV = 0.5 \, CV^2$

since $Q = CV$

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

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

$F = \frac{\varepsilon_0 \varepsilon_r AV^2}{2d^2}$

$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$

$\varepsilon_0 = \text{permittivity of free space} = 8.85 \times 10^{-12} \, \text{Farads/m}$

$\varepsilon_r = \text{relative permittivity (for air } \varepsilon_r = 1)$
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

\[ F = \frac{\varepsilon_0 \varepsilon_r AV^2}{2d^2} \]

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

\[ F = 4.42e-6 \text{ newtons} \]
DIGITAL LIGHT PROJECTION SYSTEM

www.TI.com

TIR prism (optional)

DMD (R,G,B)

Integrator rod (optional)

Color disc (R,G,B)

1-Chip DMD projector

www.TI.com
TI DLP - ELECTROSTATIC MIRRORS

www.TI.com

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
Electrostatic Impact-Drive Microactuator

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FRANCE

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 (\sim10\text{nm}). It is a micromachined and electrostatic version of the impact-drive actuator.
ELECTROSTATIC IMPACT-DRIVE MICROACTUATOR
1. Actuator can generate high power
2. Maintain a position precisely
3. Move a long distance.

Figure 1: Structure of impact actuator
ELECTROSTATIC IMPACT-DRIVE MICROACTUATOR

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 O₂ plasma ashing, the wafer is bonded 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.
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 transmission
ELECTROSTATIC IMPACT-DRIVE MICROACTUATOR

Figure 9: Wireless energy supply system

Figure 10: Micro X-Y stage
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
Electrostatic actuation (V) pulls down contactor to make connection along the signal line.
Each project has 5mm x 5mm layout space

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<th>Number of turns in meander</th>
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<tbody>
<tr>
<td>Primary length (a)</td>
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<tr>
<td>Secondary length (b)</td>
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<tr>
<td>Thickness (t)</td>
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<td>Beam width (w)</td>
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<td>Poly (Youngs Modulus) (E)</td>
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<td>Poly (Poissons Ratio) (v)</td>
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<td>Shear Modulus (G)</td>
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<td>Z-axis moment of inertia (Iz)</td>
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<td>Polar moment of inertia (Ip)</td>
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<td>Spring constant of 1 meander</td>
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<td>Actuation Electrodes length</td>
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<tr>
<td>Actuation Electrodes width</td>
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</table>

Artur Nigmatulin 2011
AC MEMS SWITCH
What actuation mechanism is this?
Electrostatic movement parallel to wafer surface

From Jay Zhao
CALCULATION OF DISPLACEMENT VS VOLTAGE

\[ F = \varepsilon_r \varepsilon_0 t V^2 / 2 d \]
SPRING ELECTROSTATIC DRIVE & CAPACITIVE READ OUT

Anchors and Electrical Ground

Anchor

C1  C1

C2  C2

Gnd

Rochester Institute of Technology
Microelectronic Engineering
PICTURES & MOVIES OF ELECTROSTATIC COMB DRIVE

PICTURES & MOVIES OF ELECTROSTATIC COMB DRIVE

Movies at www.sandia.gov
MAGNETIC TORSIONAL MIRROR

Figure 2: Cross sectional view labels with variables.

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

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

Paper by Eric Harvey
MAGNETIC FIELD

\[ B \]

\[ i \]

\[ F \]

\[ B \]
This SEM image shows the **untethered scratch drive actuator (A)** used for propulsion, and the **cantilevered steering arm (B)** which can be lowered to provide a turning pivot. The wavey lines the robot sits on are the insulated interdigitated electrode array which transmits power and control signals to the robot.

http://engineering.dartmouth.edu/microeng/robot05.html
REFERENCES

3. IEEE Journal of Microelectromechanical Systems