MECHANICAL TRANSDUCERS

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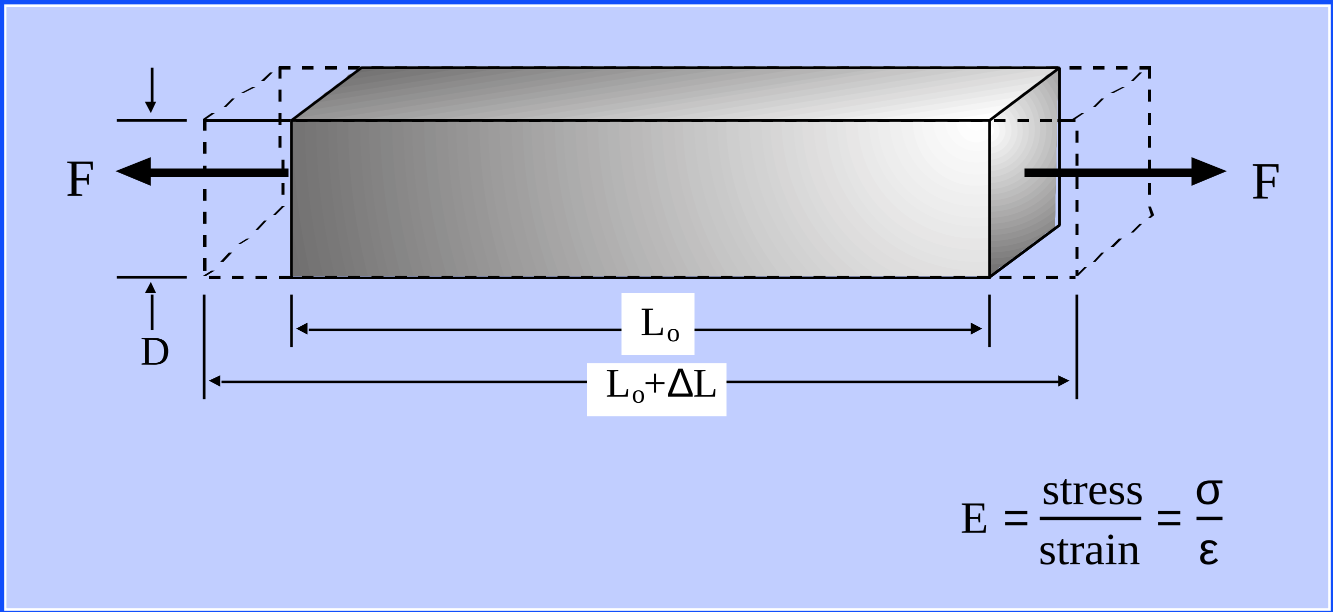
Stanford University

MECHANICAL TRANSDUCER EXAMPLES

- Strain gauges
- Accelerometers
- Gyroscopes
- Pressure sensors
- Actuators
- Others… (optical, fluidic, etc., covered in their respective sections)

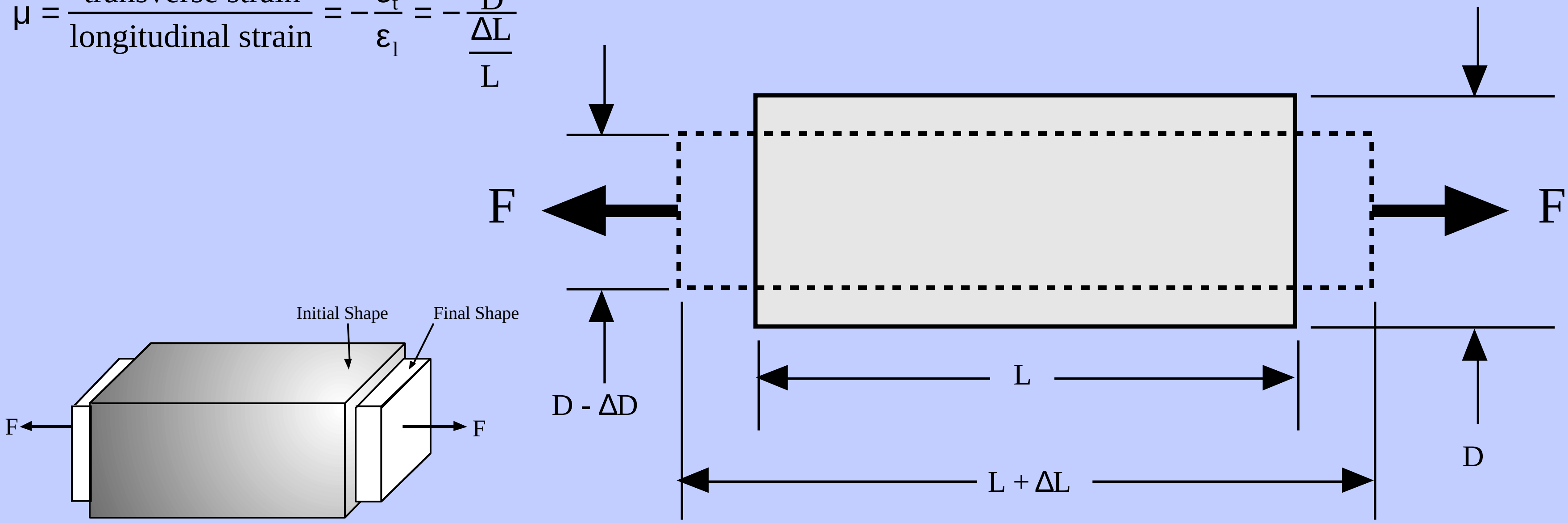
STRESS AND STRAIN



- **Strain, ε, is the deformation of a solid (ΔL/L) due to stress.**
- **Stress, σ, is the force acting on a unit area of a solid (F/A).**
- **The Young's Modulus, E, is the ratio of stress over strain, and describes the "firmness" of a material (hard, E large, soft, E small).**

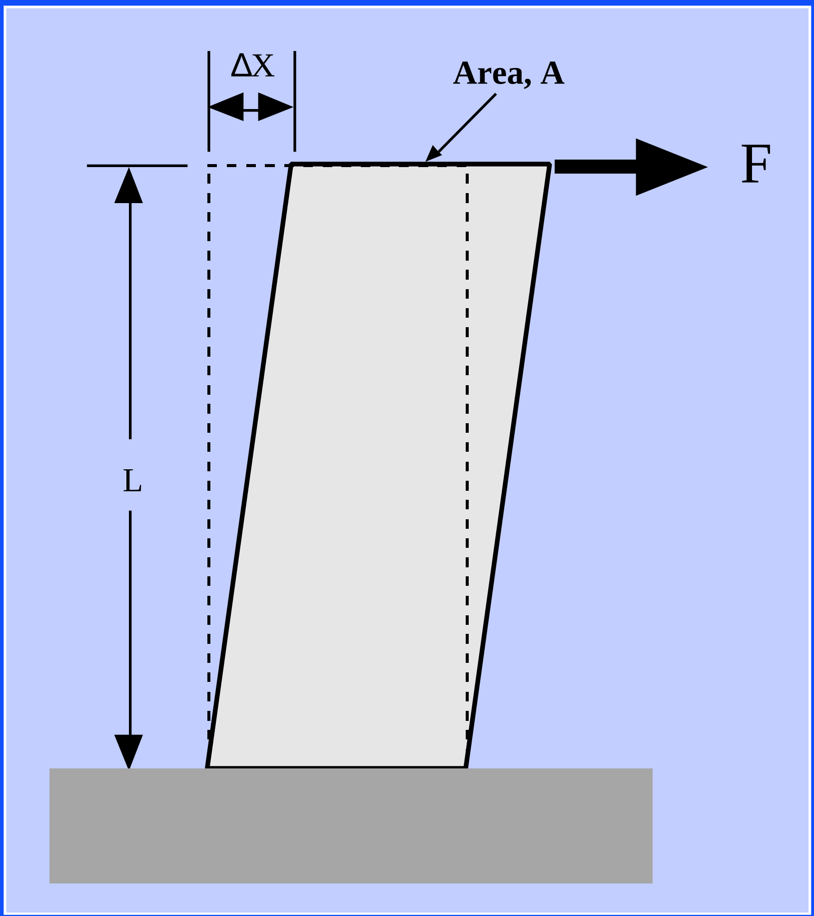
POISSON STRAIN

$$\mu = \frac{\text{transverse strain}}{\text{longitudinal strain}} = -\frac{\varepsilon_t}{\varepsilon_l} = -\frac{\frac{\Delta D}{D}}{\frac{\Delta L}{L}}$$



- **For most materials, as they lengthen in one direction, they contract in another (Poisson strain).**
- **The Poisson ratio, μ, is the ratio of dimensional change in girth to length for a bar.**

SHEAR



- Shear is force applied to an object in the plane of an opposing force, such as an anchor point.
- The shear modulus, G, represents the degree of displacement an object will allow under shear stress.

$$G = \frac{\text{shear stress}}{\text{shear displacement angle (rad)}} = \frac{\tau}{\gamma} = \frac{\frac{F}{A}}{\frac{\Delta X}{L}}$$

MECHANICAL PROPERTIES OF SILICON

Material	Yield Strength (10^9 N/m^2)	Knoop Hardness (kg/mm^2)	Young's Modulus (10^{11} N/m^2)	Density (g/cm^3)	Thermal Conductivity (W/cm°C)	Thermal Expansion Coefficient (10^6/°C)
*Diamond	53	7000	10.35	3.5	20	1
*SiC	21	2480	7	3.2	3.5	3.3
*TiC	20	2470	4.97	4.9	3.3	6.4
*Al_2O_3	15.4	2100	5.3	4	0.5	5.4
*Si_3N_4	14	3486	3.85	3.1	0.19	0.8
*Iron	12.6	400	1.96	7.8	0.803	12
SiO_2 (fibers)	8.4	820	0.73	2.5	0.014	0.55
*Si	7	850	1.9	2.3	1.57	2.33
Steel (max strength)	4.2	1500	2.1	7.9	0.97	12
W	4	485	4.1	19.3	1.78	4.5
Stainless Steel	2.1	660	2	7.9	0.329	17.3
Mo	2.1	275	3.43	10.3	1.38	5
Al	0.17	130	0.7	2.7	2.36	25

Reference: Petersen, K. E., "Silicon as a Mechanical Material," Proceedings of the IEEE, vol. 70, no. 5, May 1982, pp. 420 - 457.

SENSING IN MECHANICAL TRANSDUCERS

- **Many mechanisms can be harnessed in microstructures to sense strain or displacement.**
- ***Piezoresistive*** **sensing makes use of the fact that majority carrier mobilities in certain materials (e.g. doped regions of single crystal or polysilicon) are modulated by stress (force/area), thus varying resistivity.**
- **Piezoresistive circuits can generate fairly high power signals but generally require temperature compensation.**
- ***Piezoelectric*** **materials generate potentials proportional to change in length(no DC response) and generate large voltages.**
- ***Capacitive*** **sensing relies on measuring changes in capacitors with moving plate(s), on a micro scale producing very low power signals but with no temperature effects.**
- ***Tunneling*** **and** ***optical*** **means may also be utilized.**

MECHANICAL SENSING MECHANISMS

Mechanism	Parameter Sensed	Needs Local Circuits?	DC Response?	Complex System?	Linearity	Issues
Metal Strain Sensor	strain	NO	YES	+	+++	• low sensitivity • very simple
Piezoresistive Strain Sensor	strain	NO	YES	+	+++	• temperature effects can be significant • easy to integrate
Piezoelectric	force	NO	NO	++	++	• high sensitivity • fabrication can be complex
Capacitive	displacement	YES	YES	++	poor	• very simple • extremely low temperature coefficients
Tunneling	displacement	YES	YES	+++	poor	• sensitive to surface states • drift performance not yet proven
Optical	displacement	NO	YES	+++	+++	• rarely employed in mechanical microsensors

STRAIN GAUGES

- **Gauge factor is used to express the sensitivity of strain gauges (relative change in R over strain).**

$$GF = \frac{\text{relative resistance change}}{\text{strain}} = \frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}} = \frac{\Delta R}{\varepsilon R}$$

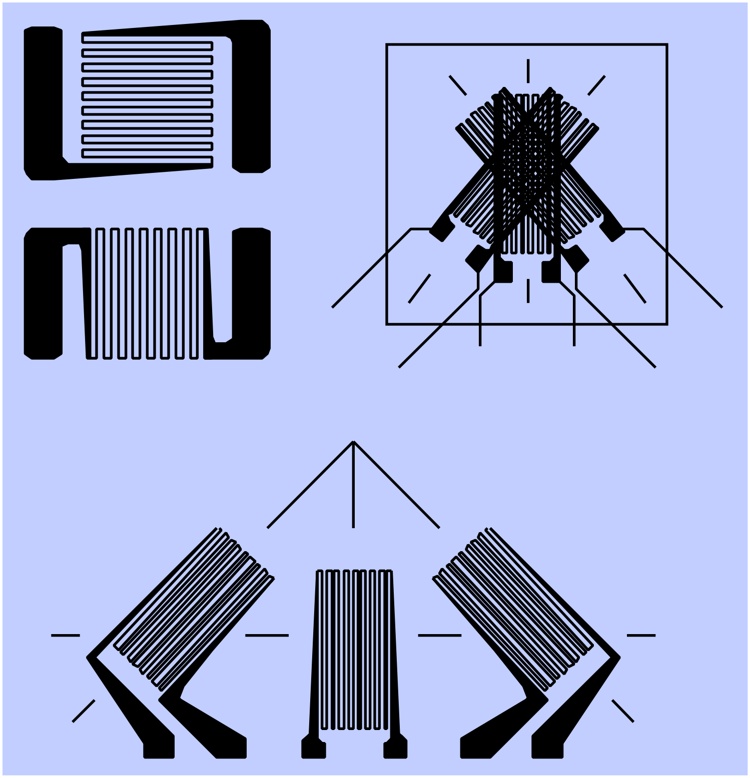
- **The resistance can vary due to a dimensional effect or if the resistivity varies under strain.**

$$GF = \frac{\frac{dR}{R}}{\frac{dL}{L}} = \frac{\frac{dR}{R}}{\varepsilon_l} = (1 + 2\mu) + \frac{\frac{d\rho}{\rho}}{\varepsilon_l}$$

- **Thin-film metallic strain gauges have a GF of roughly 2 (resistivity does not vary much), but semiconductor strain gauges have GF of up to 200 due to strain-dependent modulation of majority carrier mobilities (ΔR with strain up for p-type and down for n-type).**

STRAIN GAUGES

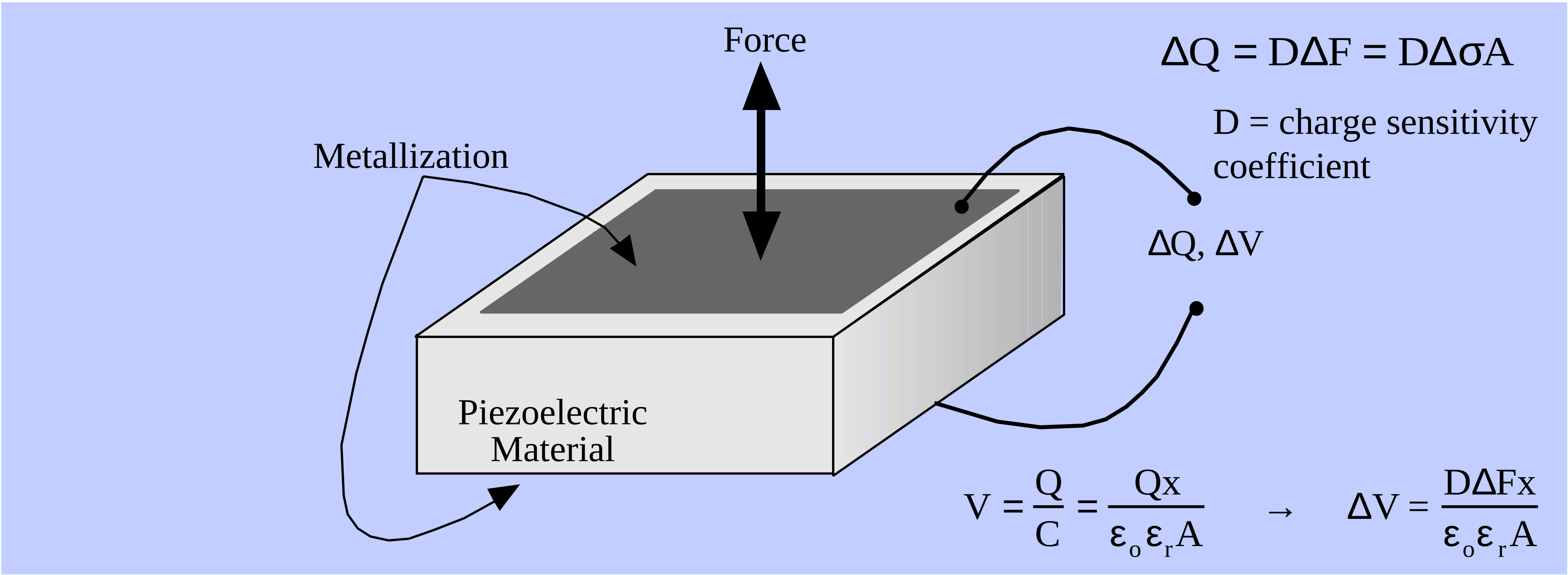
Type of Strain Gauge	Gauge Factor
Metal Foil	1 - 5
Thin-Film Metal	≈ 2
Bar Semiconductor	80 - 150
Diffused Semiconductor	80 - 200



Metal foil strain gauges, after Norton (1989).

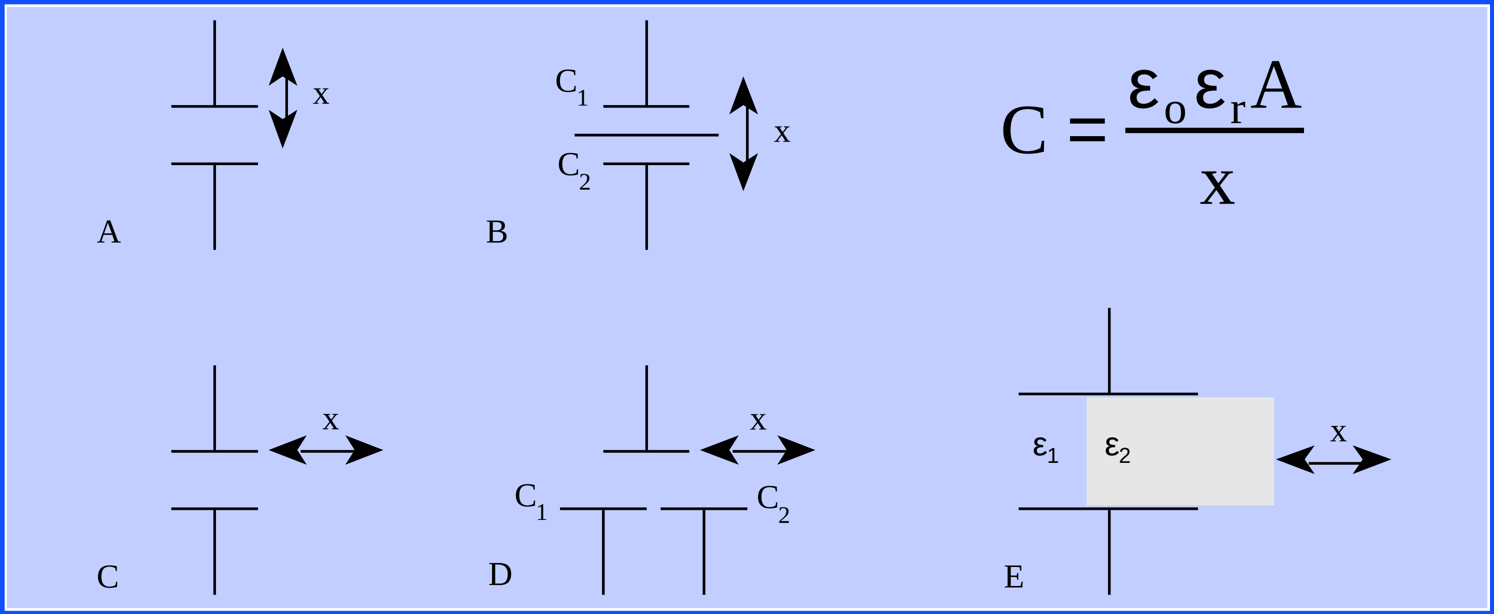
Reference: Norton, A. N., "Handbook of Transducers," Prentice-Hall, Inc., Englewood Cliffs, NJ, 1989.

PIEZOELECTRIC SENSING



- **Electrical potential develops on opposite faces of a slab under externally-applied stress, and has no DC response.**
- **Piezoelectric materials must have a built-in polarization (silicon is not piezoelectric, but GaAs is).**
- **Example materials: quartz, polyvinylidene fluoride (PVDF), lead zirconate-titanate (PZT), barium titanate, zinc oxide, etc.**

CAPACITIVE SENSING



Modes of capacitive sensing, after Cobbold (1974).

Reference: Cobbold, R. S. C., "Transducers for Biomedical Measurements," John Wiley and Sons, New York, NY, 1974.

TUNNELING-BASED SENSING

- Tunneling current is extremely sensitive to position and, with external feedback, can be used to construct extremely sensitive mechanical transducers.

$$I = I_o e^{\left(-\beta \sqrt{\varphi} z\right)}$$

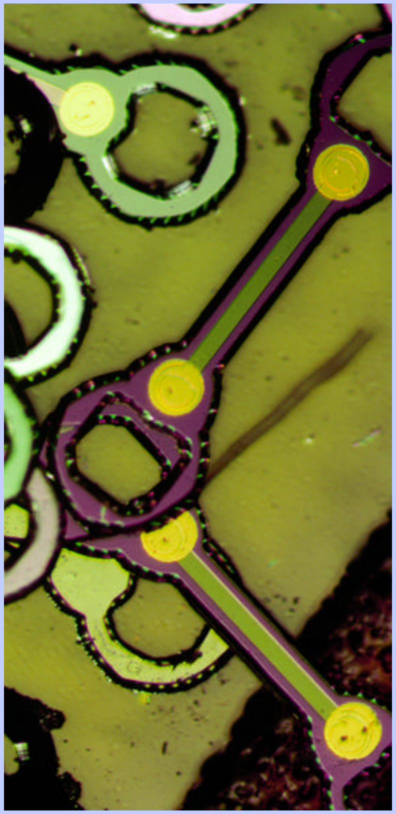
I_o = scaling factor

β = conversion factor = 1.025 eV-1/2/Å

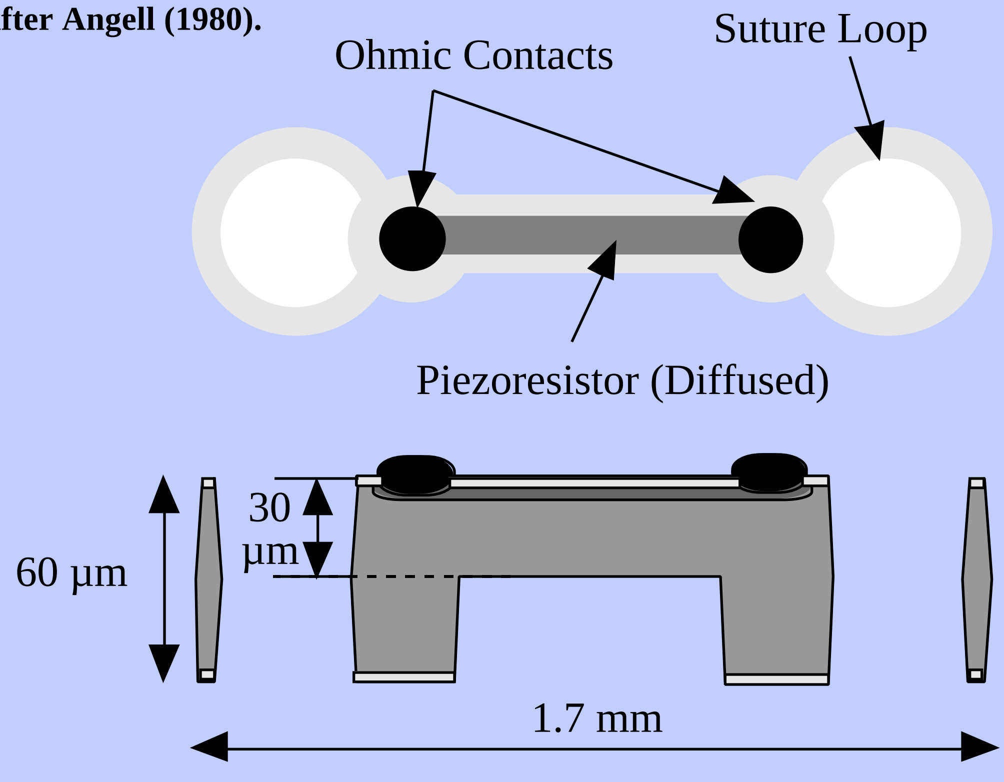
ϕ = tunnel barrier height in eV = 0.5 eV

z = tip/surface separation in Å = 10 Å

MICROMACHINED STRAIN GAUGES



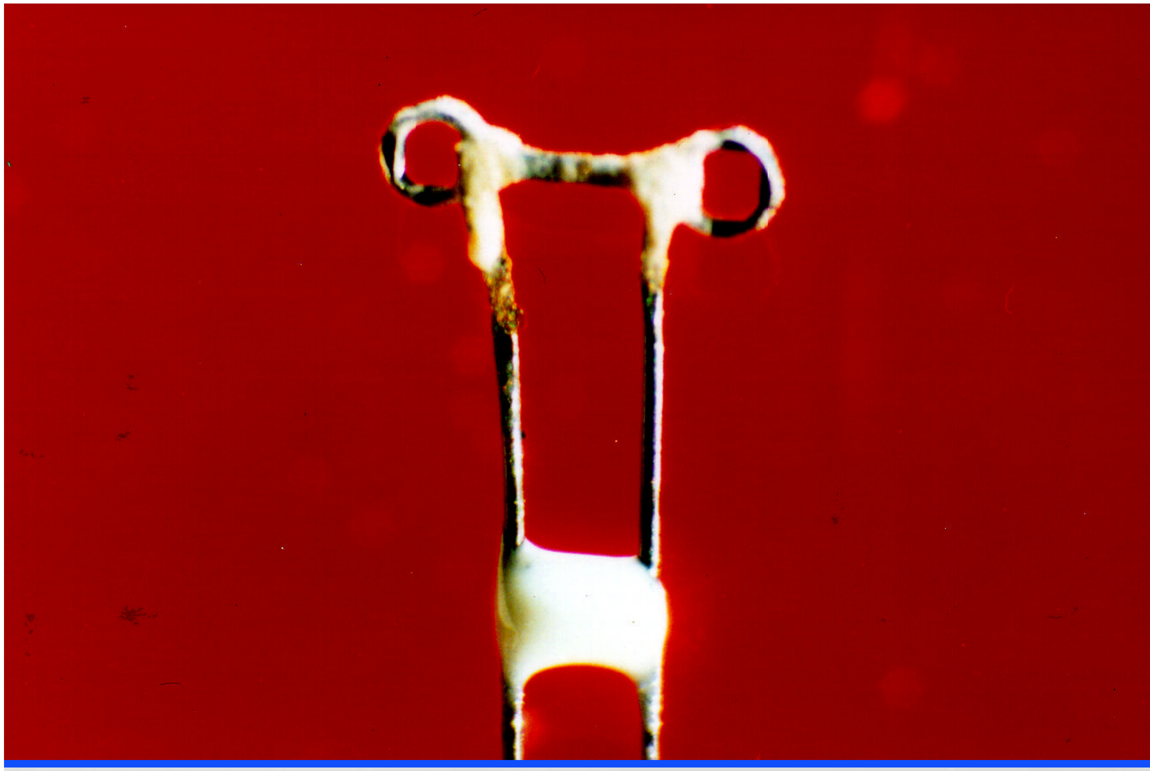
After Angell (1980).

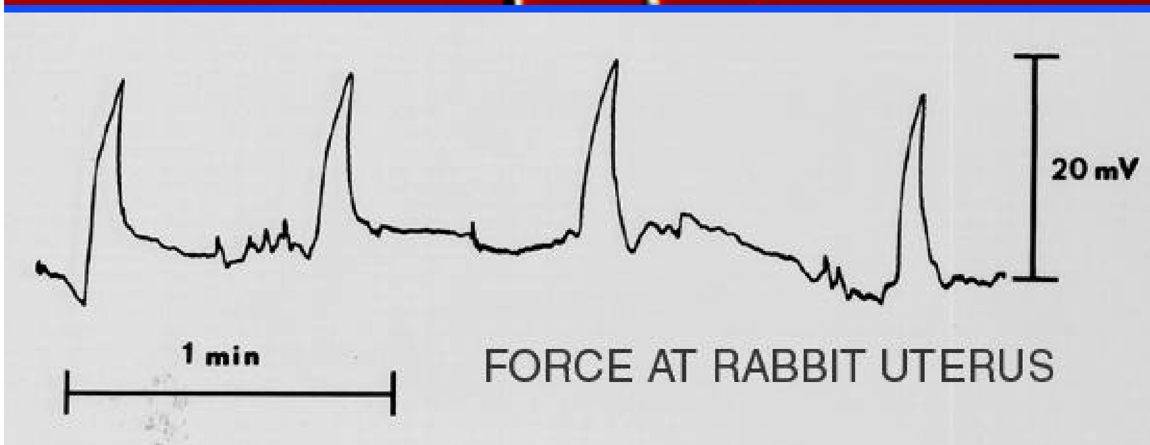


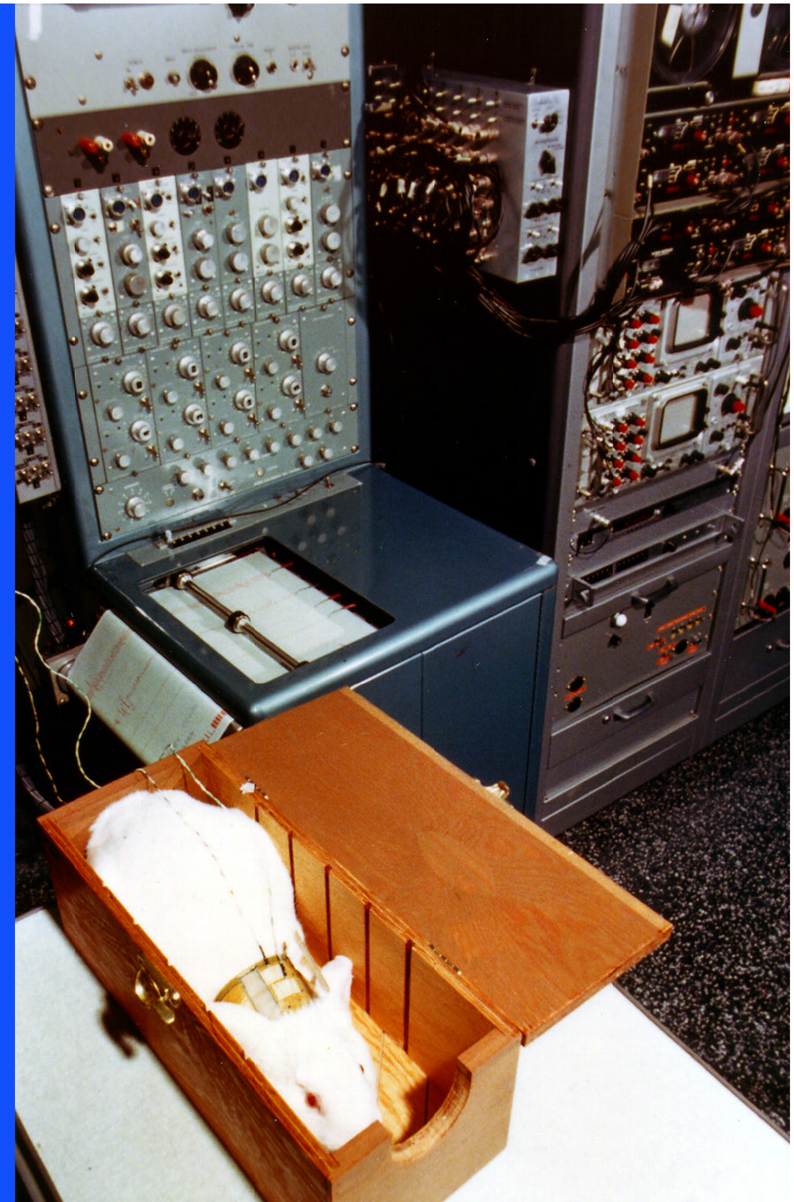
Reference: Angell, J. B., "Transducers for in vivo measurement of force, strain and motion," in "Physical Sensors for Biomedical Applications," Neuman, M. R., Fleming, D. G., Cheung, P. W., and Ko, W. H. [eds.], CRC Press, Boca Raton, FL, 1980, pp. 46 - 53.

Implantable strain gauges on a penny.

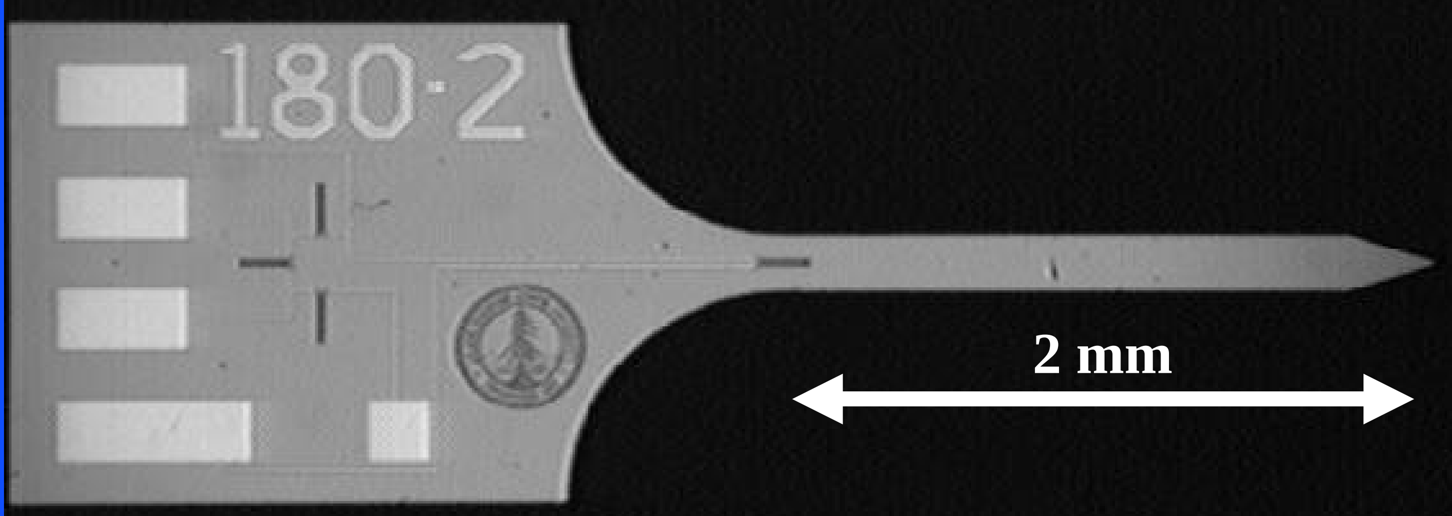
Reference: Angell, J. B., "Transducers for in vivo measurement of force, strain and motion," in Physical Sensors for Biomedical Applications, Neuman, M. R., Fleming, D. G., Cheung, P. W., and Ko, W. H., (Eds.), CRC Press, Boca Raton, FL, 1980, pp. 46 - 53.




20 mV
1 min
FORCE AT RABBIT UTERUS



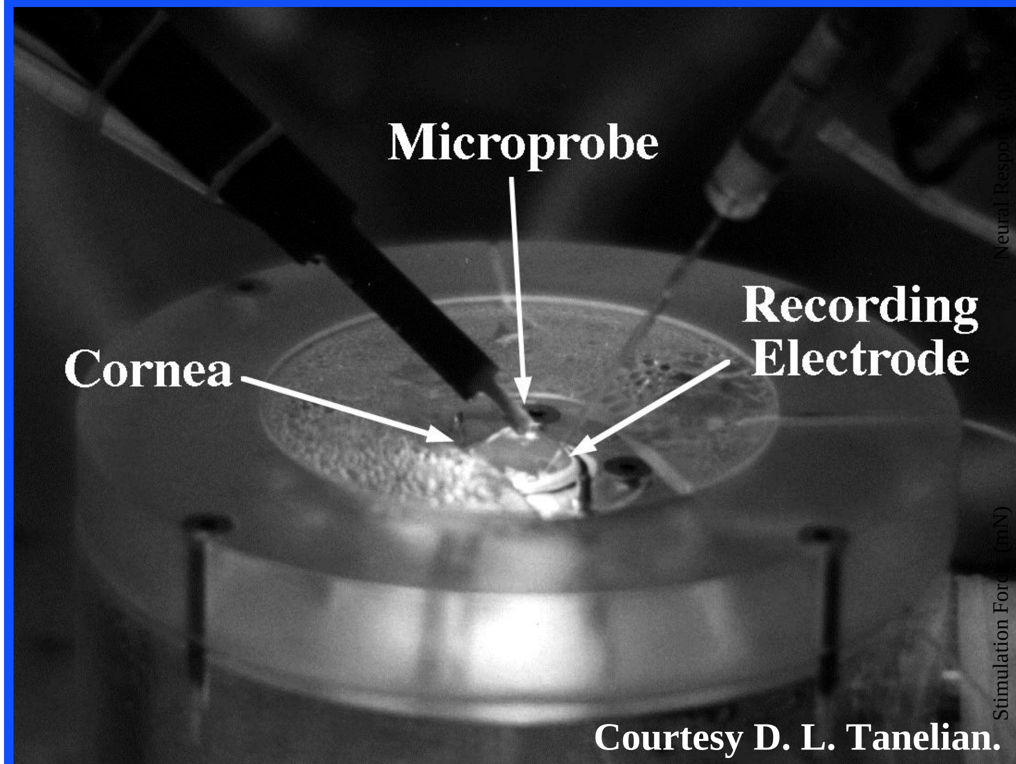
SILICON STRAIN GAUGE PROBE

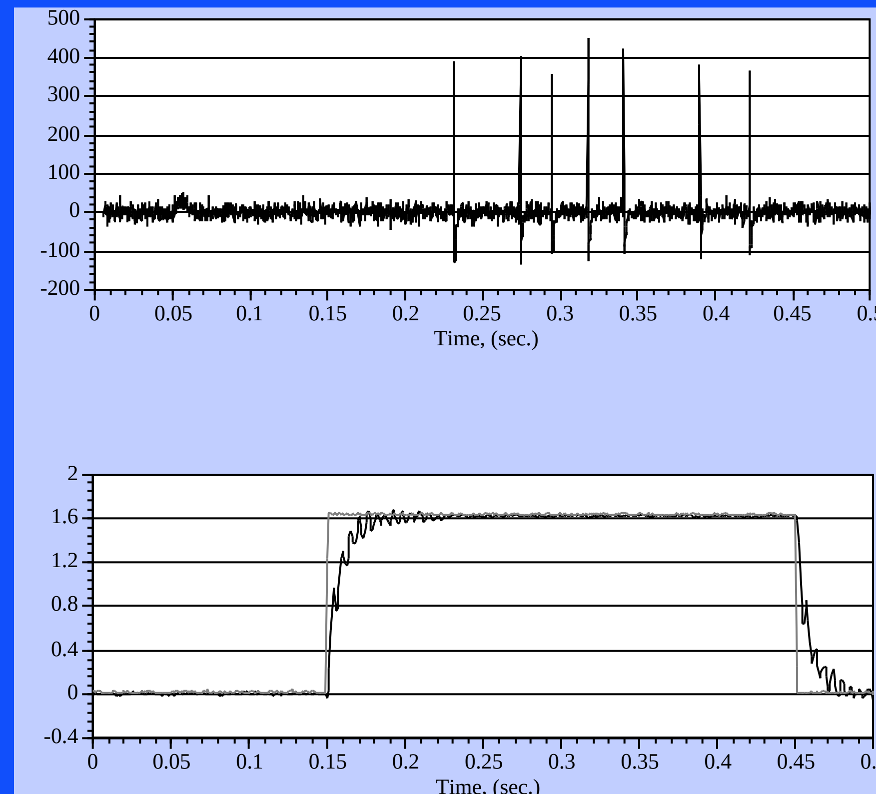


Courtesy B. J. Kane.

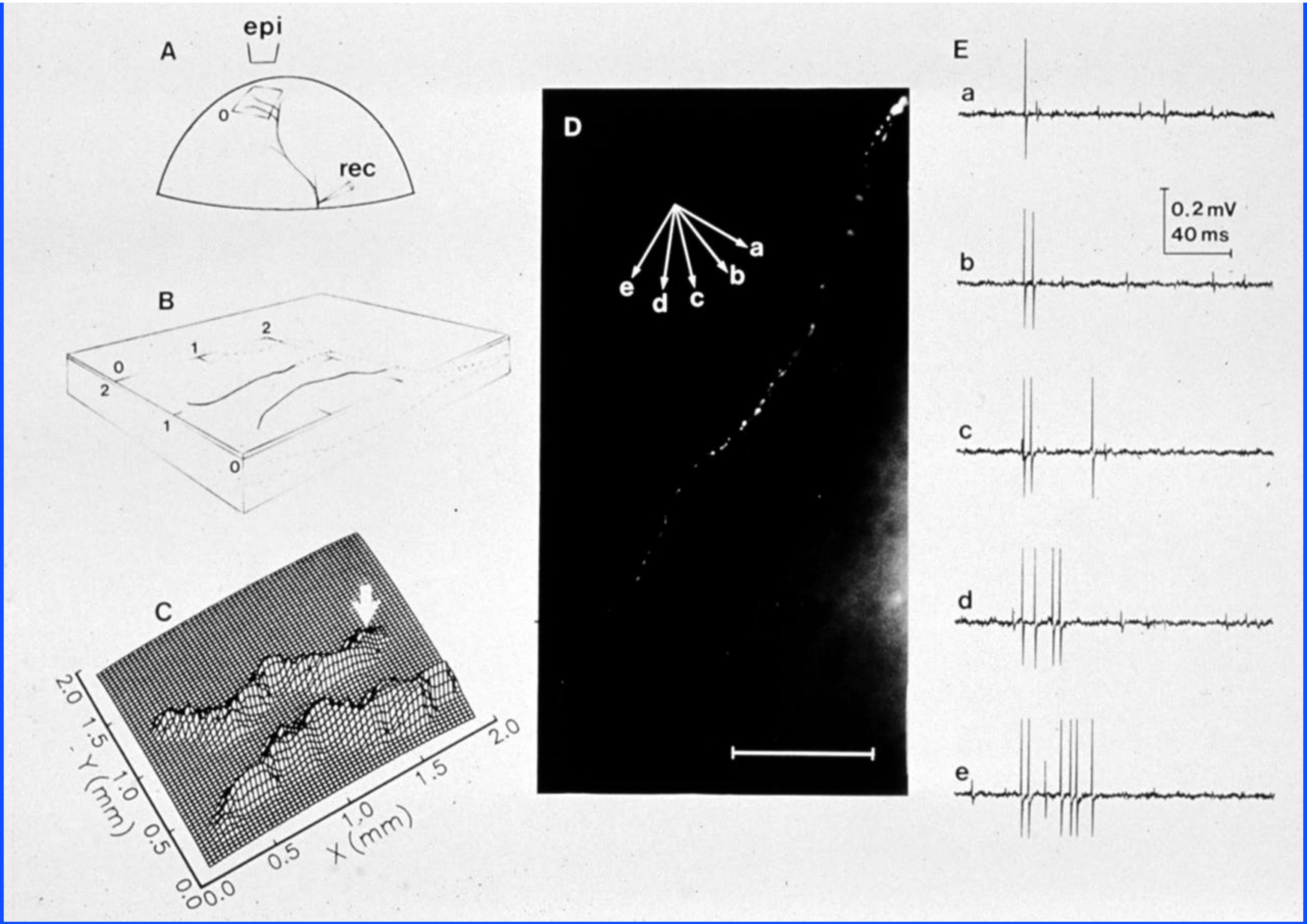
Reference: Kane, B. J., Storment, C. W., Crowder, S. W., Tanelian, D. L., and Kovacs, G. T. A., "Force-Sensing Microprobe for Precise Stimulation Of Mechanosensitive Tissues," IEEE Transactions on Biomedical Engineering, vol. 42, no. 8, Aug. 1995, pp. 745 - 750.

MICROPROBES USED IN MAPPING MECHANORECEPTORS OF THE CORNEA

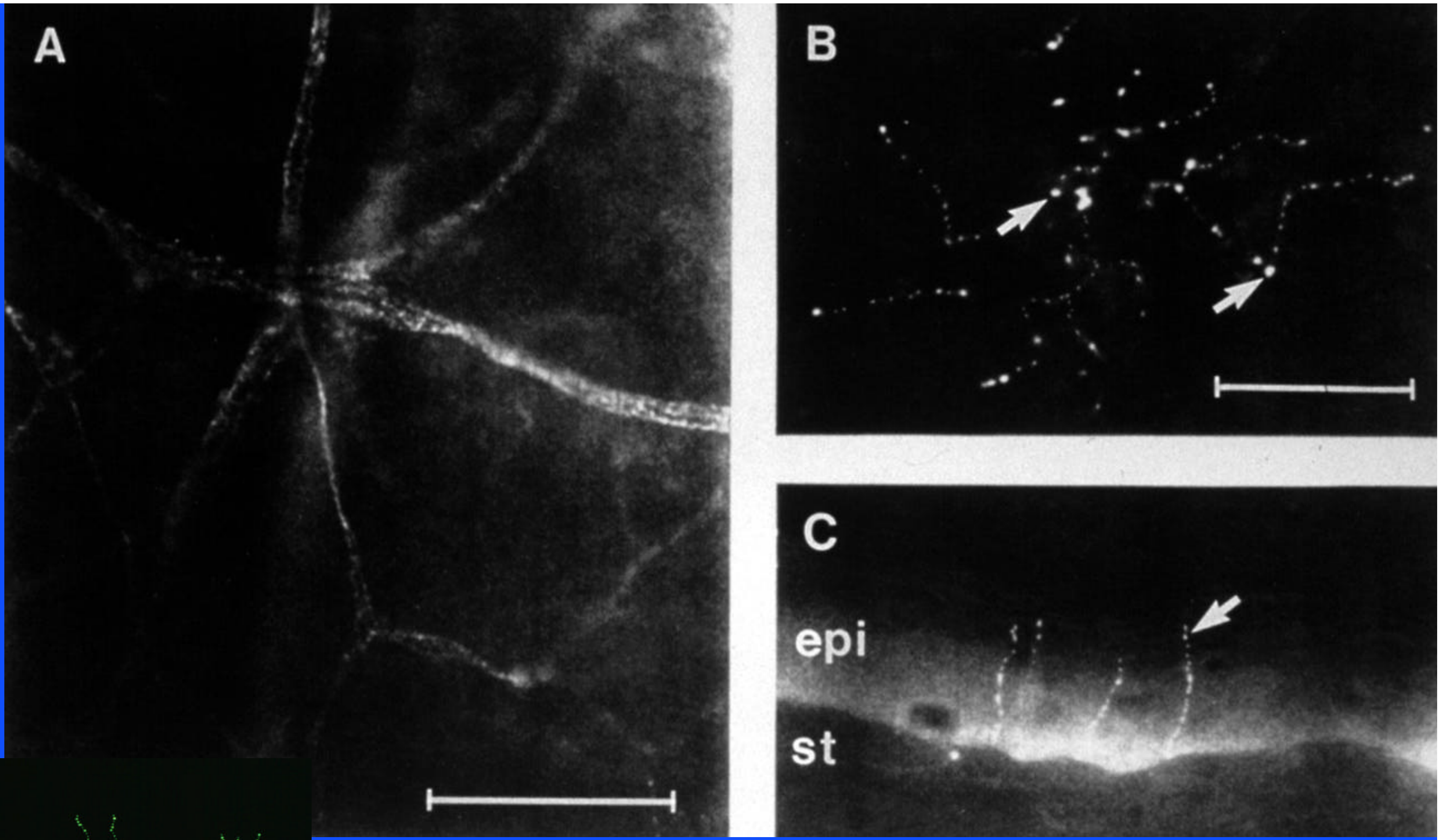


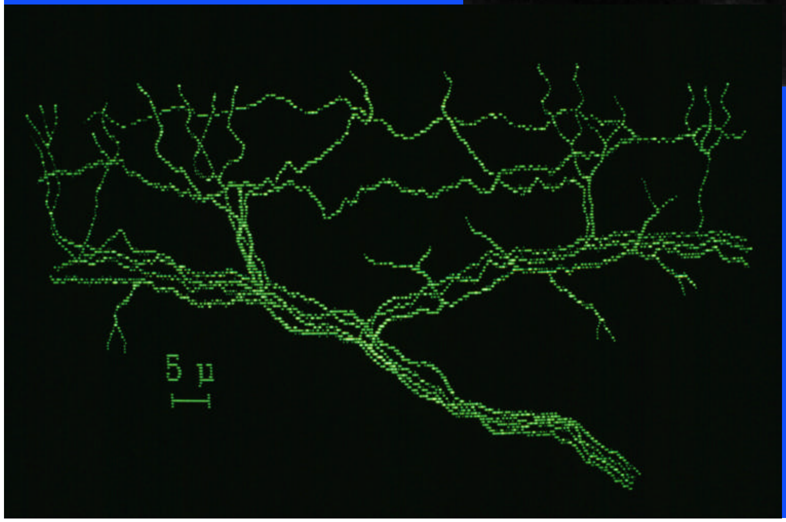


Reference: Kane, B. J., Storment, C. W., Crowder, S. W., Tanelian, D. L., and Kovacs, G. T. A., "Force-Sensing Microprobe for Precise Stimulation Of Mechanosensitive Tissues," IEEE Transactions on Biomedical Engineering, vol. 42, no. 8, Aug. 1995, pp. 745 - 750.

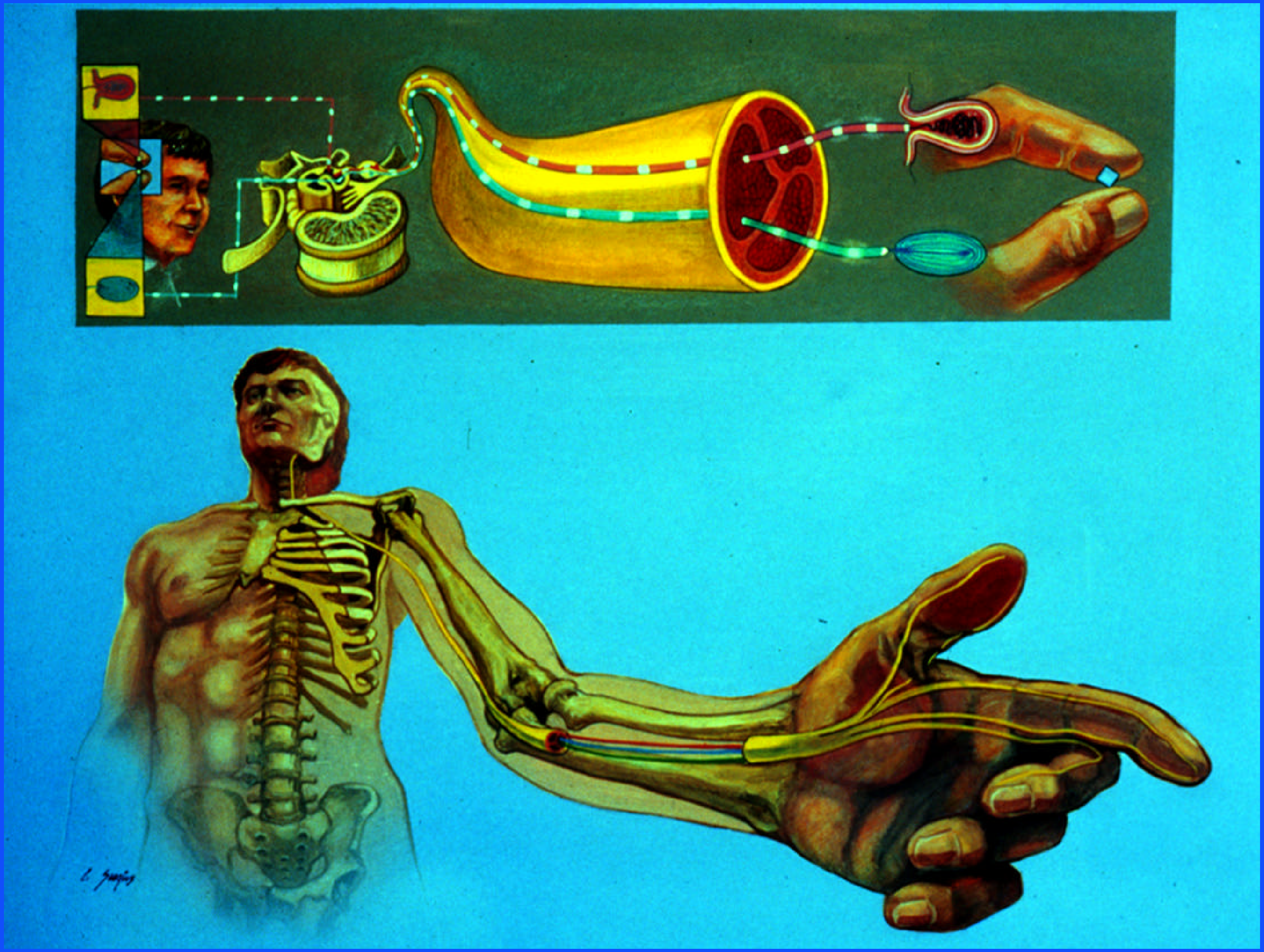


Courtesy Dr. D. Tanelian.

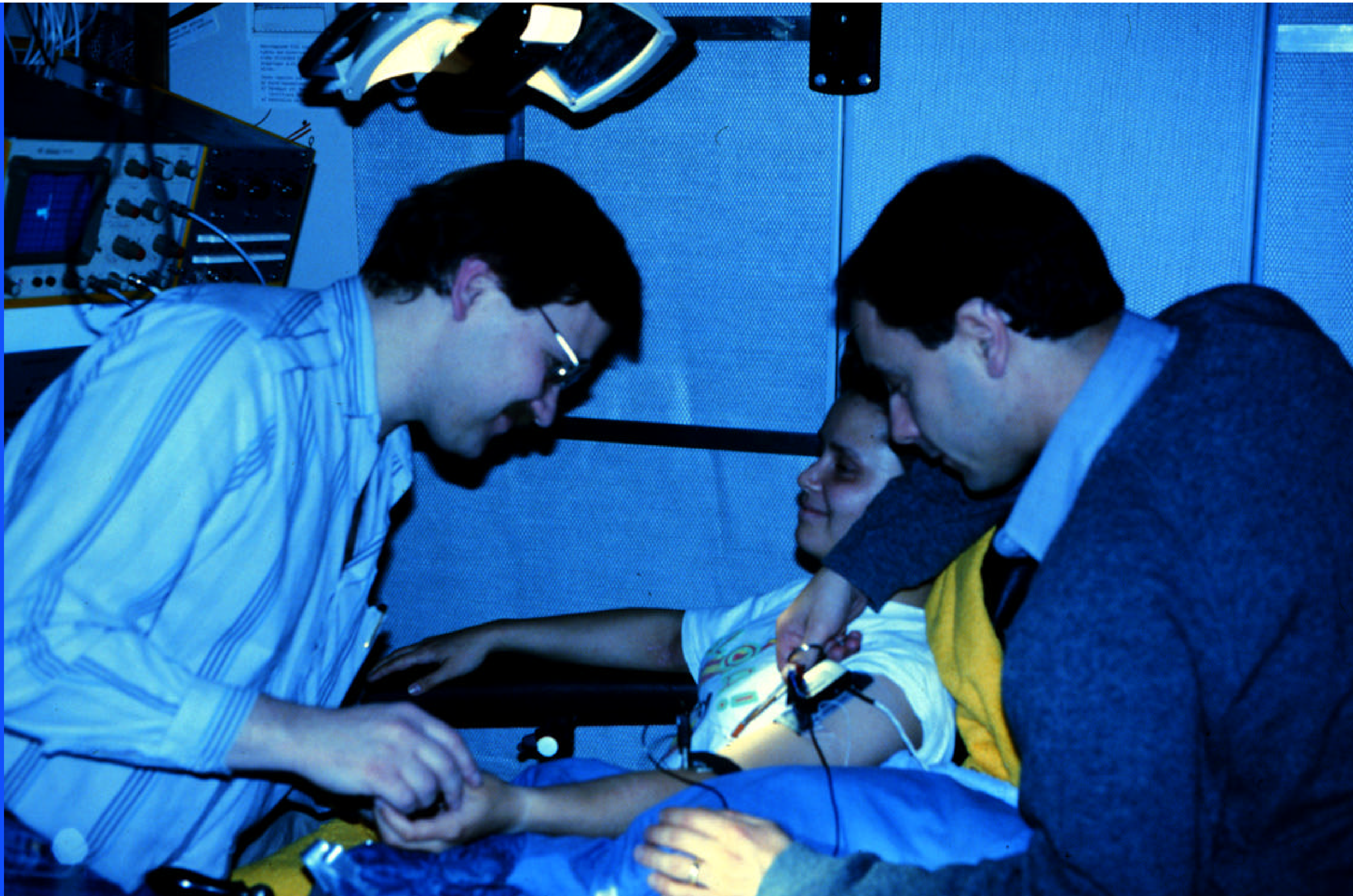


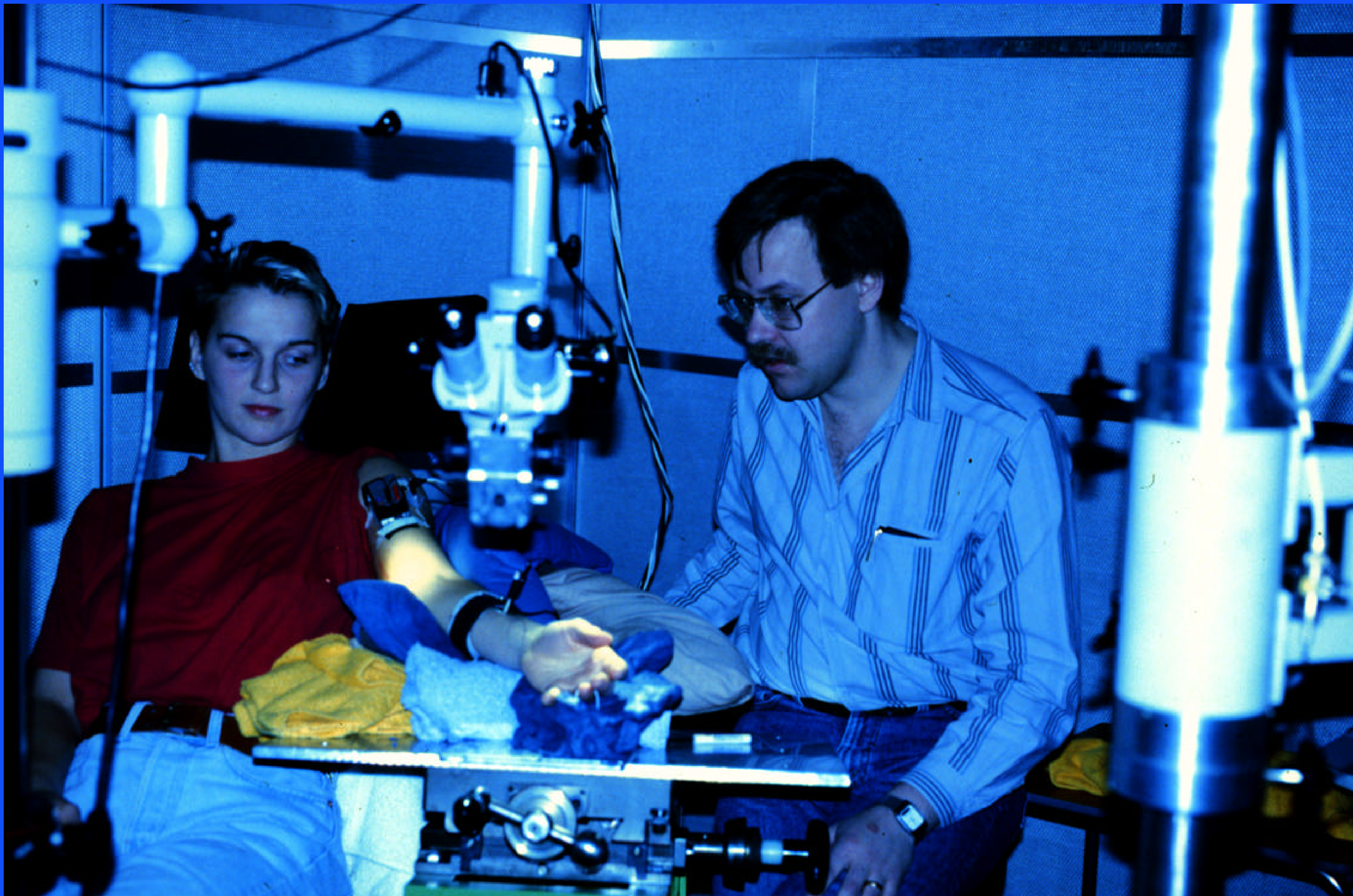


Courtesy Dr. D. Tanelian.

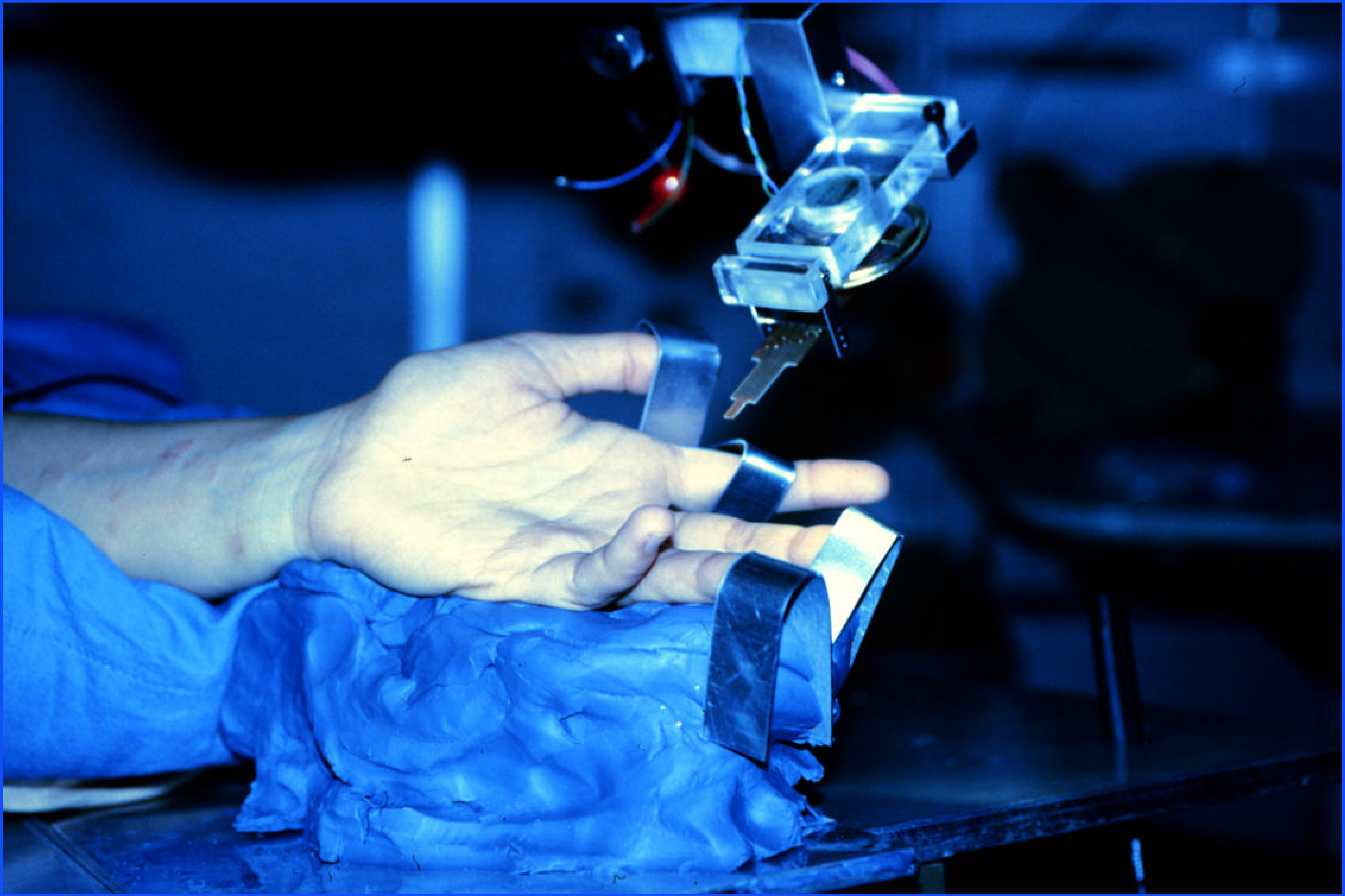


Courtesy Dr. J. Rosen.






HA!

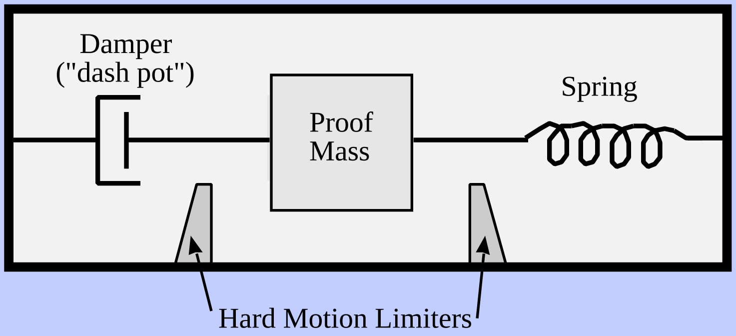


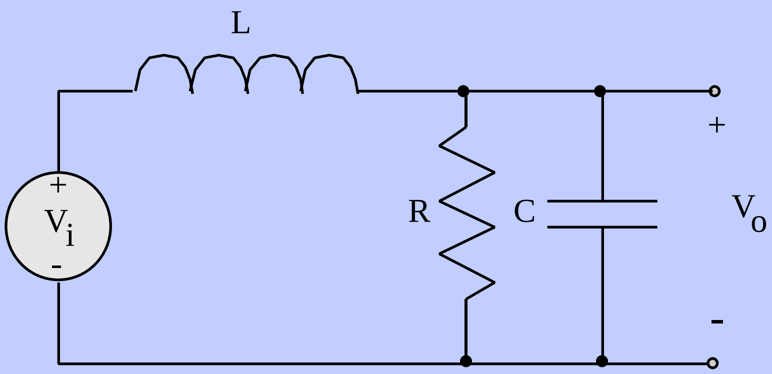
BASIC ACCELEROMETER CONCEPTS

- Accelerometers use a proof mass to sense acceleration by measuring the force on the mass (F=ma).
- The mass may be allowed to move against a restoring force (e.g. spring, F=kx) and the displacement measured.
- The mass may be held in place by a closed loop force balancing system and the balancing force (error signal) measured.
- The basic accelerometer is a second-order system with a damping term.

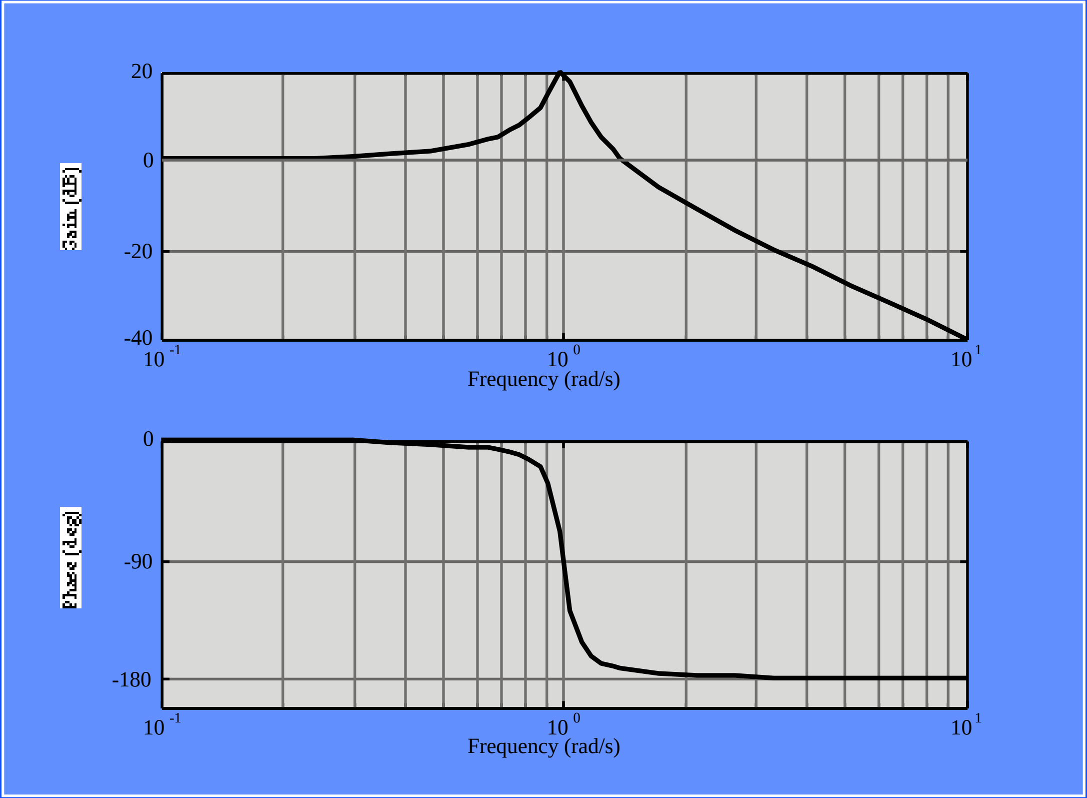
$$H(S) = \frac{\frac{k}{m}}{S^2 + \left(\frac{b}{m}\right)S + \frac{k}{m}}$$

$$H(S) = \frac{\frac{1}{LC}}{S^2 + \left(\frac{1}{RC}\right)S + \frac{1}{LC}} = \frac{\omega_o^2}{S^2 + \frac{\omega_o}{Q}S + \omega_o^2}$$





TYPICAL SECOND-ORDER RESPONSE

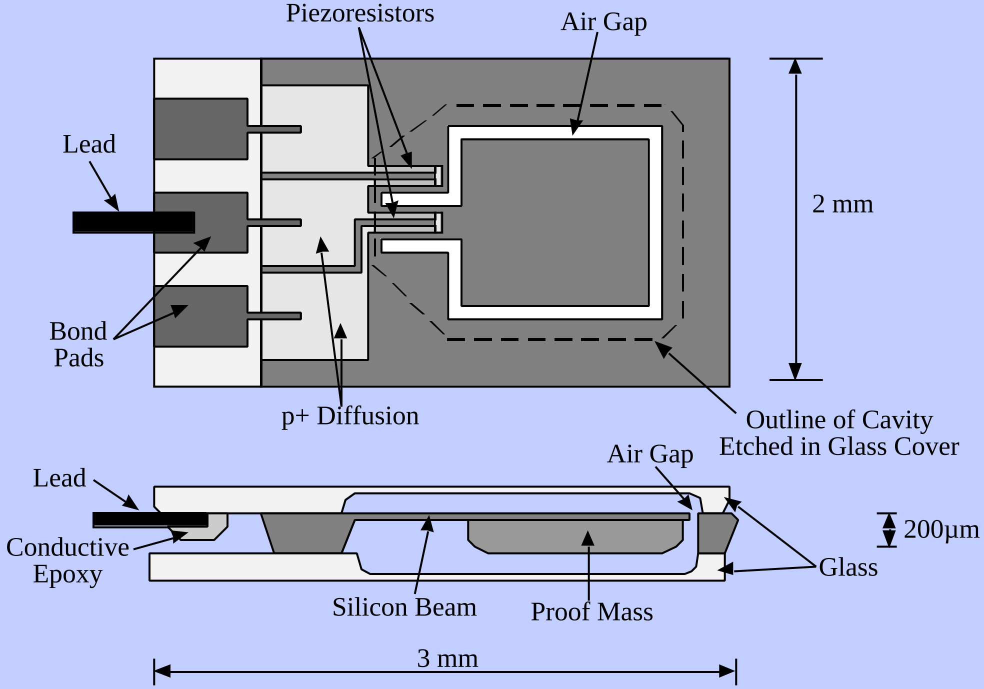


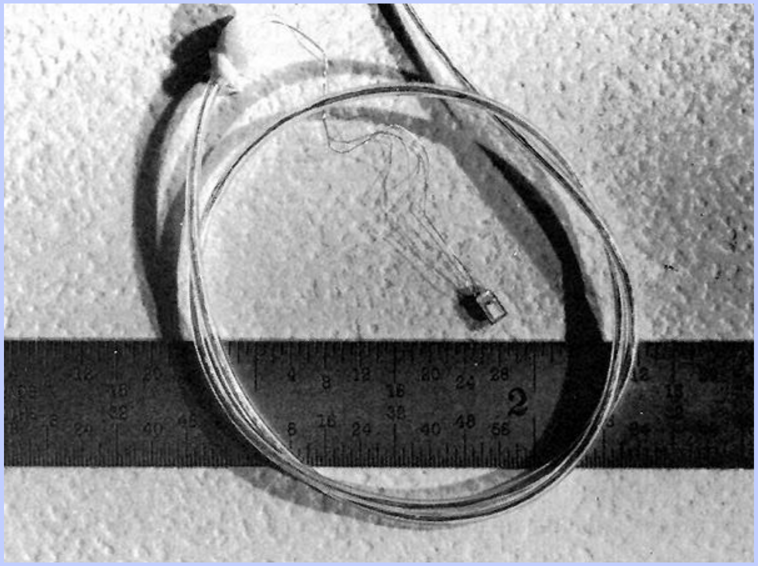
ACCELEROMETERS FOR AUTOMOTIVE APPLICATIONS

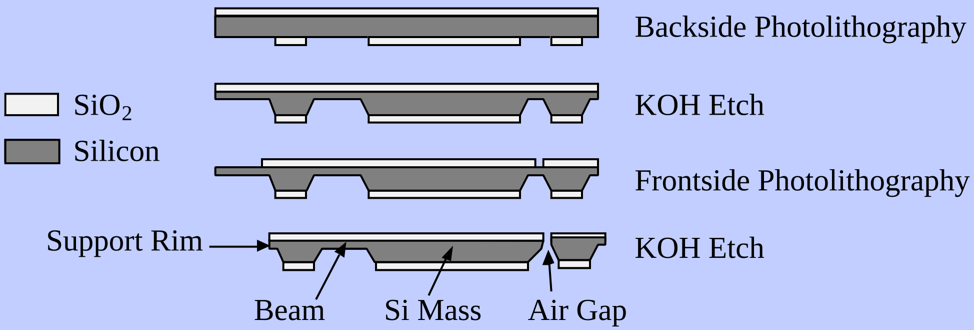
Range	± 1g	antilock braking (ABS)/traction control system (TCS)
	± 2g	vertical body motion
	± 40g	wheel motion
	± 50g	airbag deployment
	± 100°/s	steering feedback
Accuracy	± 2 %	5% at temperature extremes
Cross-Axis Sensitivity	< 1 - 3 %	all applications
Shock Survivability	> 500g	1 m drop onto concrete
Frequency Response	0 to 5 Hz	vertical motion
	0.5 to 50 Hz	horizontal motion (up to 1 kHz for airbags)
Temperature Range	-40 to 85 °C	most applications
	-40 to 125°C	under hood

Reference: MacDonald, G. A., "A Review of Low Cost Accelerometers for Vehicle Dynamics," Sensors and Actuators A, vol. A21 - A23, 1990, pp. 303 - 307.

EARLY MICROMACHINED ACCELEROMETER (ROYLANCE)



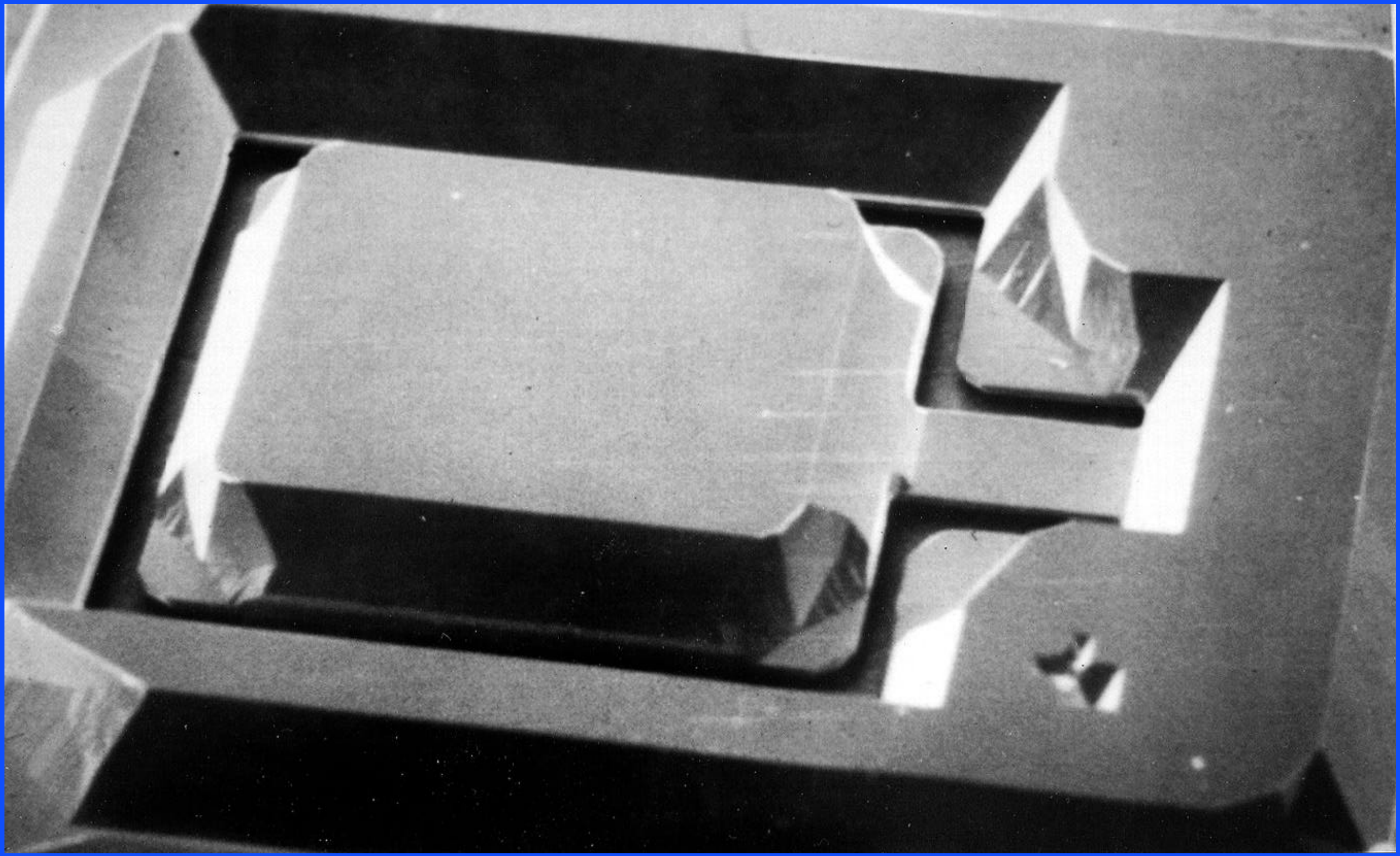




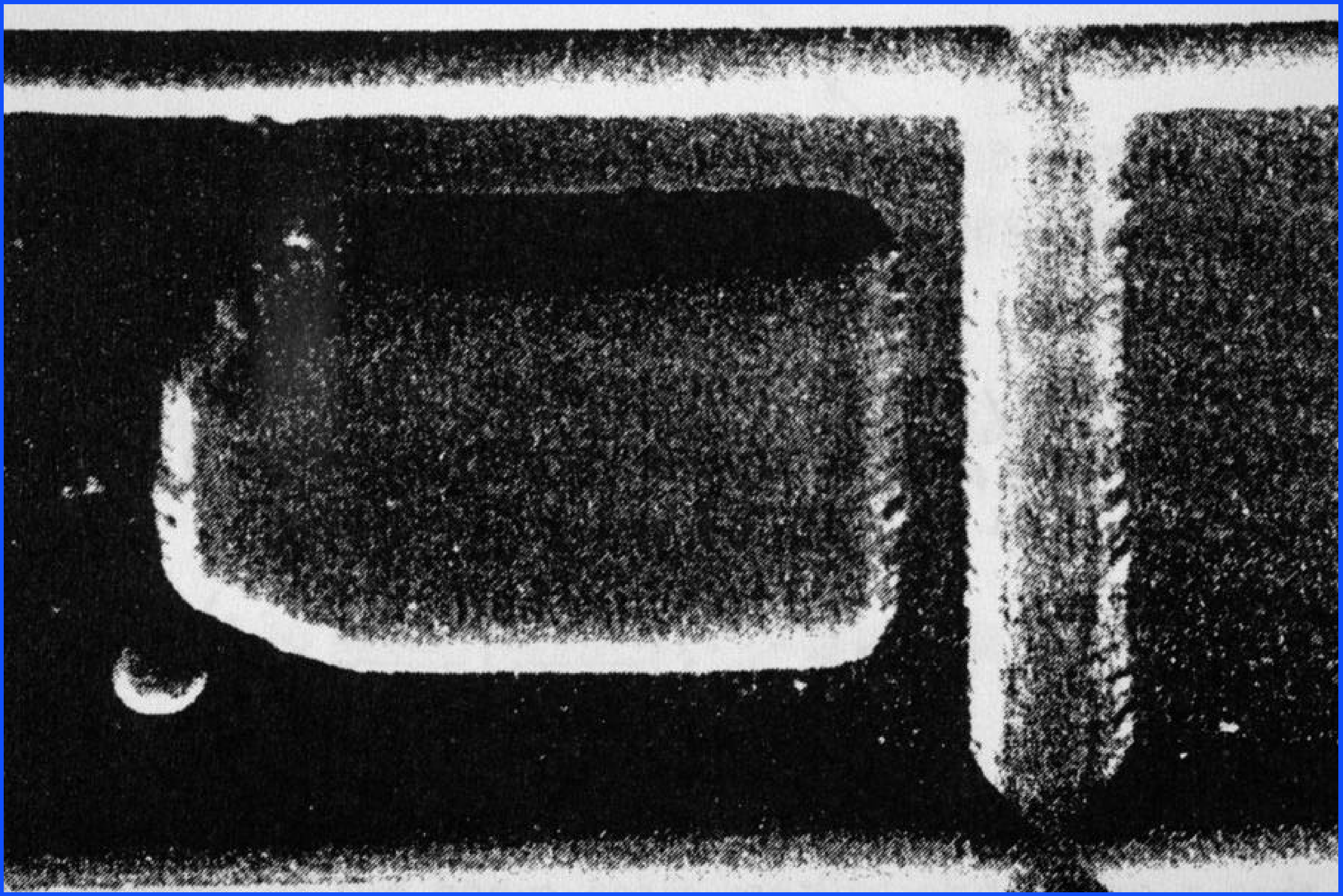
Reference: Roylance, L. M. and Angell, J. B., "A Batch-Fabricated Silicon Accelerometer," IEEE Transactions on Electron Devices, vol. ED-26, no. 12, Dec. 1979, pp. 1911 - 1917.

After Roylance and Angell (1979).

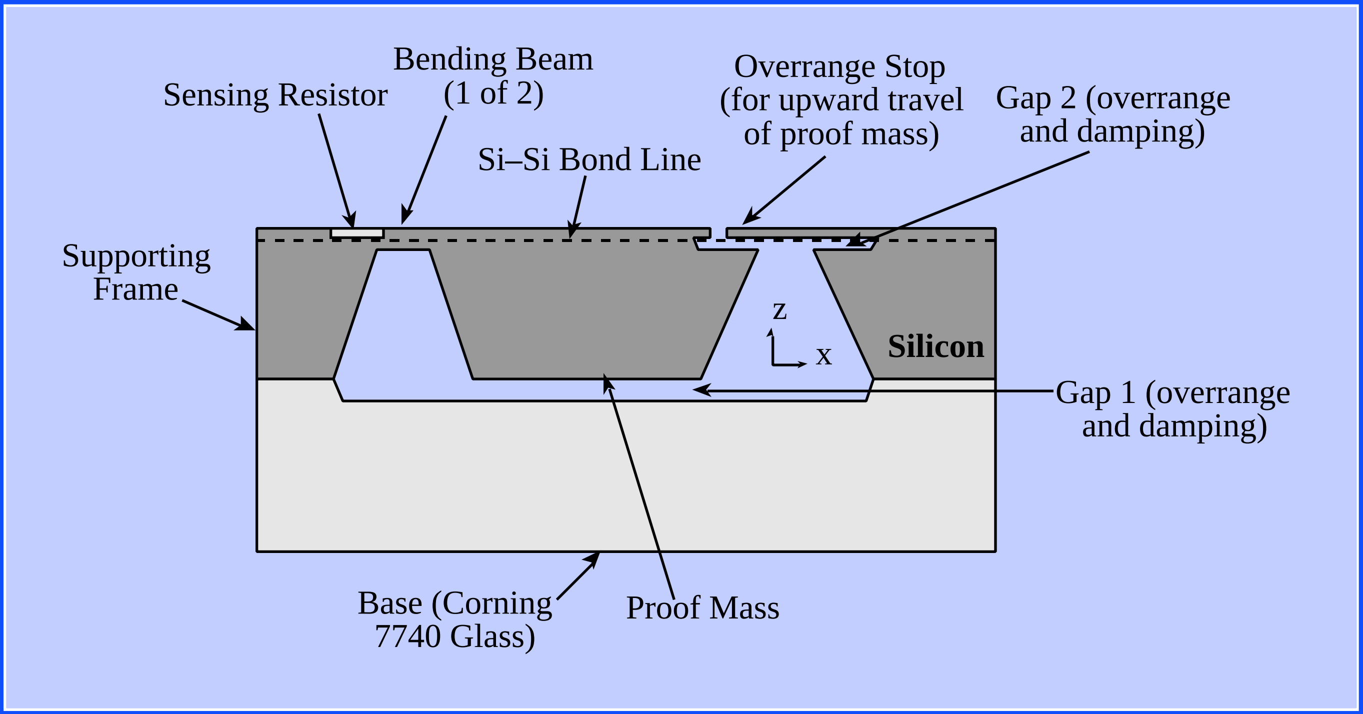
Roylance - Micromachined Accelerometer - 1974



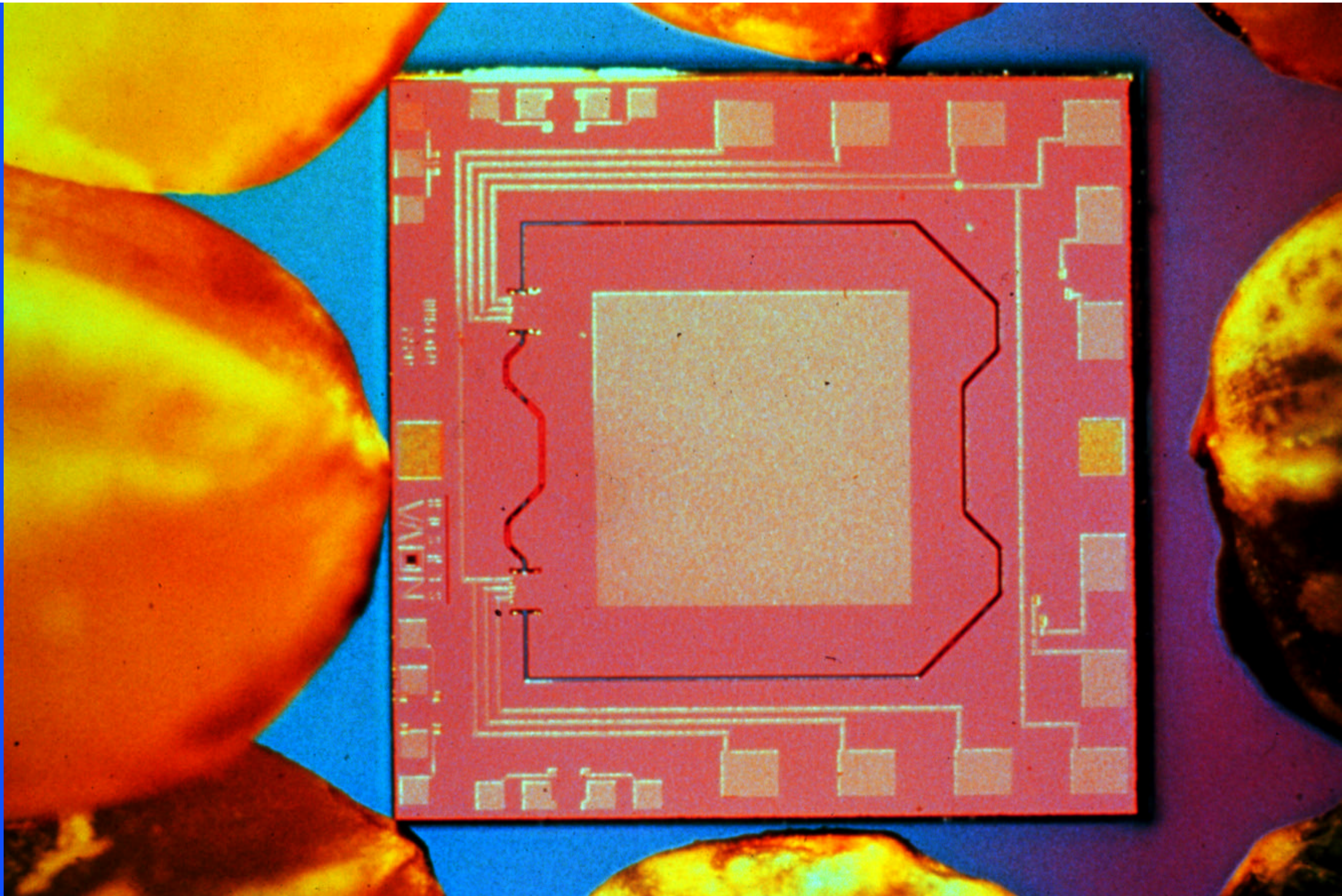
GLASS CAVITY ETCH



MODERN MICROMACHINED ACCELEROMETER (STRAIN GAUGE TYPE)

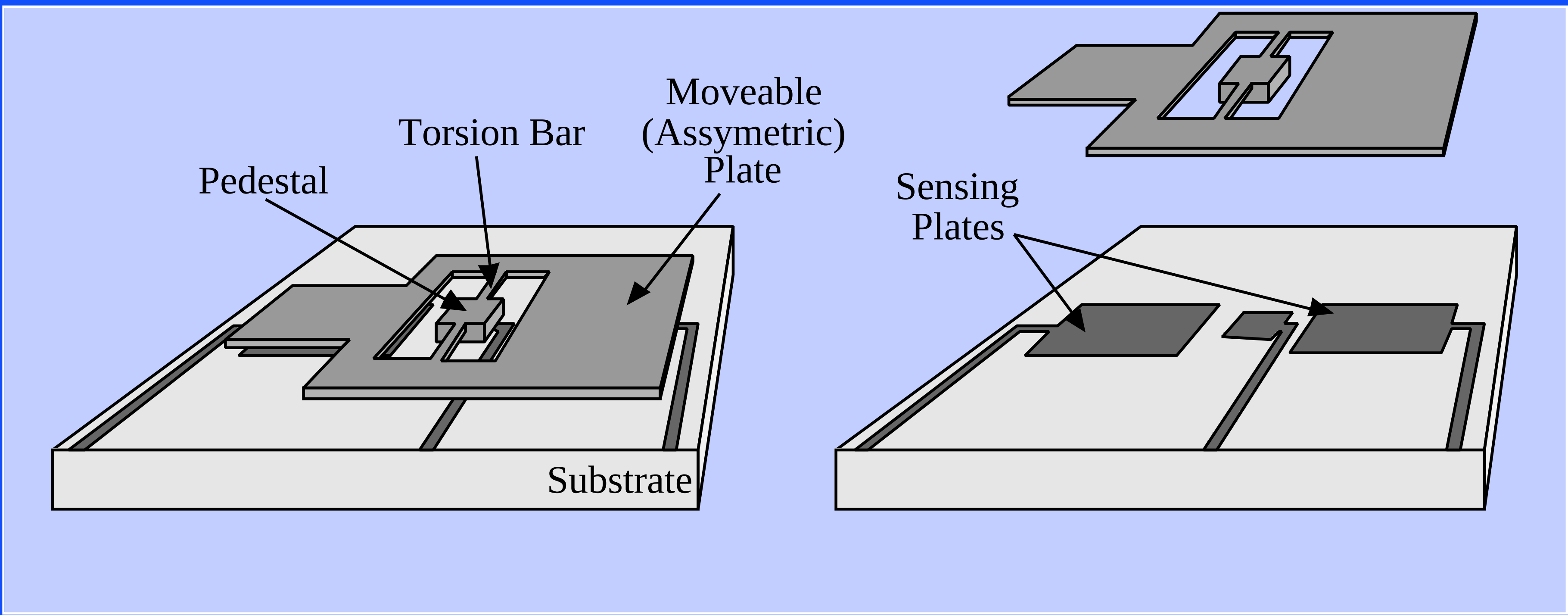


Courtesy of K. Petersen.



Courtesy of Lucas NovaSensor.

OPEN-LOOP CAPACITIVE ACCELEROMETER

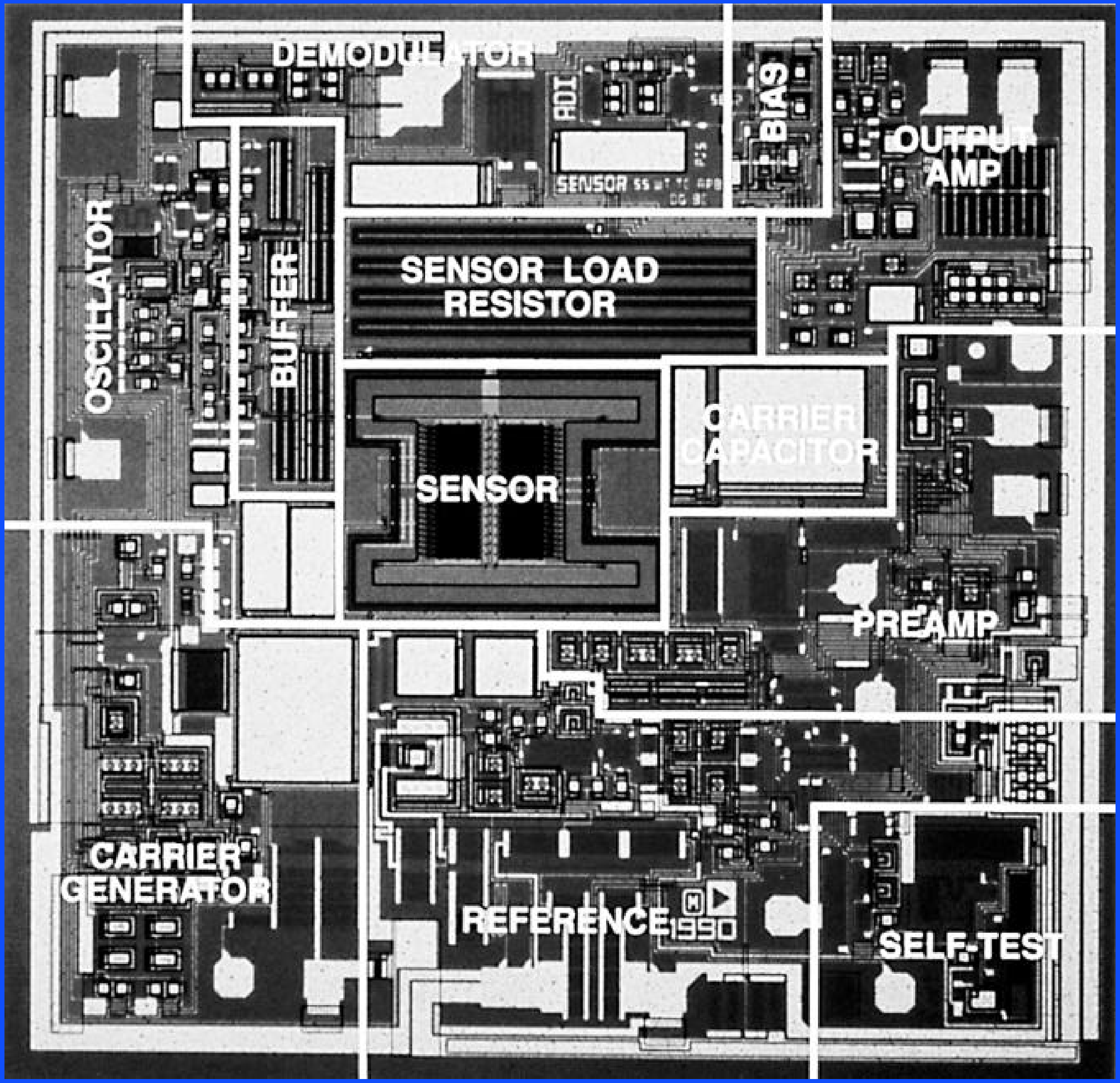


Adapted from Cole (1991).

Reference: Cole, J. C., "A New Sense Element Technology for Accelerometer Subsystems," Proceedings of the International Conference on Solid-State Sensors and Actuators, Transducers '91, San Francisco, CA, June 24 - 27, 1991, pp. 93 - 96.

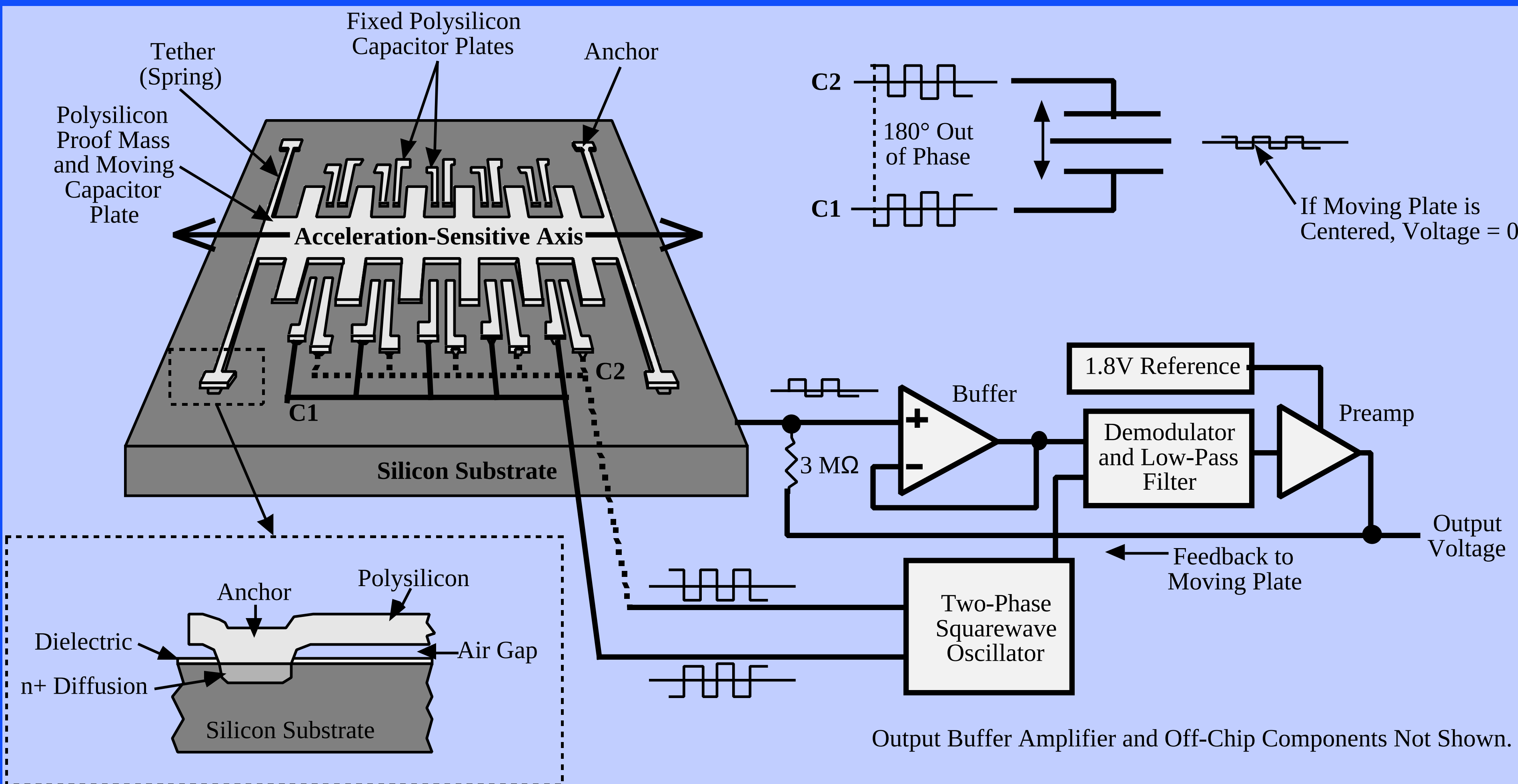
CAPACITIVE ACCELEROMETER ANALOG DEVICES ADXL-50

- **Micromachined polysilicon proof mass formed from 2 μm thick polysilicon on BiMOS.**
- **Capacitive force-rebalance method keeps mass stationary.**
- **On-chip circuitry provides signal conditioning and self-test.**



(3 X 3 mm chip)

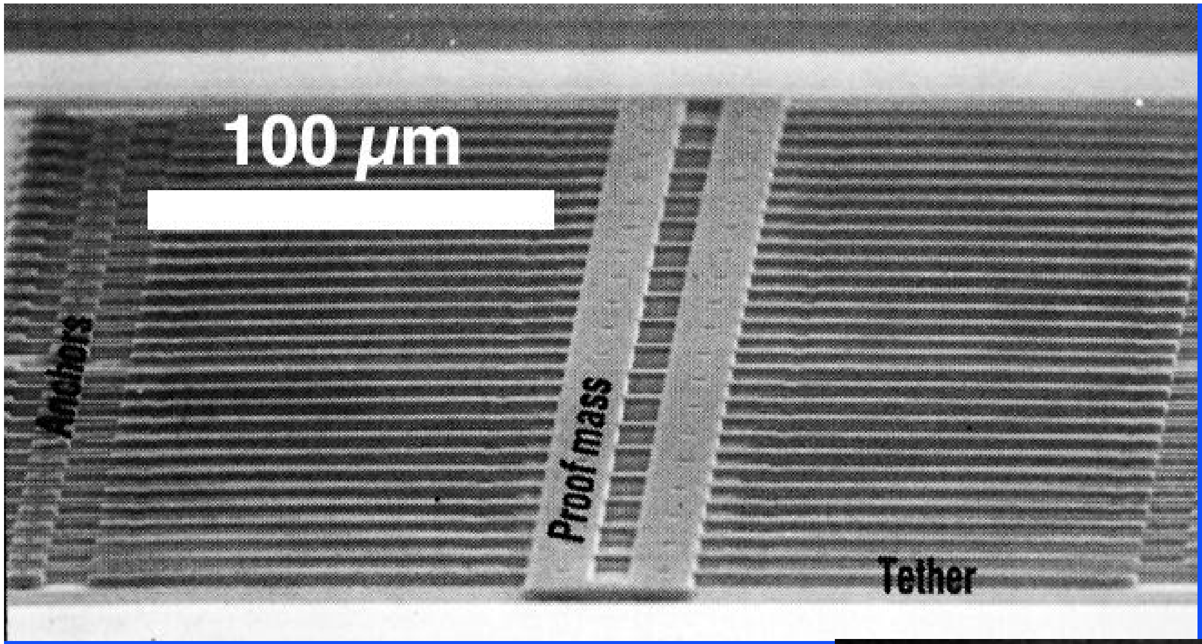
Image courtesy of Dr. R. Payne.

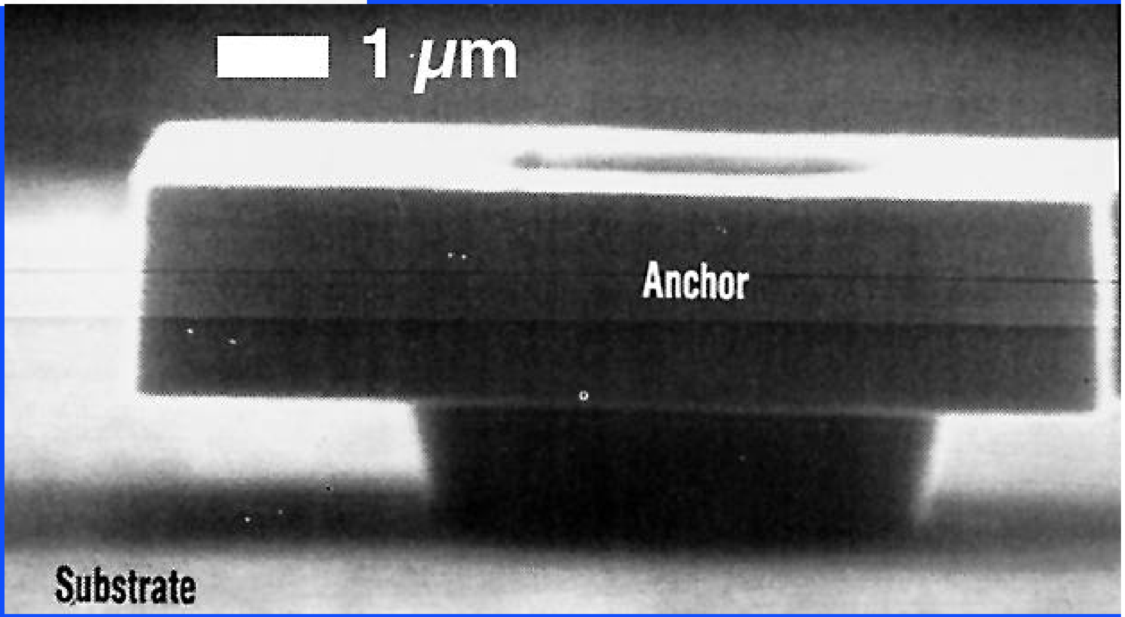


Output Buffer Amplifier and Off-Chip Components Not Shown.

Adapted from Goodenough (1991) and Analog Devices data sheet.

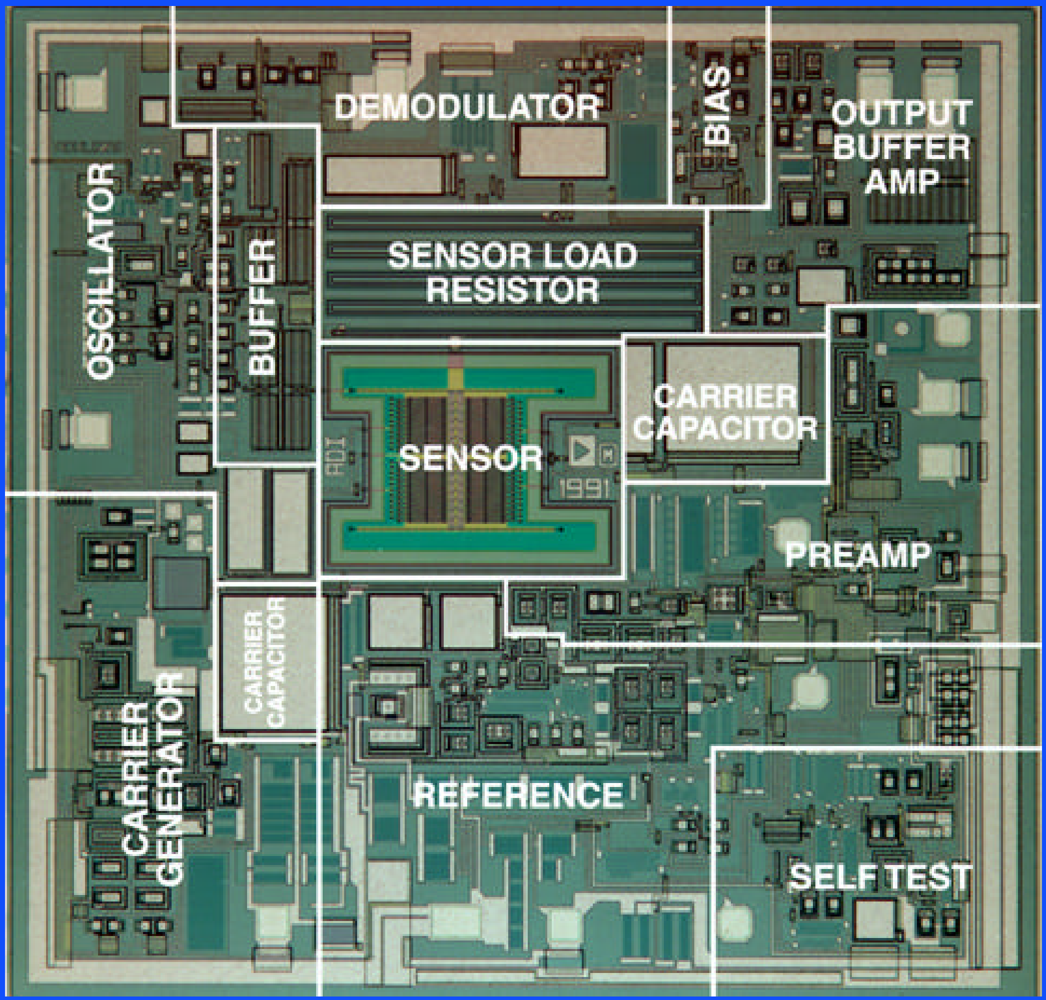
Reference: Goodenough, F., "Airbags Boom When IC Accelerometer Sees 50g," Electronic Design, vol. 39, no. 15, Aug. 8, 1991.

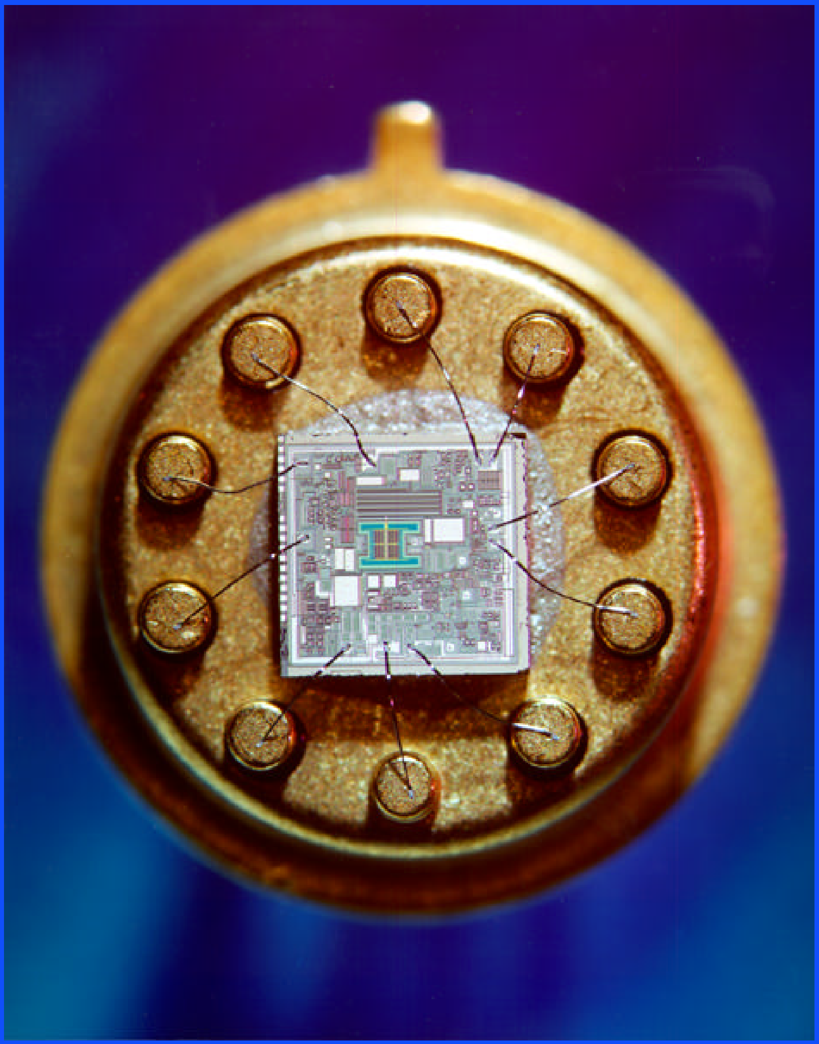




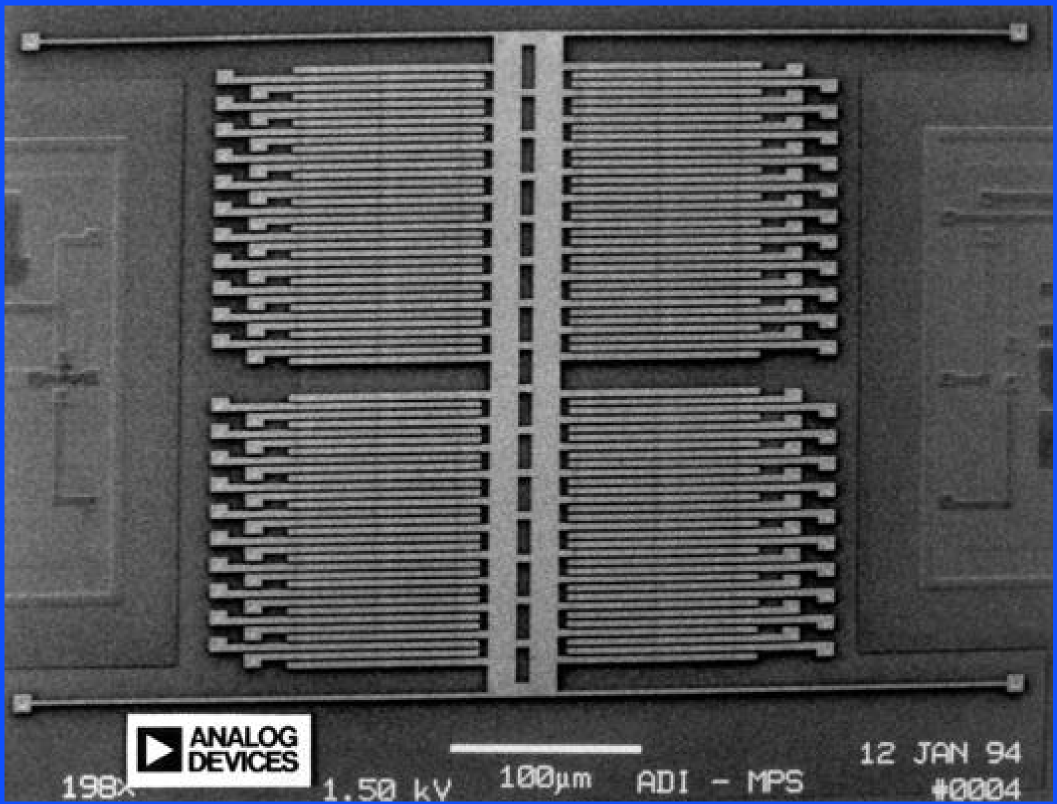
Images courtesy Dr. R. Payne, Analog Devices, Inc.

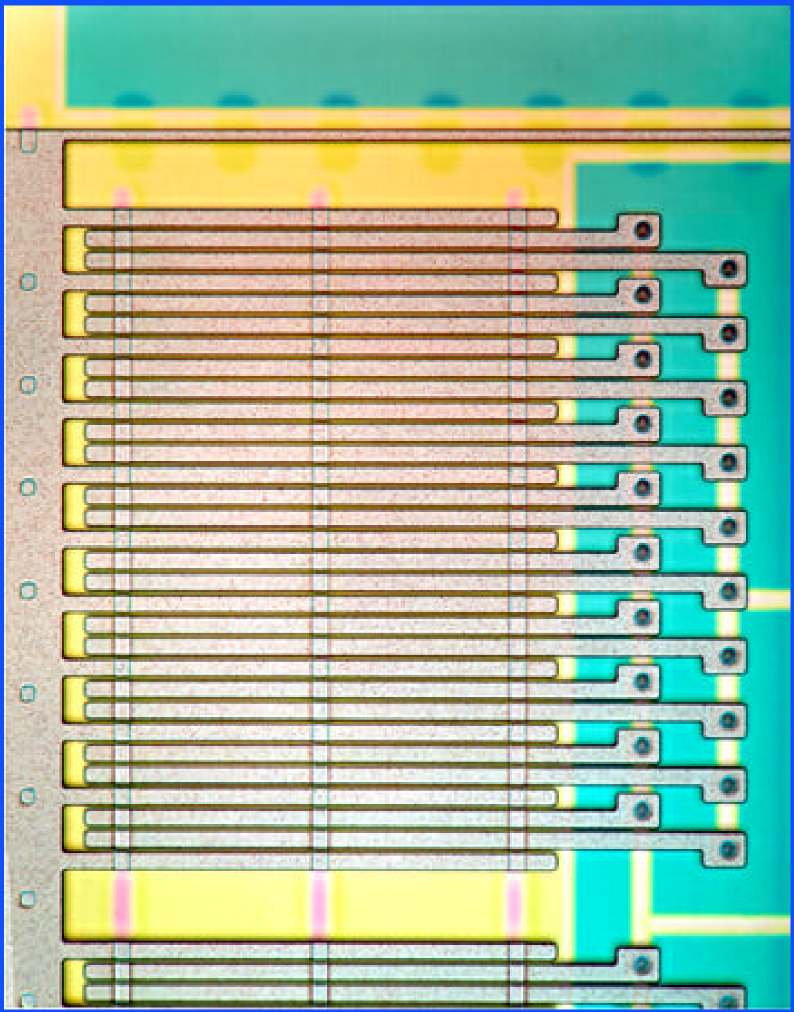
ANALOG DEVICES ADXL-50





Images courtesy Dr. R. Payne, Analog Devices, Inc.





Images courtesy Dr. R. Payne, Analog Devices, Inc.

ADXL-05 ACCELEROMETER

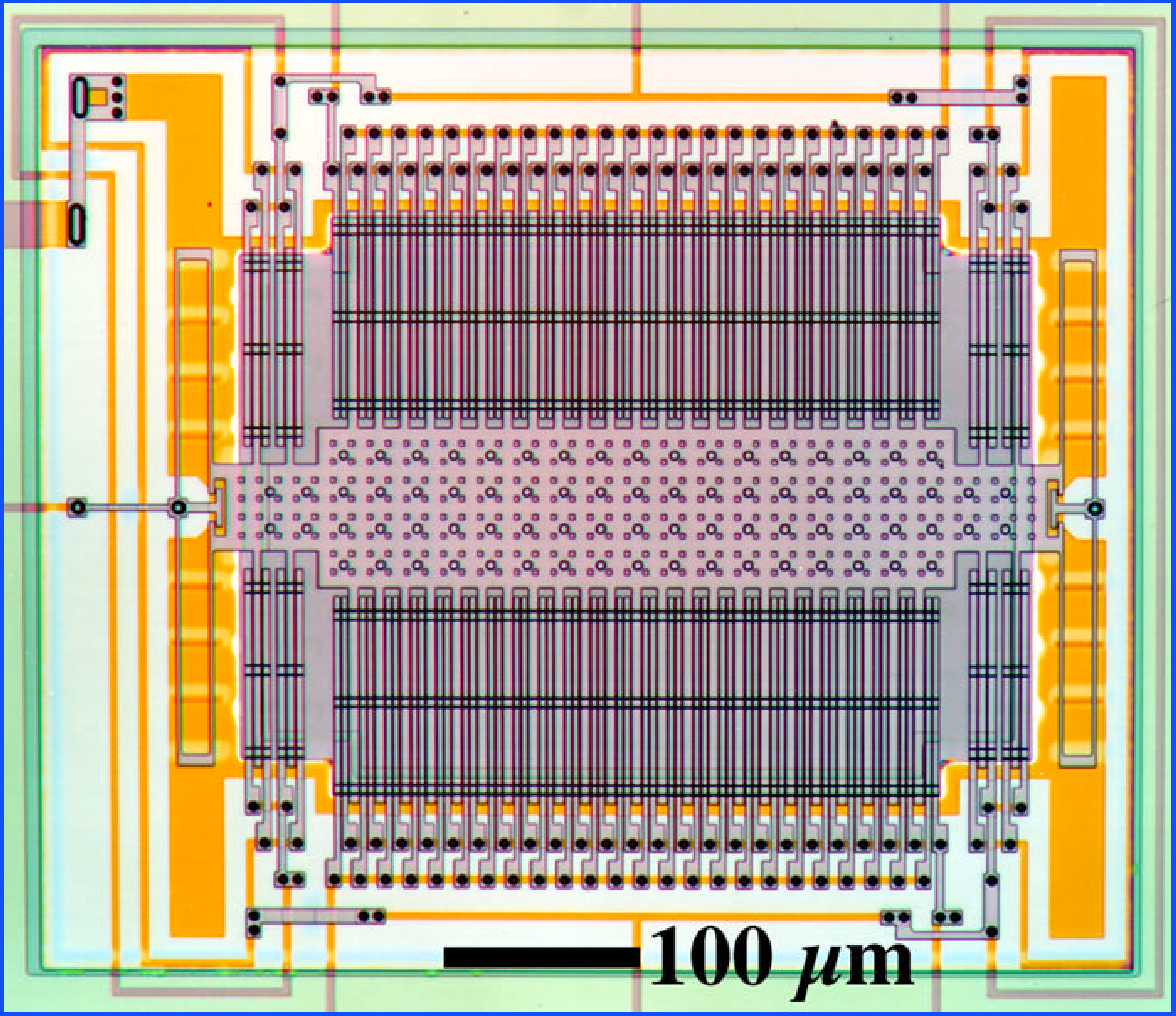
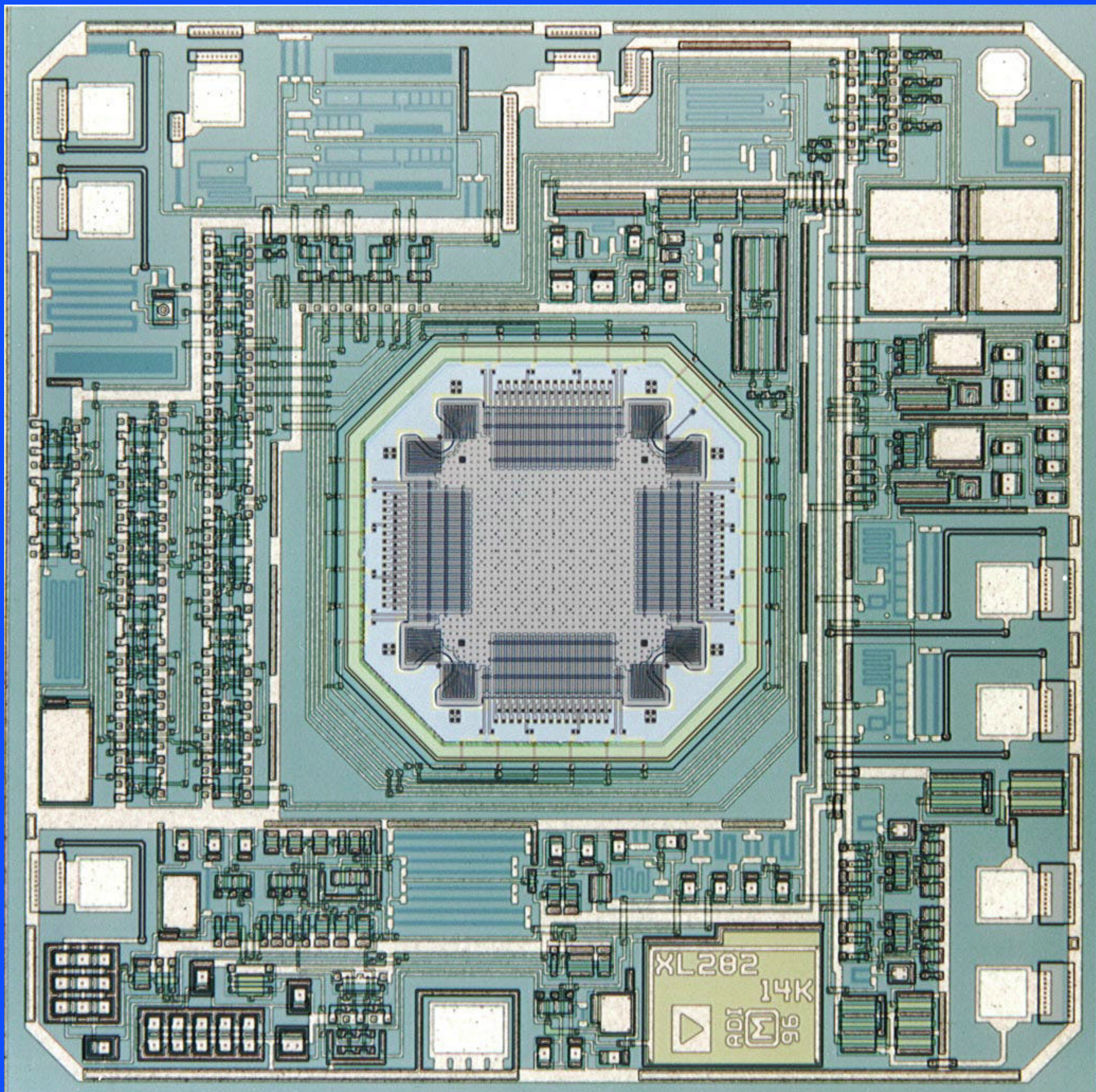
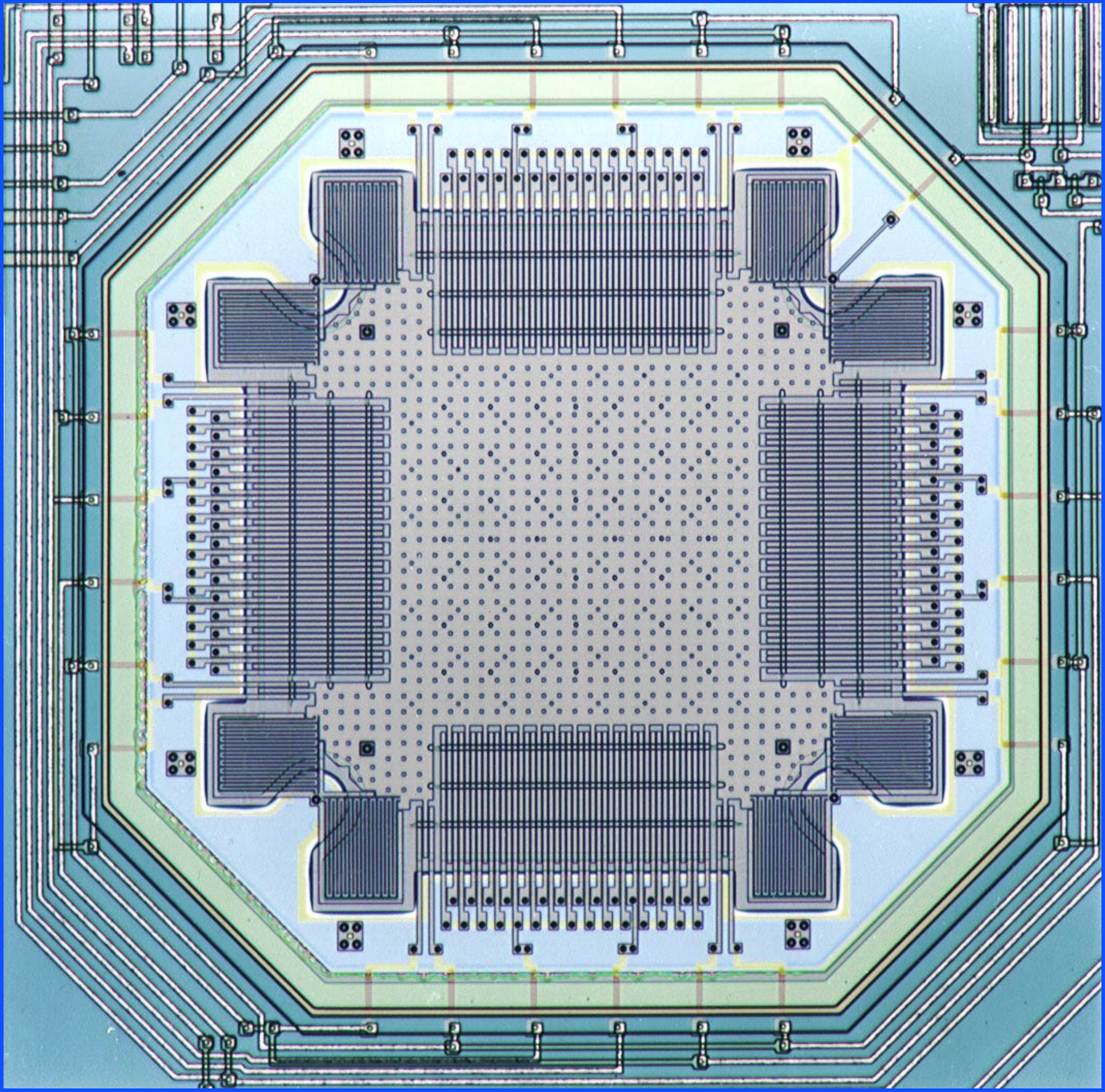


Image courtesy Dr. R. Payne, Analog Devices, Inc.



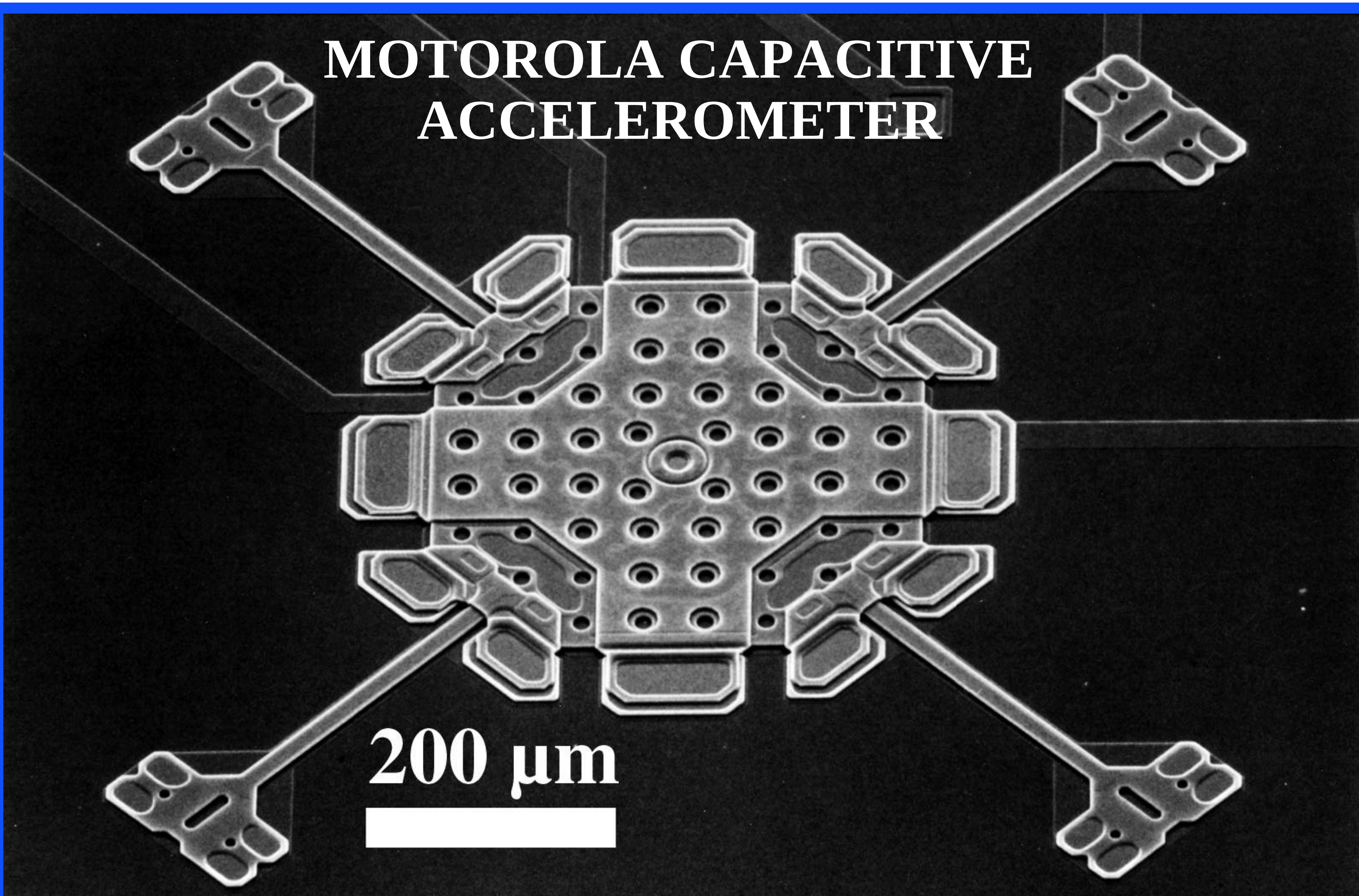
ADXL-202

Courtesy Dr. M. Judy, Analog Devices, Inc.

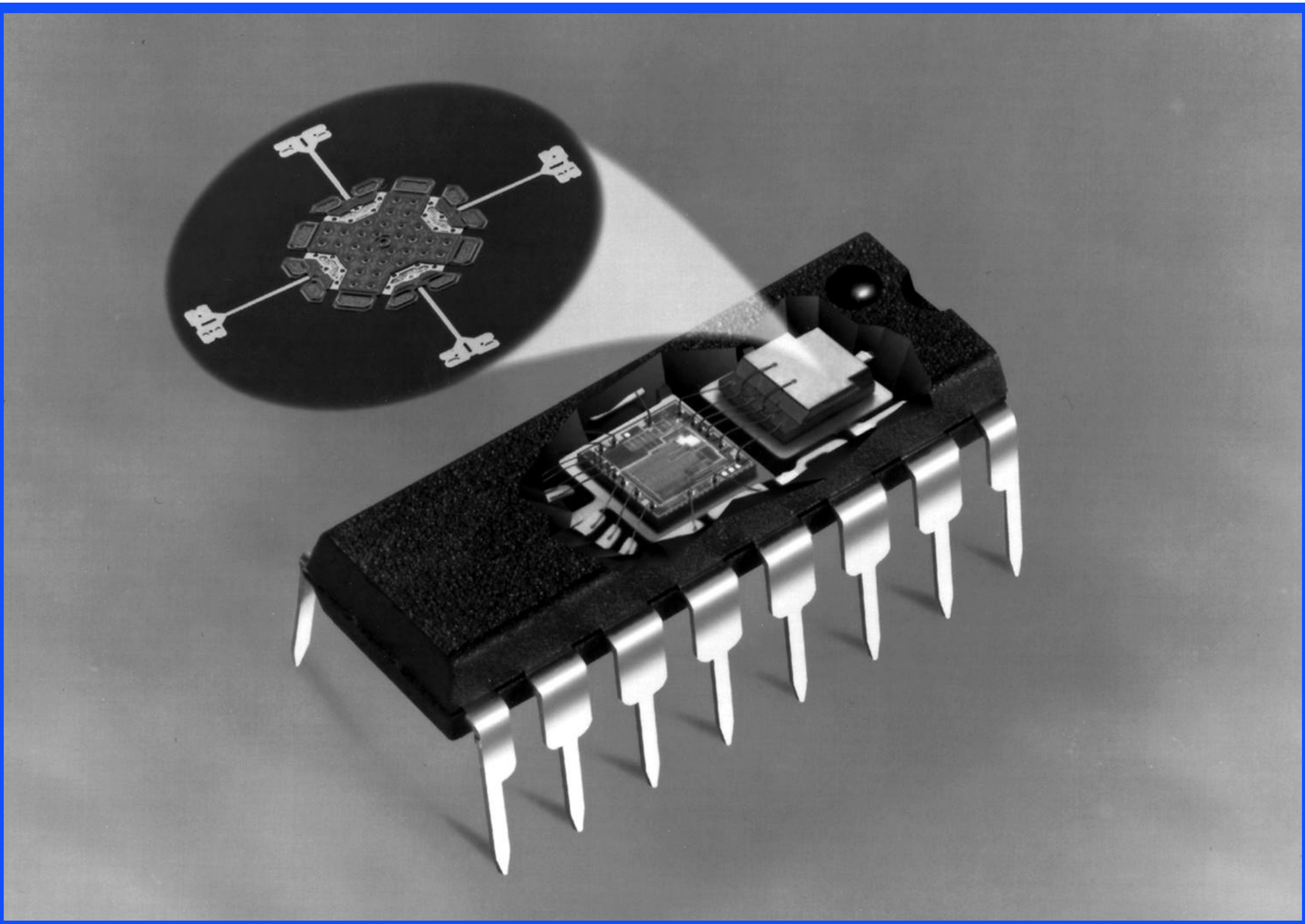


ADXL-202 CORE

Courtesy Dr. M. Judy, Analog Devices, Inc.

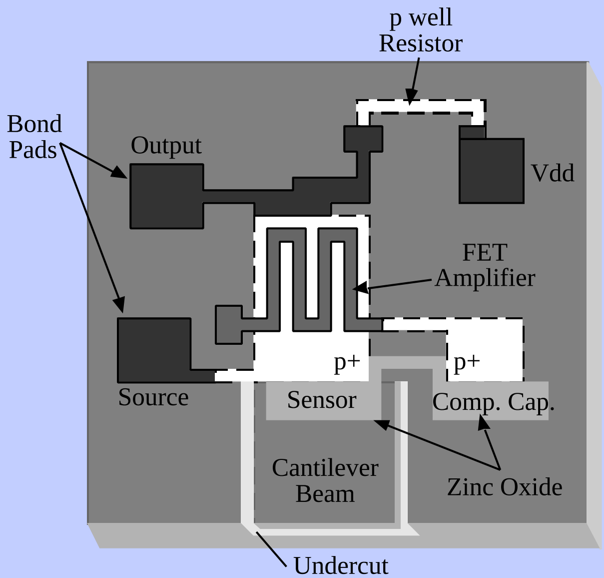


Courtesy Dr. Lj. Ristic, Motorola, Inc.



Courtesy Dr. Lj. Ristic, Motorola, Inc.

PIEZOELECTRIC ACCELEROMETERS



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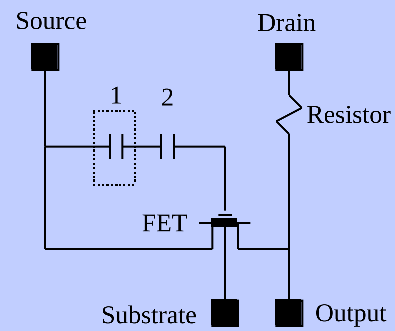
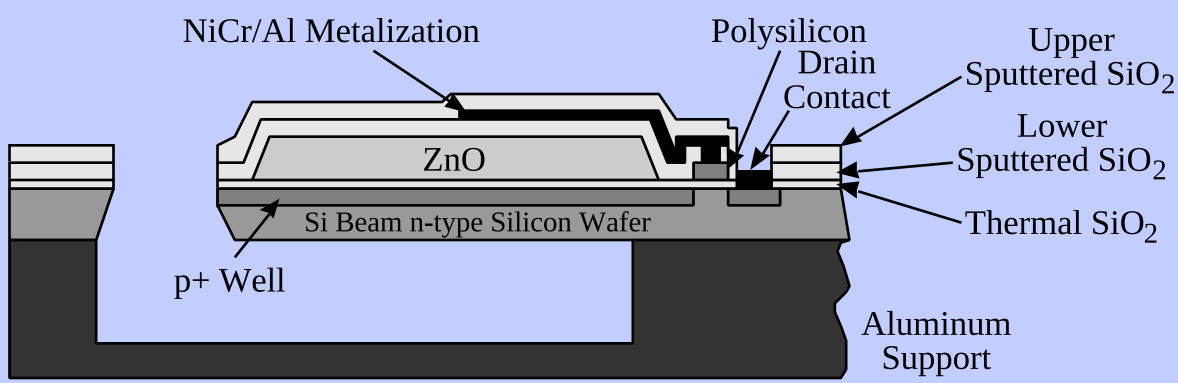
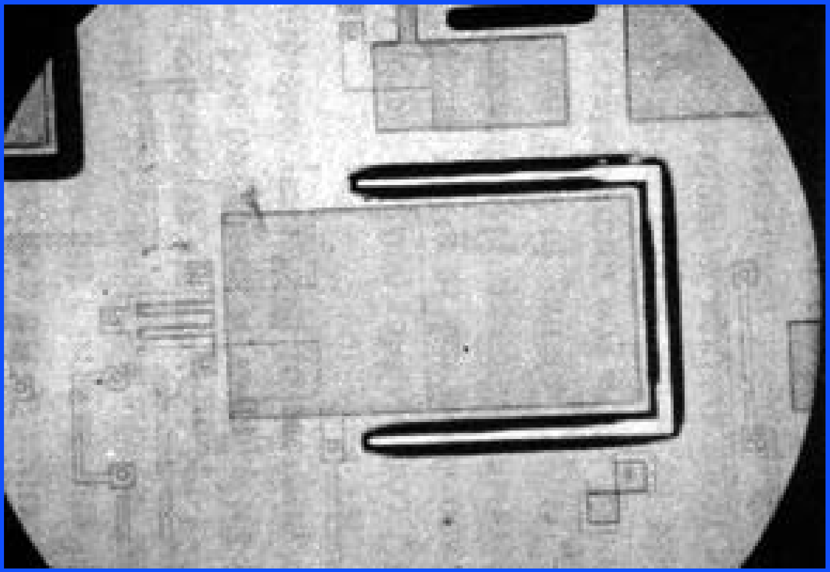
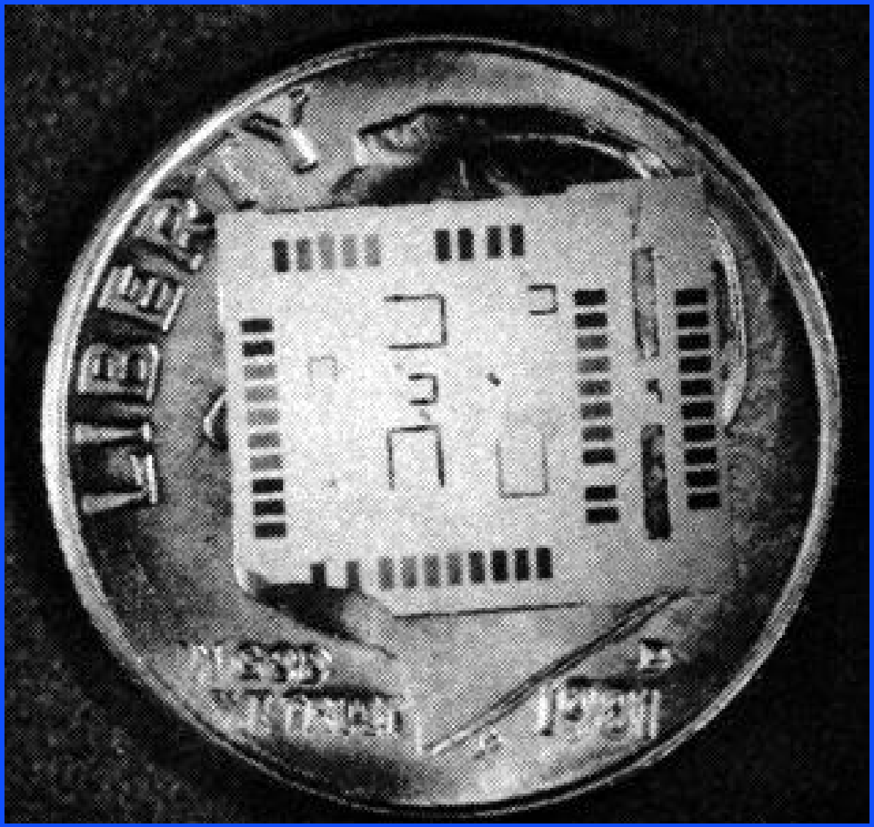


Piezoelectric thin film capacitors:
1 - Strained capacitor on beam
2 - Unstrained compensation capacitor



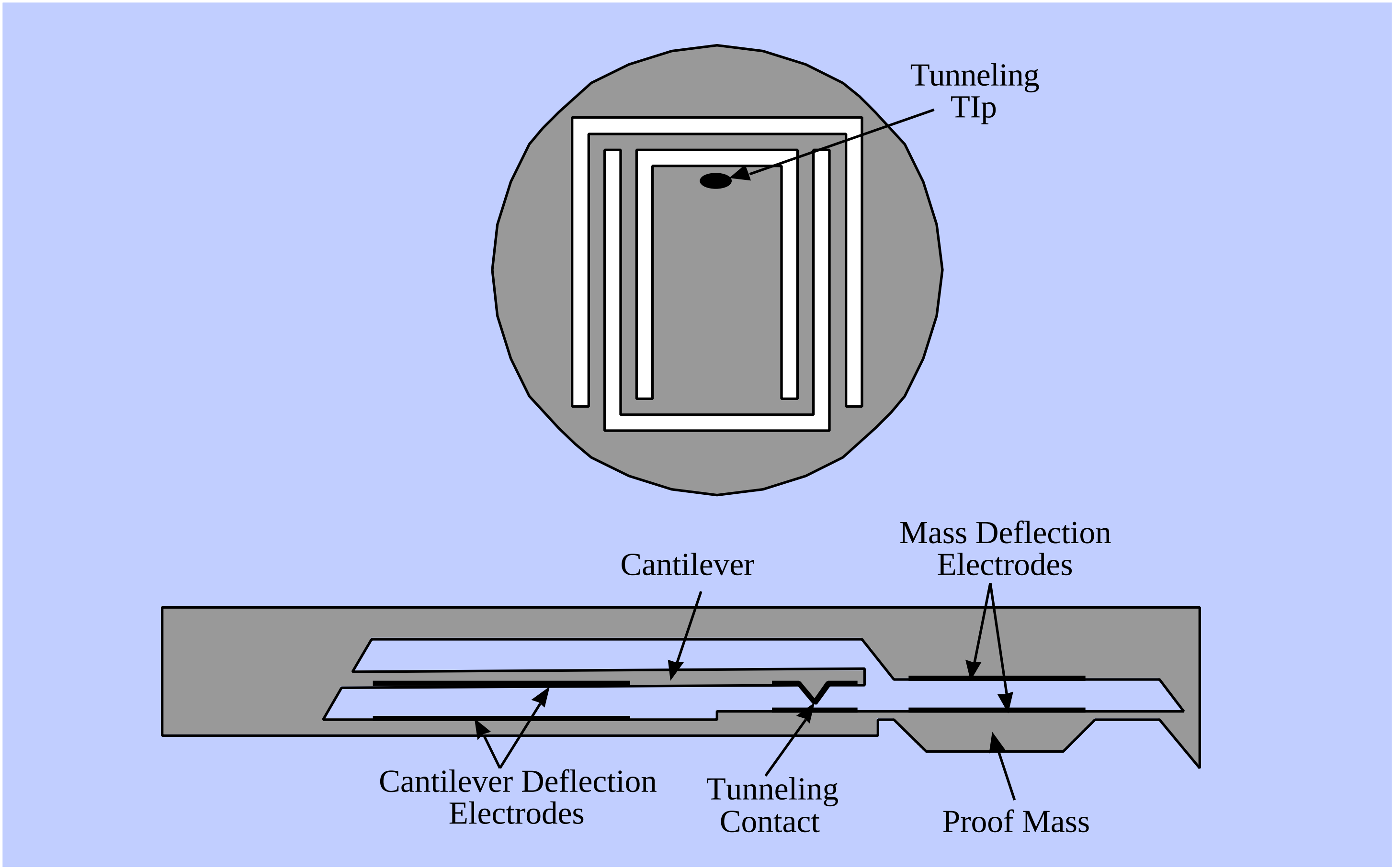
Reference: Chen, P.-L., Muller, R. S., Shiosaki, T., and White, R. M., "Silicon Cantilever Beam Accelerometer Utilizing a PI-FET Capacitive Transducer," IEEE Transactions on Electron Devices, vol. ED-26, 1979, p. 1857.



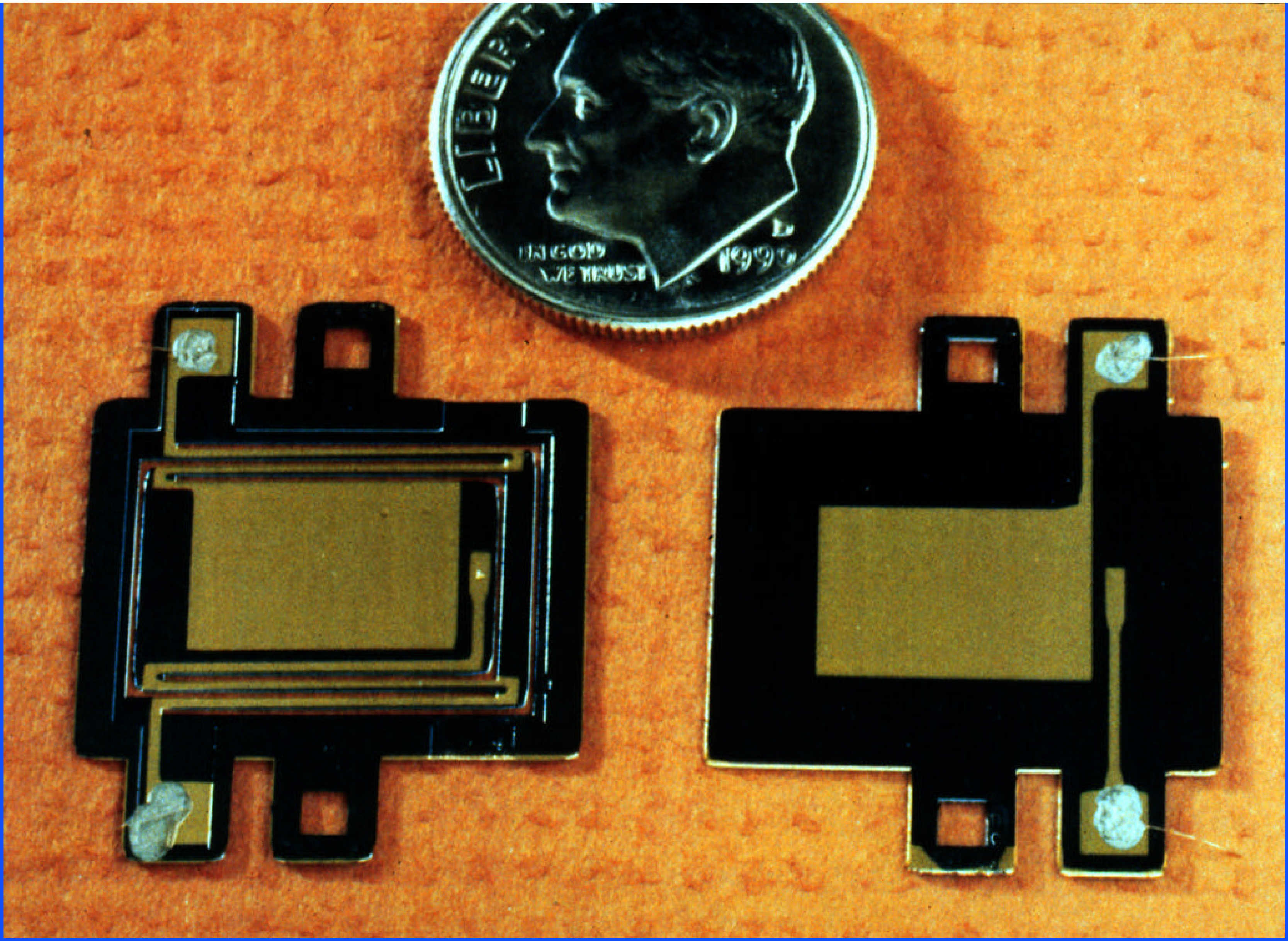


Source: Chen, P.-L., Muller, R. S., Shiosaki, T., and White, R. M., "Silicon Cantilever Beam Accelerometer Utilizing a PI-FET Capacitive Transducer," IEEE Transactions on Electron Devices, vol. ED-26, 1979, p. 1857.

TUNNELING ACCELEROMETERS

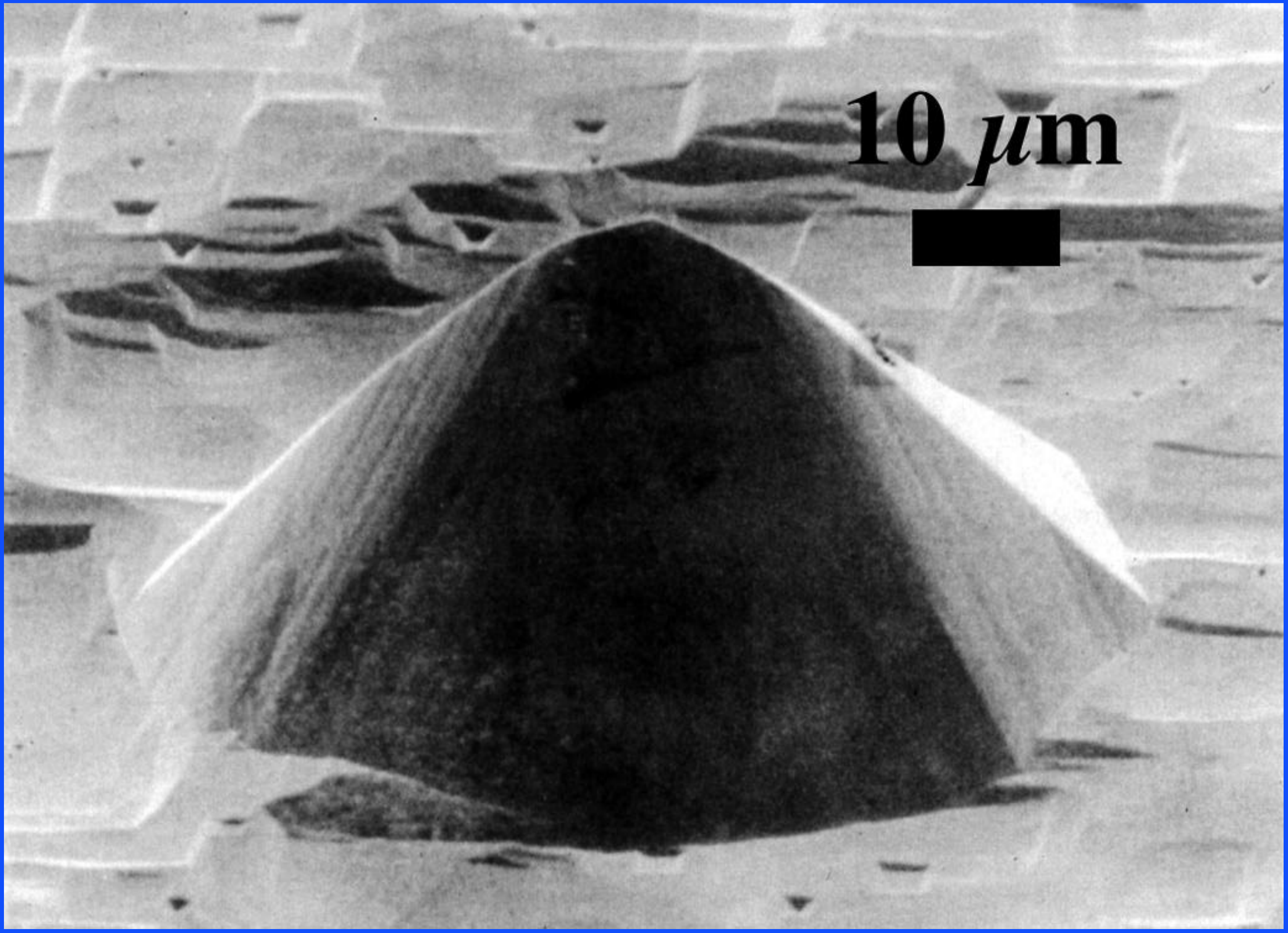


Reference: Rockstad, H. K., Kenny, T. W., Reynolds, J. K., Kaiser, W. J., and Gabrielson, T. B., "A Miniature High-Sensitivity Broad-Band Accelerometer Based on Electron Tunneling Transducers," Proceedings of the 7th International Conference on Solid State Sensors and Actuators, Transducers '93, Yokohama, Japan, 7-10 June 1993, pp. 836 - 839 (also published in Sensors and Actuators A, vol. A43, no. 1 - 3, May 1994, 107 - 114).



Courtesy Prof. T. Kenny, Stanford University.

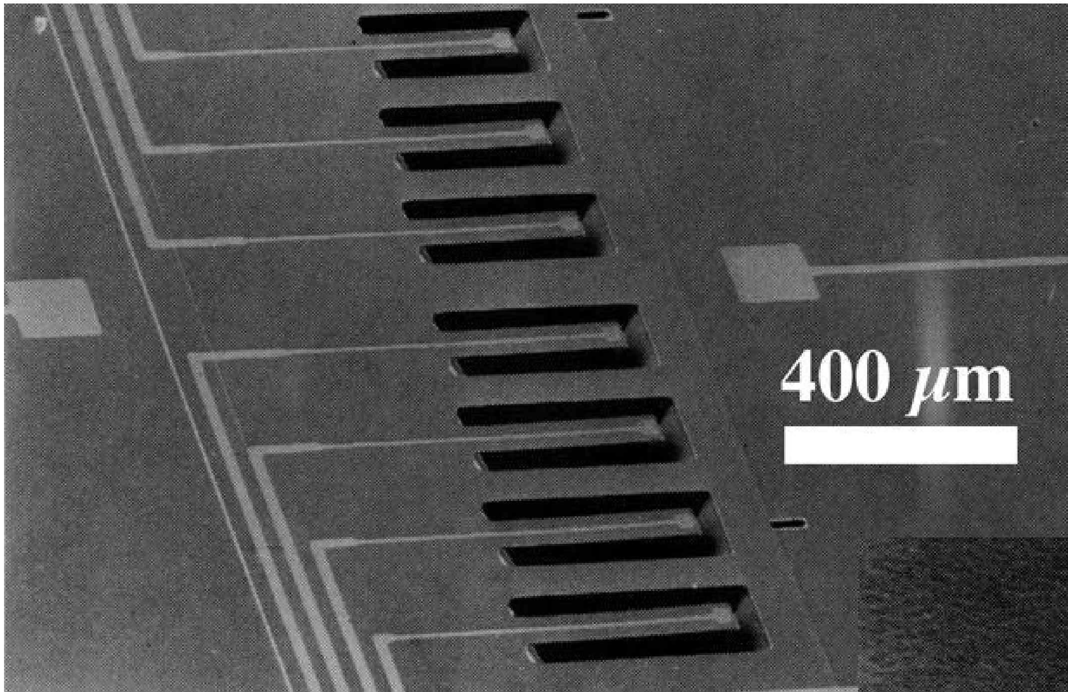
TUNNELING TIP



Courtesy Prof. T. Kenny, Stanford University.

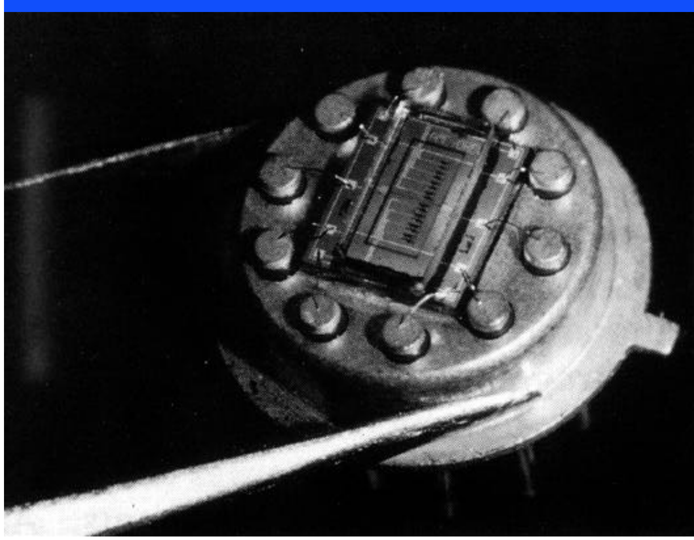
ACCELEROMETER ARRAYS

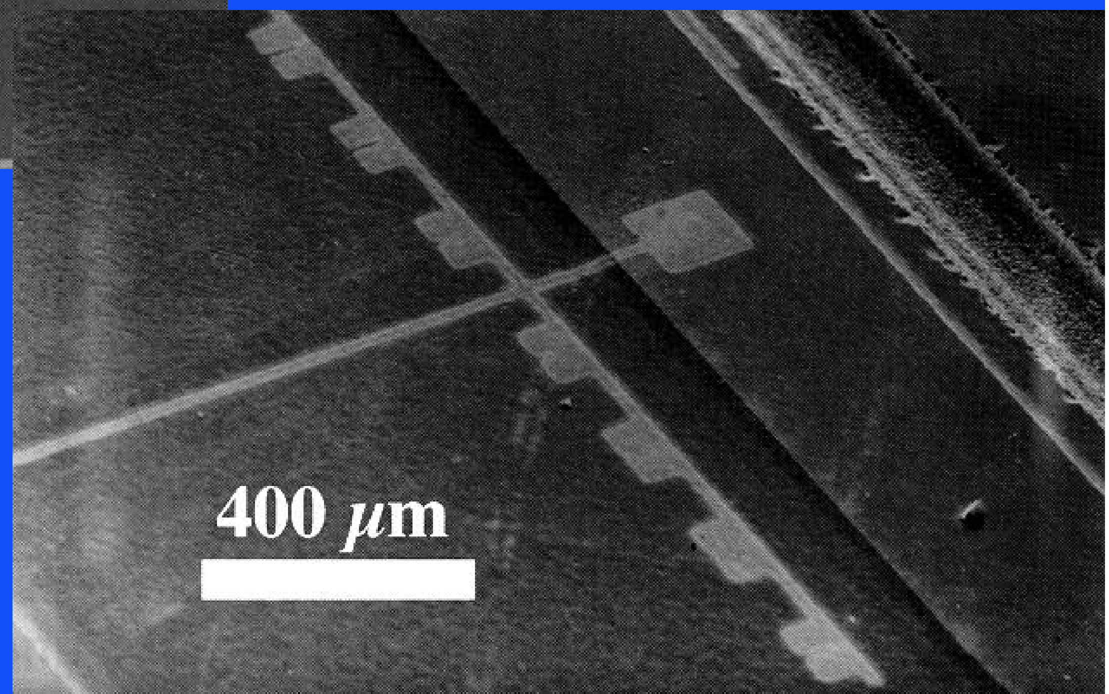
- Can use scaled arrays of accelerometers to create a system with greatly extended dynamic range.
- In nature, this type of scaling of a particular type of transducer is often employed.
- Circuitry or other means must be able to detect which sensing element in the array is in its optimally linear range, and use its output.
- Overlapping sensor ranges ensure continuous coverage.
- Most sensitive sensors must be able to withstand “full-scale” signals.
- This concept can be applied to many other types of sensors and actuators.



THRESHOLD ACCELEROMETER ARRAY

Source: Loke, Y., McKinnon, G. H., and Brett, M. J., "Fabrication and Characterization of Silicon Micromachined Threshold Accelerometers," Sensors and Actuators, vol. A29, no. 3, Dec. 1991, pp. 235 - 240.





MICROMACHINED GYROSCOPES

- **It is believed that there is tremendous market potential for micromachined gyroscopes in automotive and other applications.**
- **There are three basic modes of gyroscope operation:**

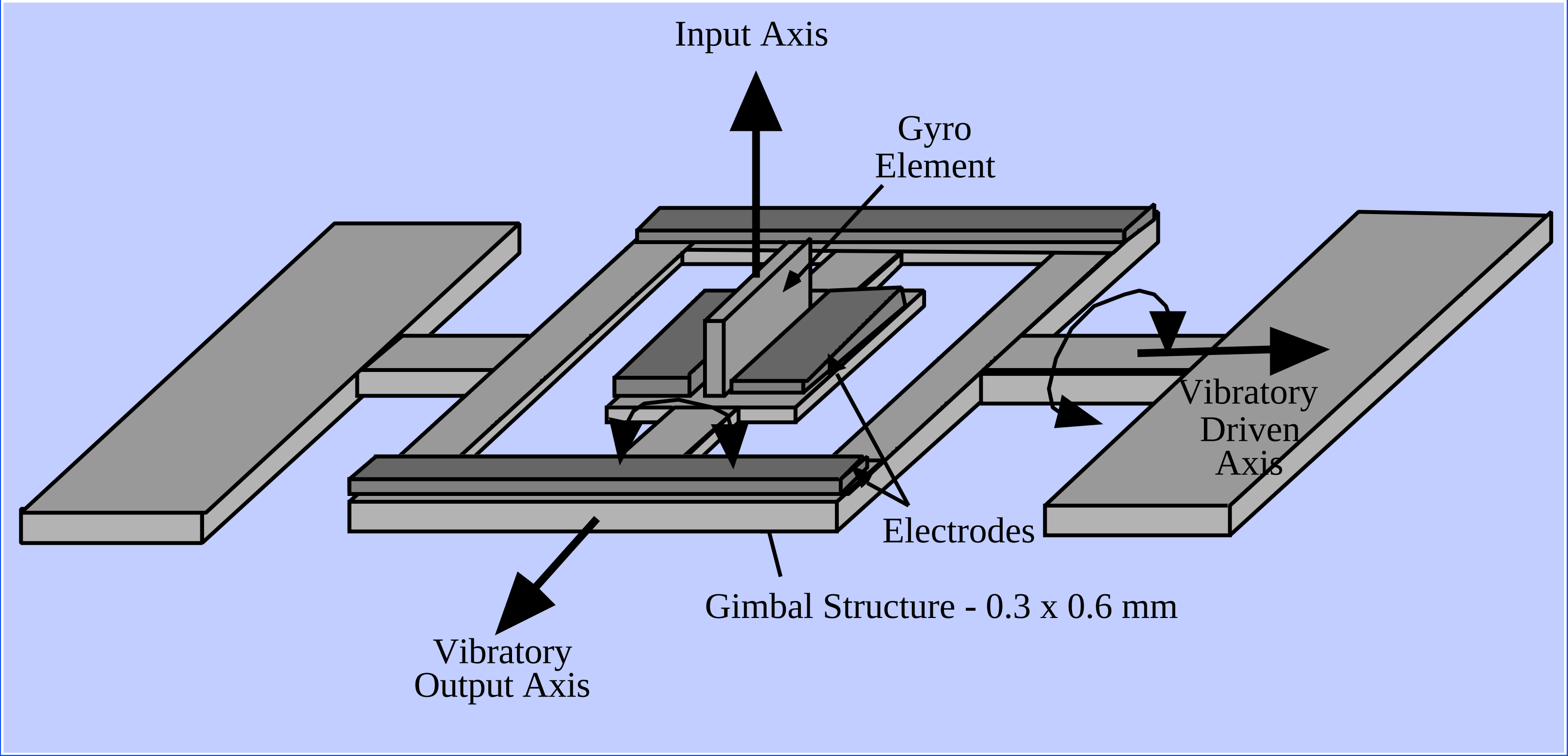
1) Whole Angle Mode - allow free movement and measure angle of deflection.

2) Open-Loop Vibration Mode - set up fixed vibration modes and measure the deviation (Coriolis acceleration) of these modes to determine rotation rate.

3) Force-to-Rebalance Mode - set up fixed vibration modes, but operate closed loop. (as a deviation is measured it is continuously driven to zero by feedback circuitry)

- **Micromachined gyroscopes are generally of the latter two types.**

MICROMACHINED FORCE-TO-REBALANCE GYRO

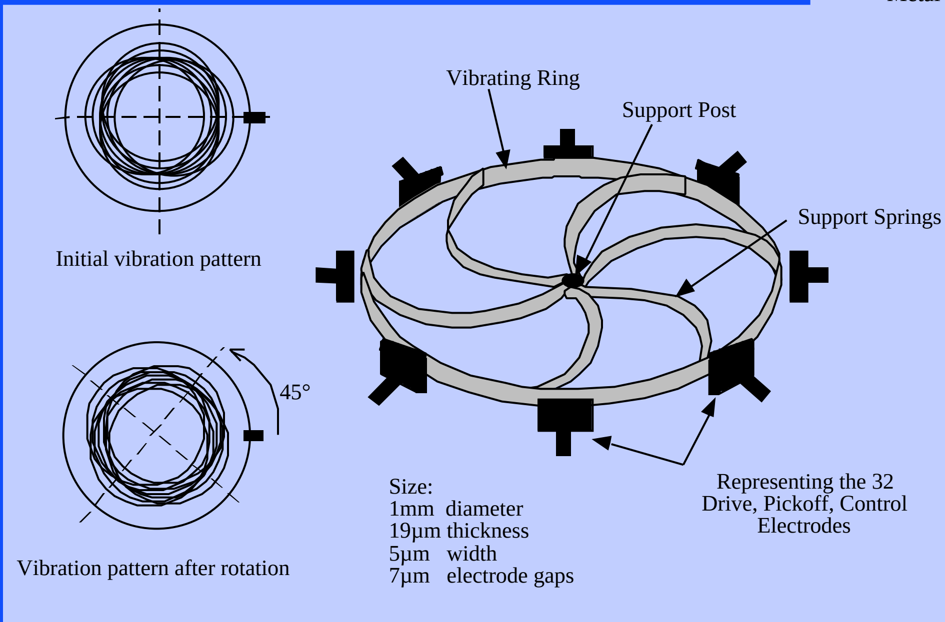


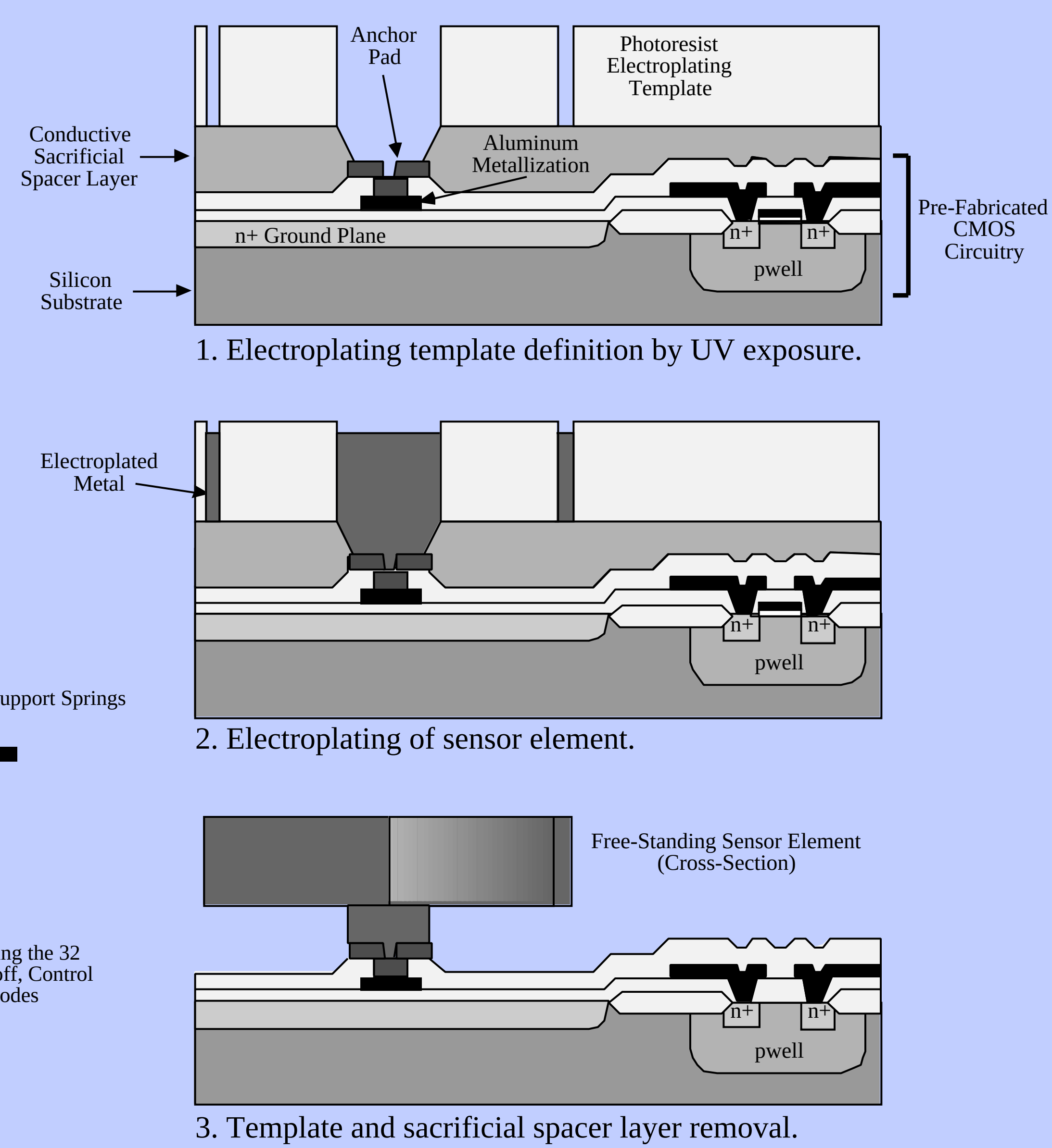
After Greiff, et al. (1991).

Reference: Greiff, P., Boxenhorn, B., King, T., and Niles, L., "Silicon Monolithic Micromechanical Gyroscope," Transducers '91, p. 966-968.

MICROMACHINED RESONANT RING GYRO

Reference: Putty, M. and Najafi, K., “A Micromachined Vibrating Ring Gyroscope,” Solid State Sensor and Actuator Workshop, Hilton Head, South Carolina, June 13-16, 1994, p. 213-220.

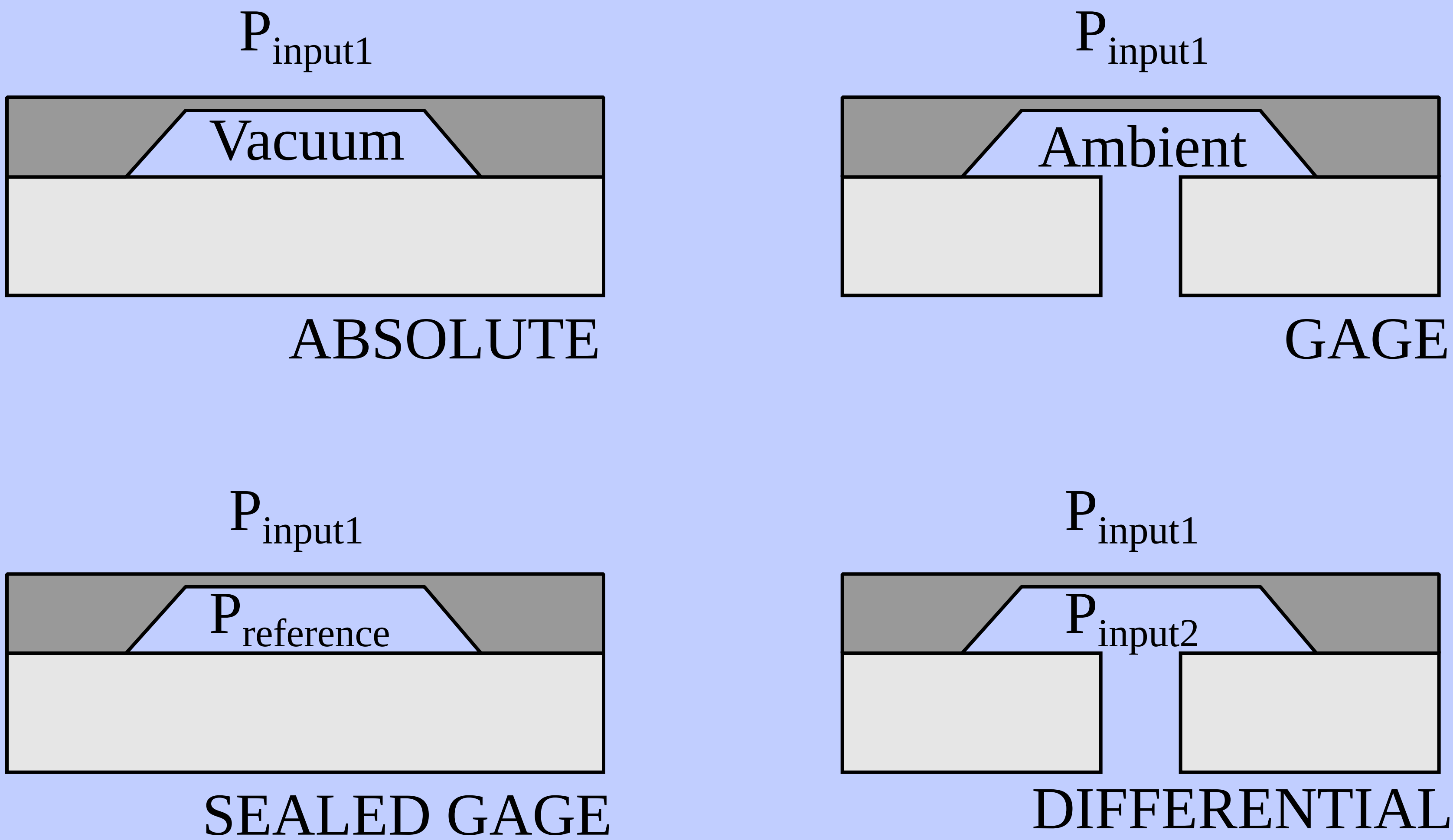




Source: Putty, M. and Najafi, K., “A Micromachined Vibrating Ring Gyroscope,” Solid State Sensor and Actuator Workshop, Hilton Head, South Carolina, June 13-16, 1994, p. 213-220.

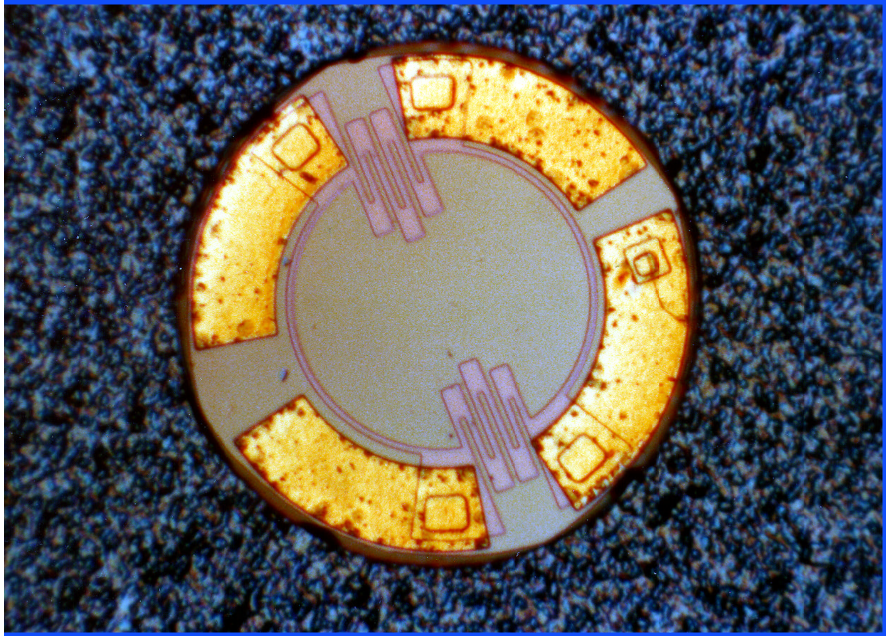
BASIC PRESSURE SENSOR CONCEPTS

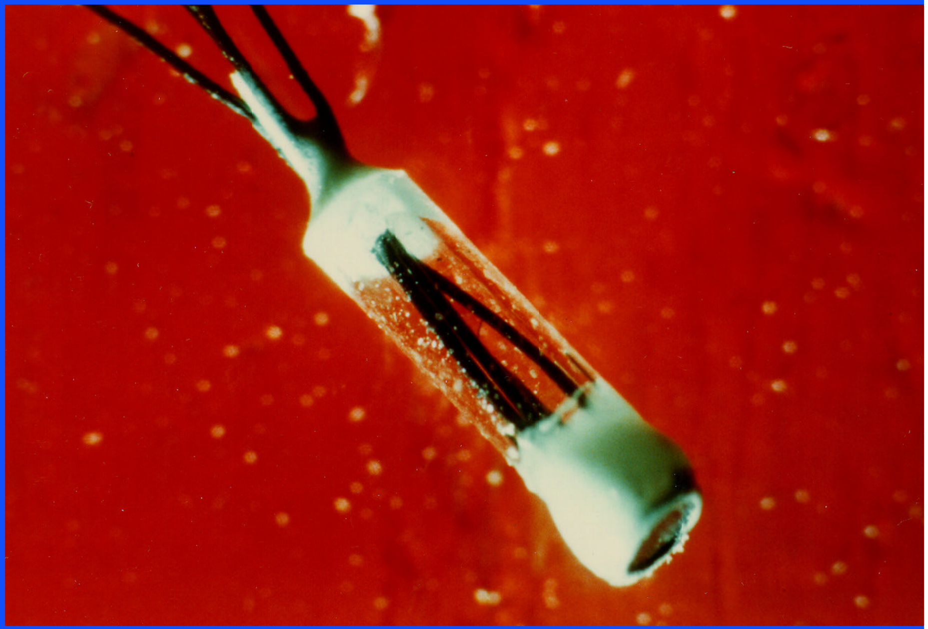
- Generally, the deflection of a membrane is used to measure pressure via displacement/strain measurements (generally piezoresistive or capacitive).
- Resonant frequency of a damped resonator can be used to measure membrane deflection (very accurately).
- Heat dissipation from a heated element can also be used (Pirani technique), generally only useful for moderate vacuum levels.
- Most shipping pressure sensors use membrane deflection methods.



Reference: Bryzek, J., Petersen, K., Mallon, J. R., Christel, L., and Pourahmadi, F., "Silicon Sensors and Microstructures," Lucas NovaSensor, 1055 Mission Court, Fremont, CA, 1991.

SAMAUN RELATIVE PRESSURE SENSOR - 1969





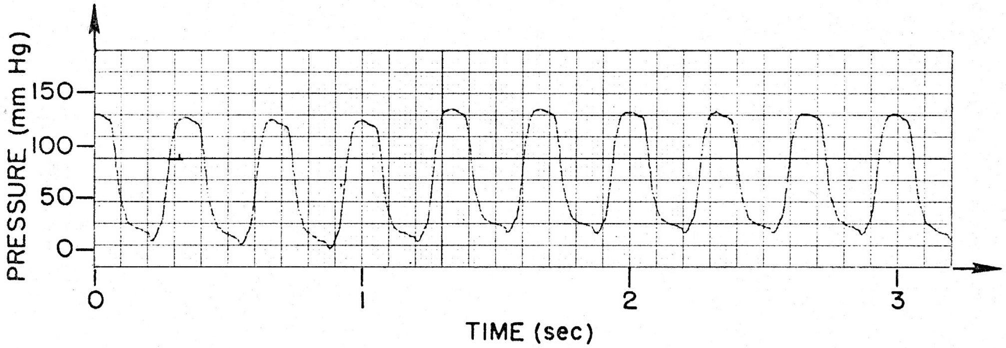
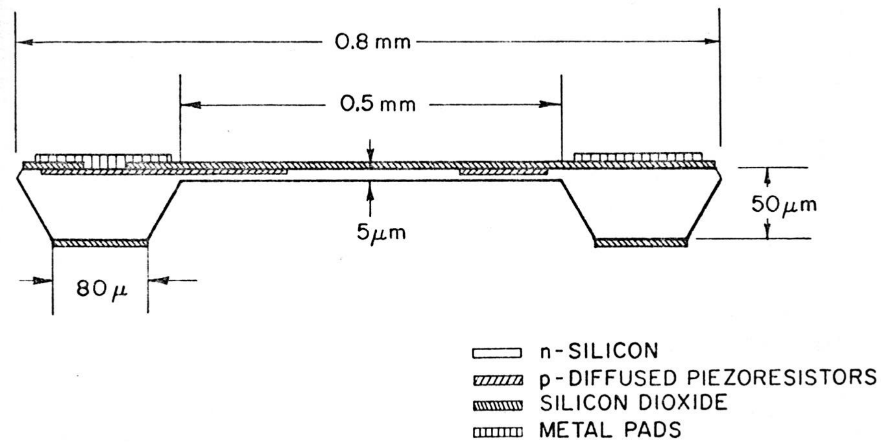
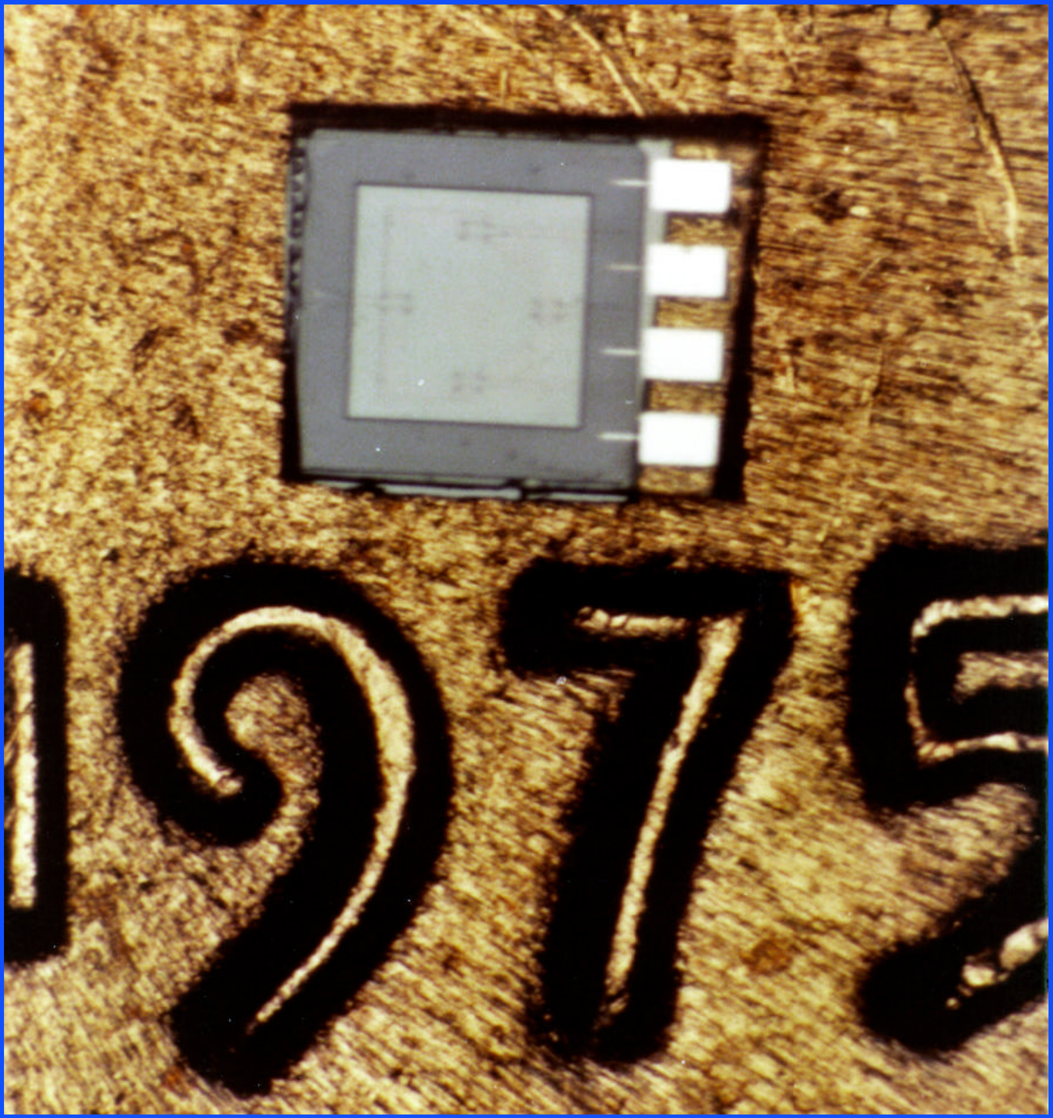


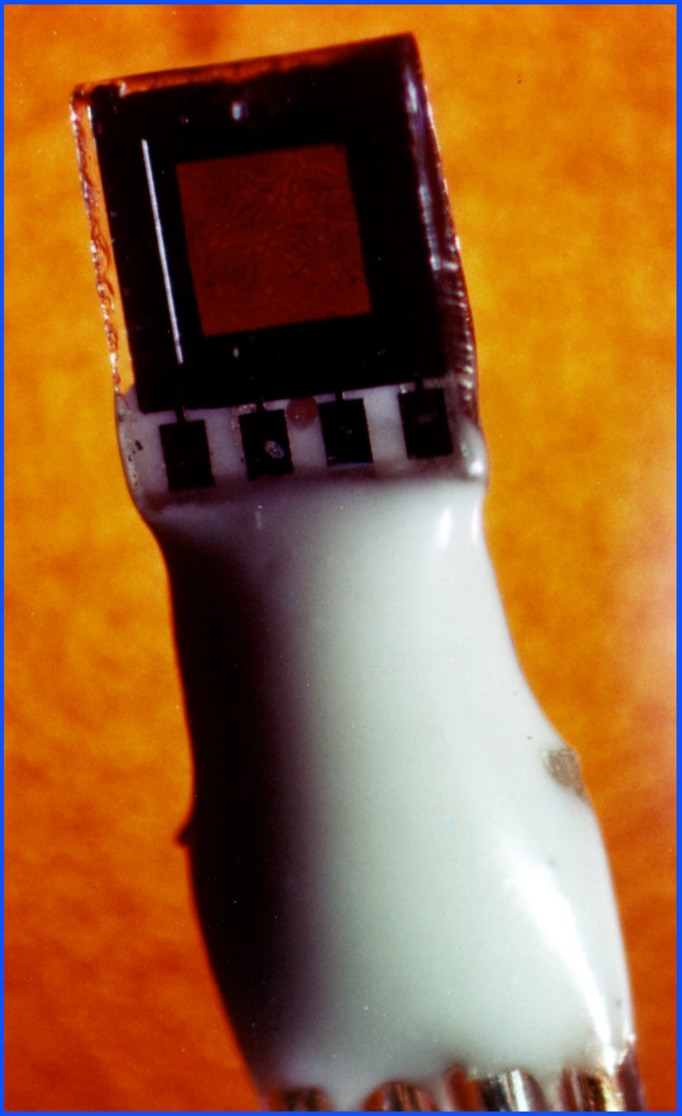
Fig. 5.2. Recording of the blood pressure in the left ventricle of a dog.



Courtesy Prof. J. Angell, Stanford University.

BARTH - ABSOLUTE PRESSURE SENSOR - 1974

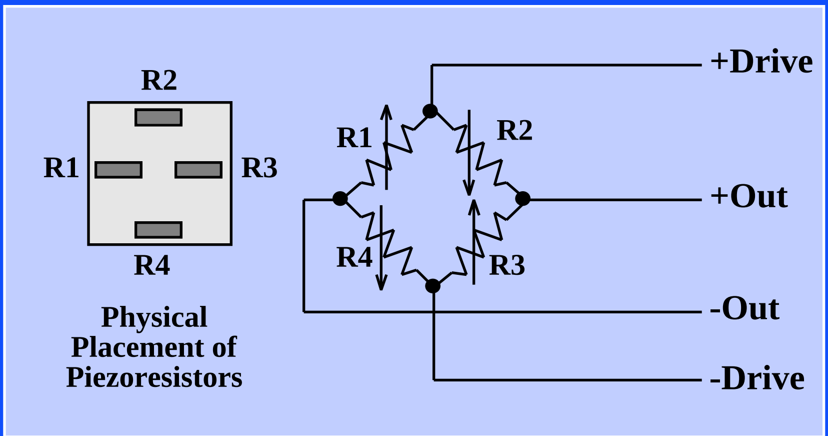


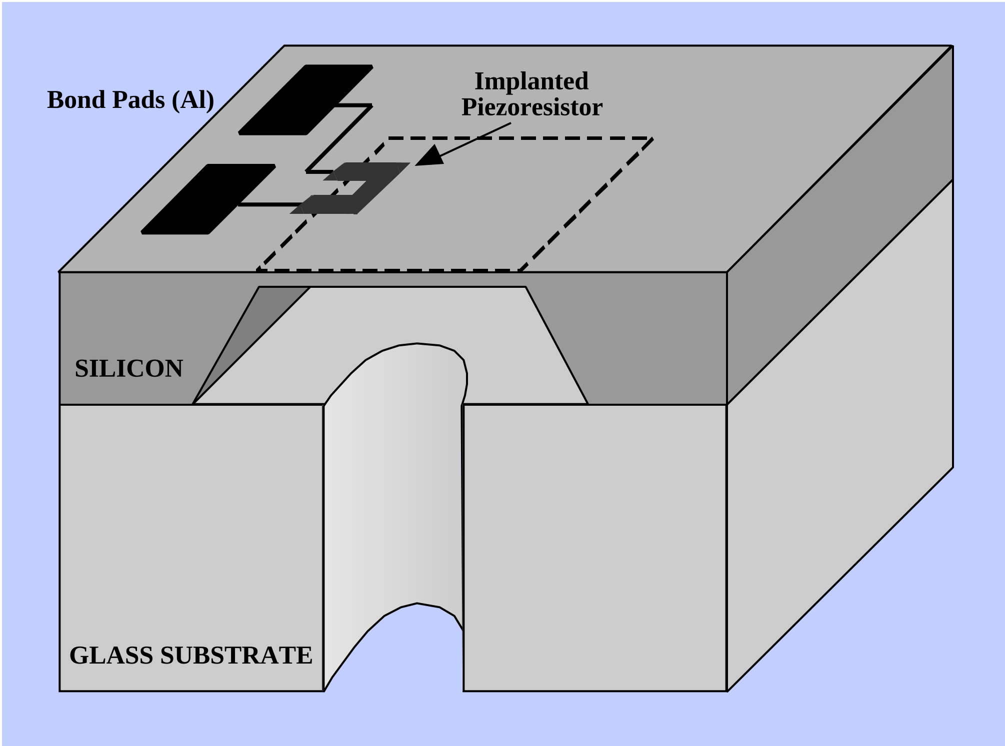


Courtesy Prof. J. Angell, Stanford University.

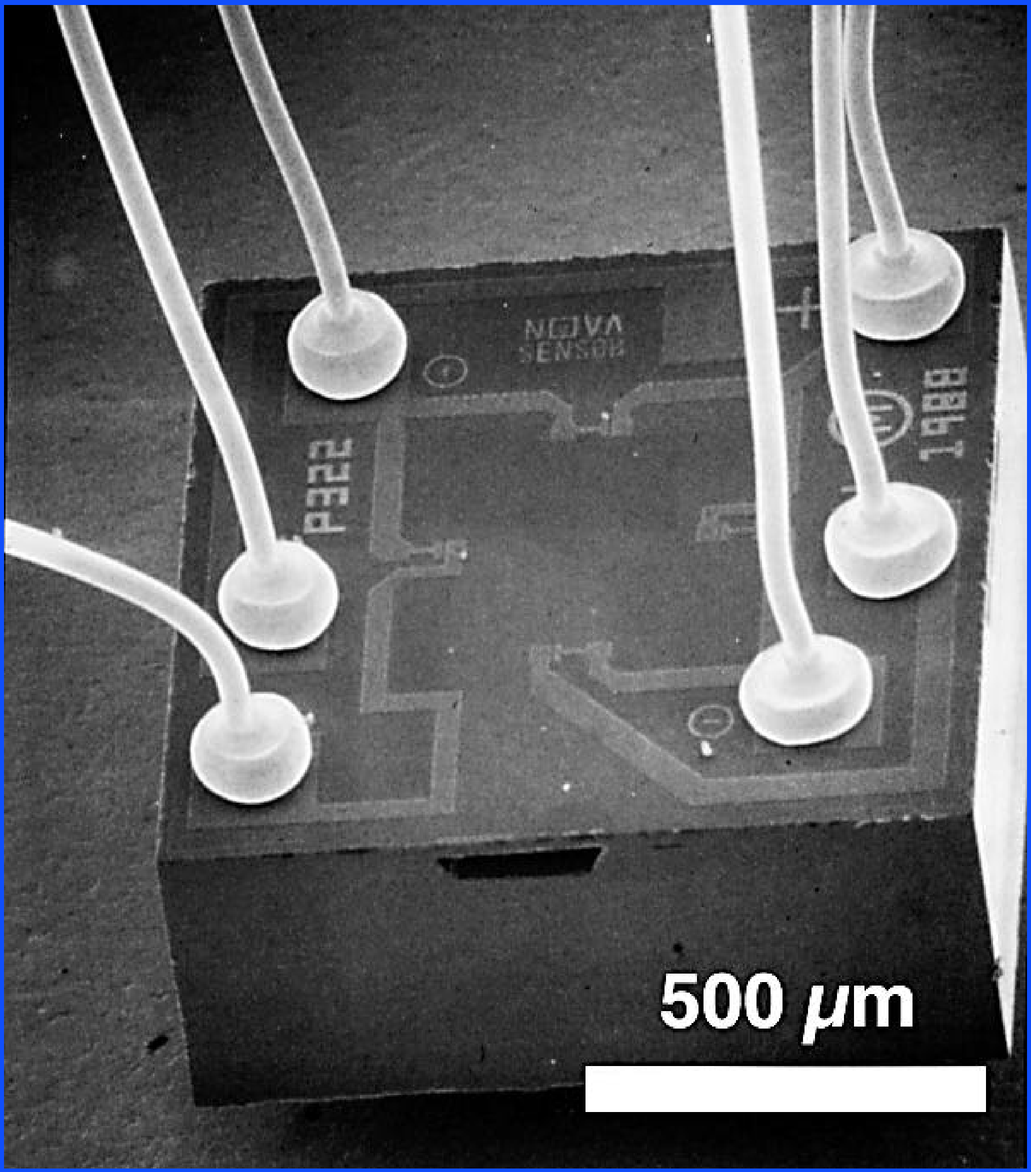
EXAMPLE PRESSURE SENSOR (LUCAS NOVASENSOR)

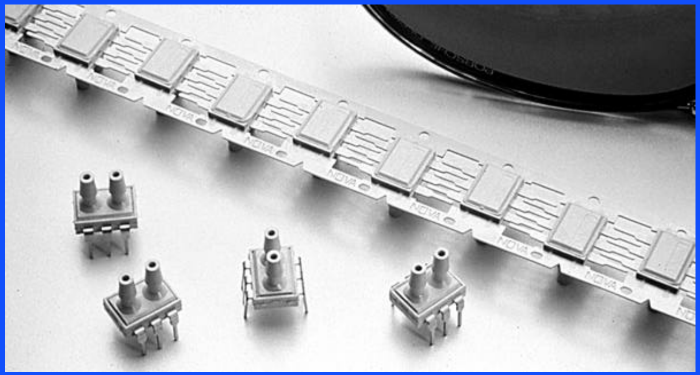
- Piezoresistive strain sensors.
- Electrochemical etch stop membrane.
- Fusion bonded reference cavity or port.
- On-chip temperature compensation.

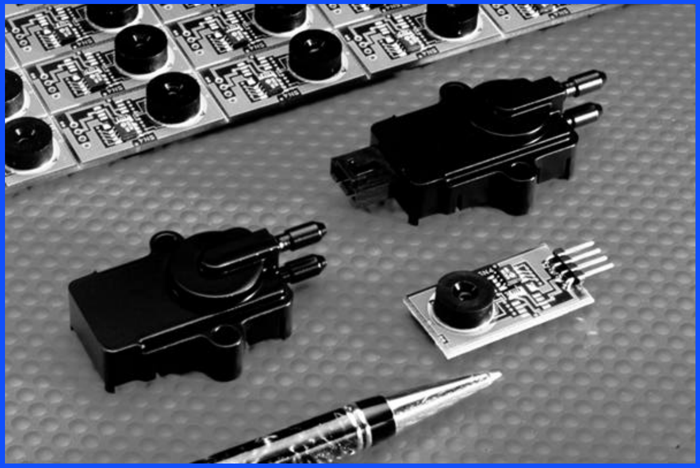




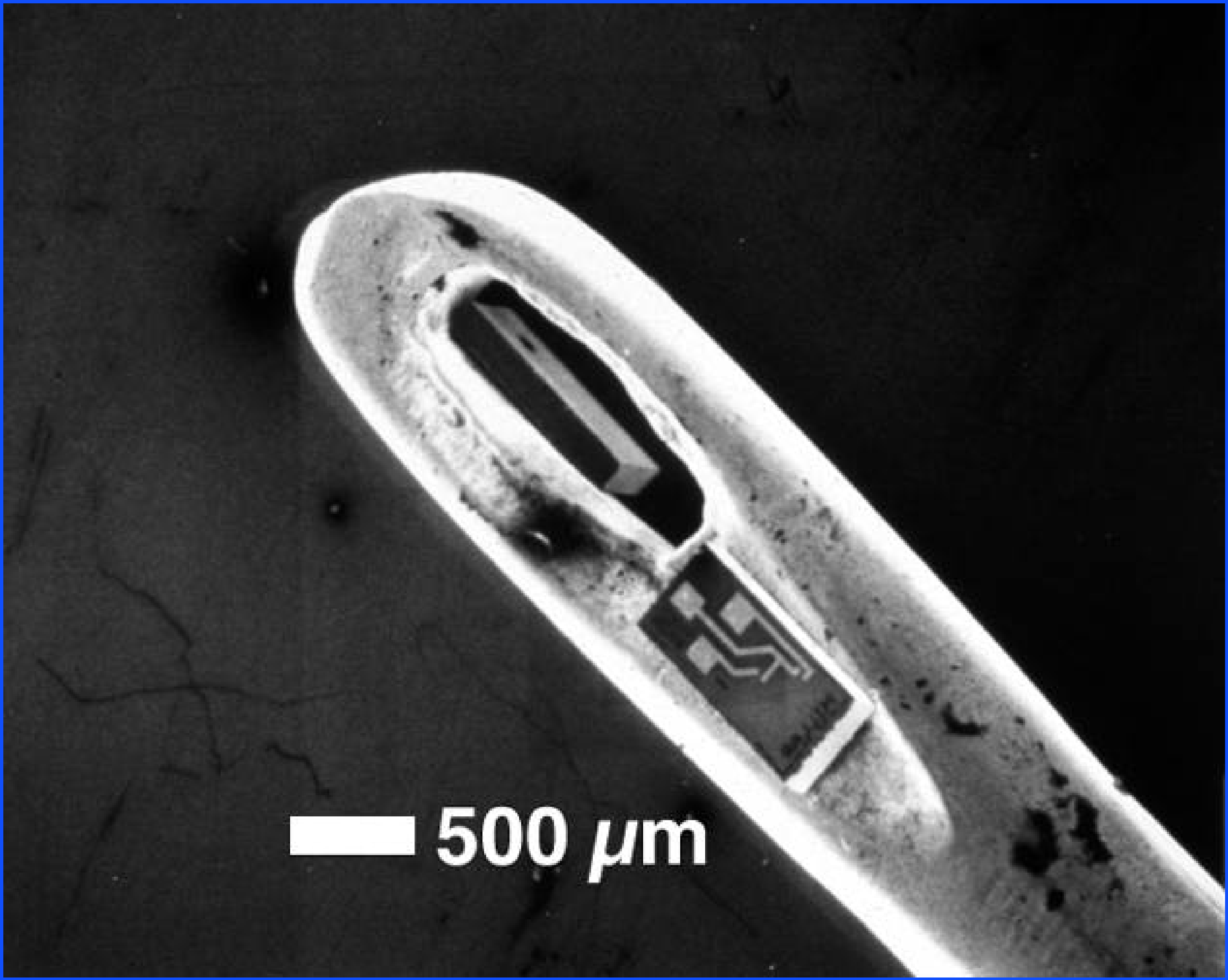
Reference: Bryzek, J., Petersen, K., Mallon, J. R., Christel, L., and Pourahmadi, F., “Silicon Sensors and Microstructures,” Lucas NovaSensor, 1055 Mission Court, Fremont, CA, 1991.



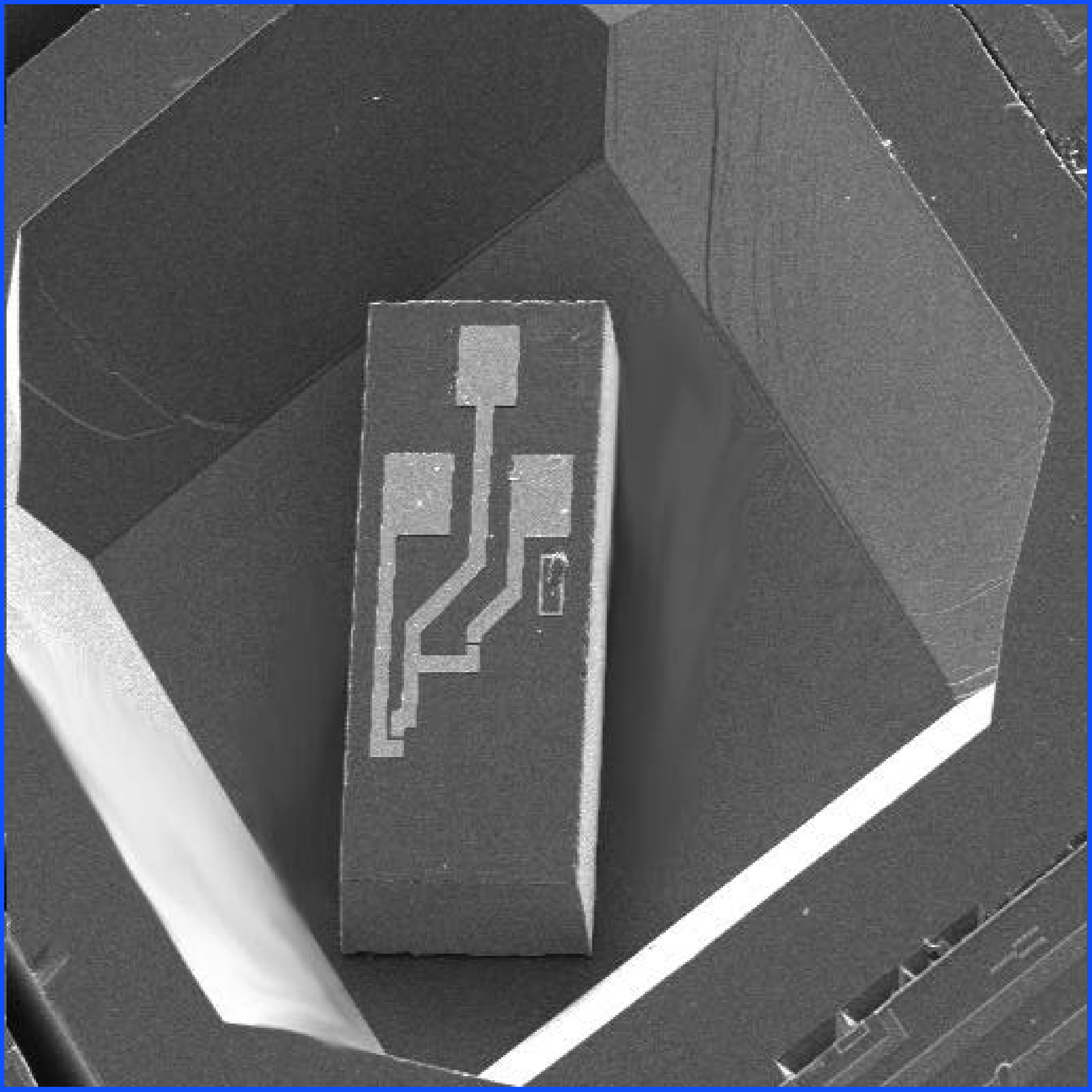




Images courtesy of Lucas NovaSensor.



Courtesy of Lucas NovaSensor.



Courtesy Prof. K. Petersen, Stanford University.

Order this document
by MPX5100/D

MOTOROLA
SEMICONDUCTOR
TECHNICAL DATA

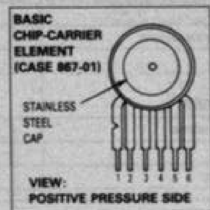
Advance Information

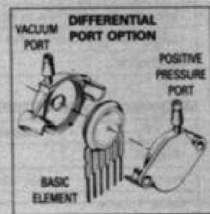
On-Chip Signal Conditioned, 0.5 V to 4.5 V Output, Temperature Compensated & Calibrated, 0 to 15 PSI Silicon Pressure Sensors

MPX5100 SERIES

0–15 PSI X-ducer™ SILICON PRESSURE SENSORS

- Ideally Suited for Microprocessor Based Systems
- Temperature Compensated Over 0°C to +85°C
- Patented Silicon Shear Stress Strain Gage
- 0 to 15 PSI (0 to 100 kPa) Differential Pressure Range
- Full Scale Output Calibrated: 0.5 V to 4.5 V
- Easy to use Chip Carrier Package
- Basic Element, Single and Dual Ported Devices Available
- Customized Output Available (Consult Factory)
- Available in Absolute, Differential & Gage Configurations





Pin Number					
1	2	3	4	5	6
V_{out}	Ground	V_{source}	N/C	N/C	N/C

NOTE: Pins 4, 5 and 6 are internal device connections. Do not connect to external circuitry or ground.

MAXIMUM RATINGS (T_C = 25°C unless otherwise noted)

Rating	Symbol	Value	Unit
Overpressure	P_{max}	700	kPa
Burst Pressure	P_{BURST}	1000	kPa
Supply Voltage (See Note 11, Page 2)	$V_{S(max)}$	10	Vdc
Storage Temperature	T_{stg}	−50 to +150	°C
Operating Temperature	T_A	0 to +85	°C

The MPX5100 Series piezoresistive transducer is a state-of-the-art, monolithic silicon pressure sensor designed for a wide range of applications, but particularly those employing a microcontroller or microprocessor with A/D inputs. This patented, single element X-ducer combines advanced micromachining techniques, thin film metallization and bipolar semiconductor processing to provide an accurate, high level analog output signal that is proportional to applied pressure.

Figure 1 shows a schematic of the internal circuitry integrated on-chip to provide temperature compensation, offset and span calibration and signal conditioning.

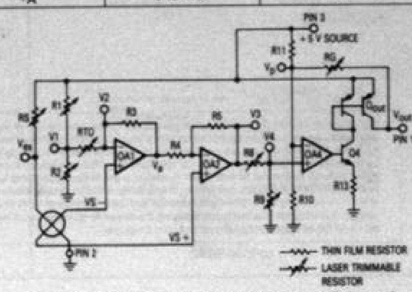


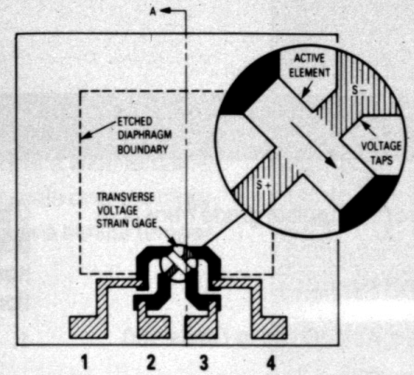
Figure 1. Fully Integrated Pressure Sensor Schematic

X-ducer is a trademark of Motorola Inc.

This document contains information on a new product. Specifications and information herein are subject to change without notice.

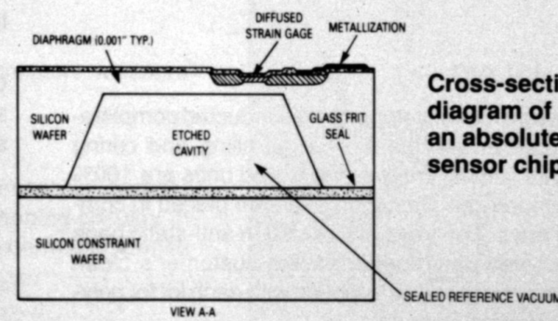
MOTOROLA

Rev. 1
(Replaces ADI1799)

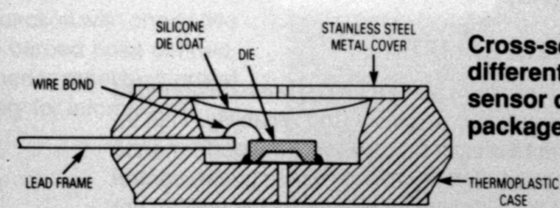


PIN #
1. GROUND
2. POSITIVE OUTPUT
3. SUPPLY
4. NEGATIVE OUTPUT

Figure 4. Basic Uncompensated Sensor Element — Top View



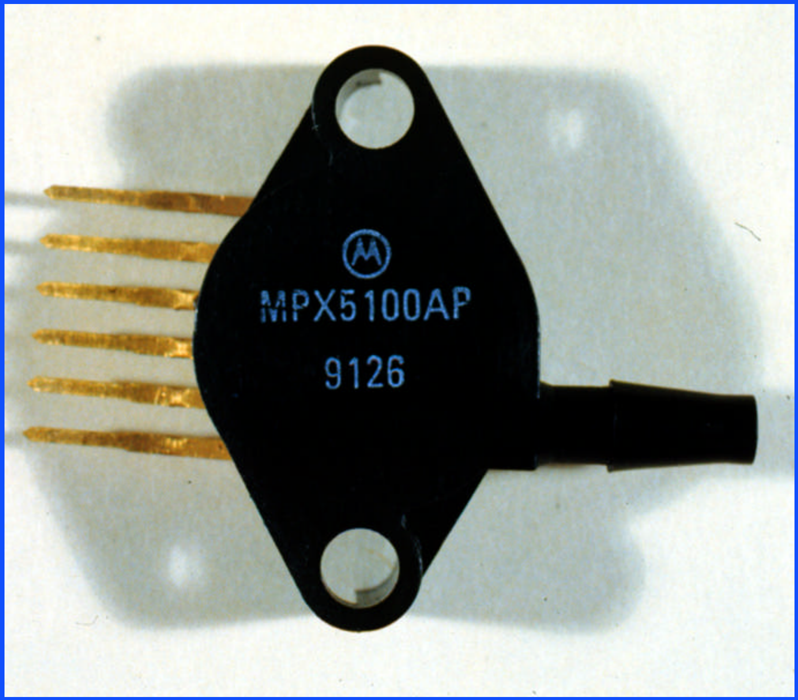
Cross-sectional diagram of an absolute sensor chip

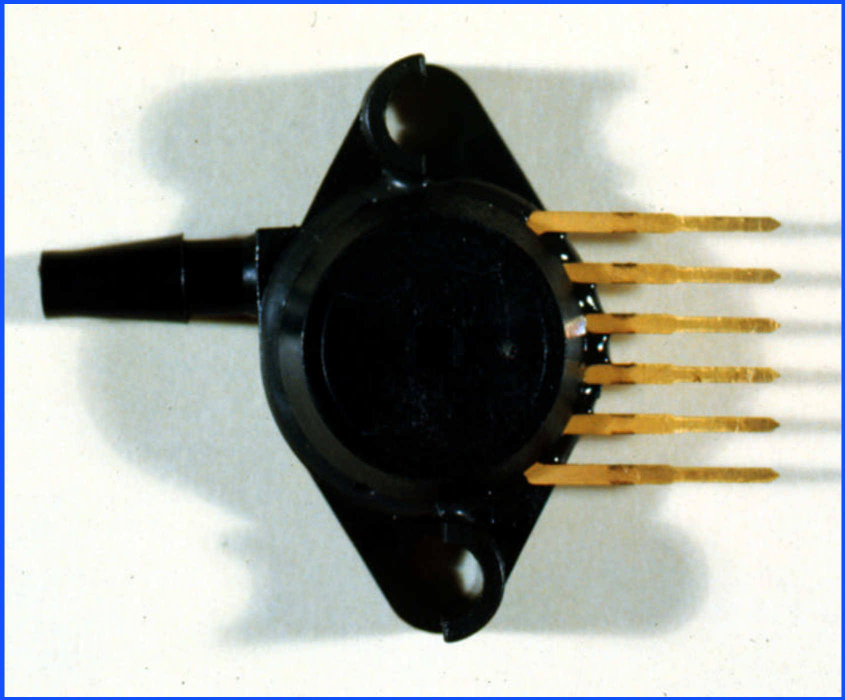


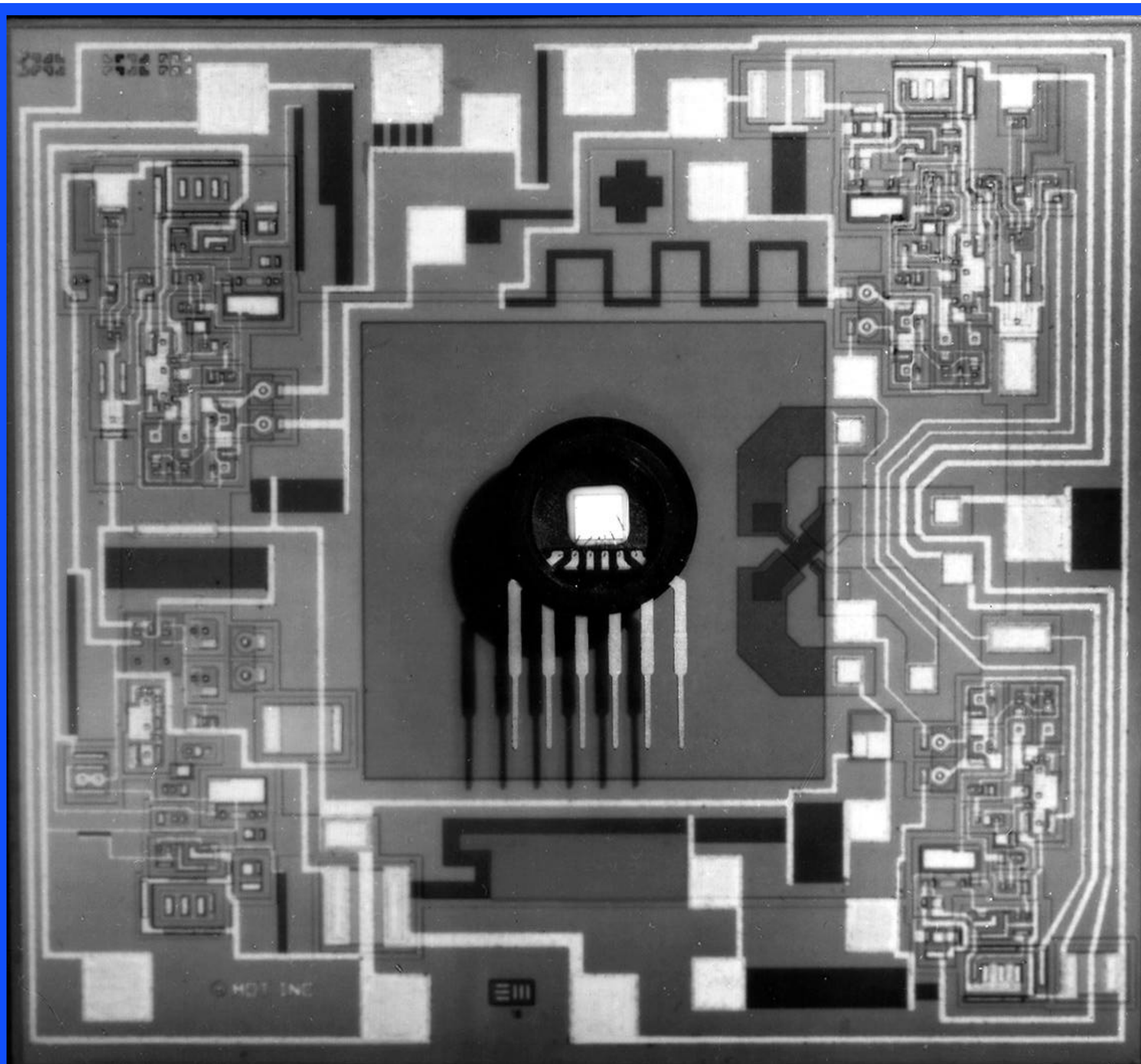
Cross-section of differential pressure sensor die in its basic package

Figure 5. Cross-Sectional Diagrams

MOTOROLA PRESSURE SENSOR PACKAGING

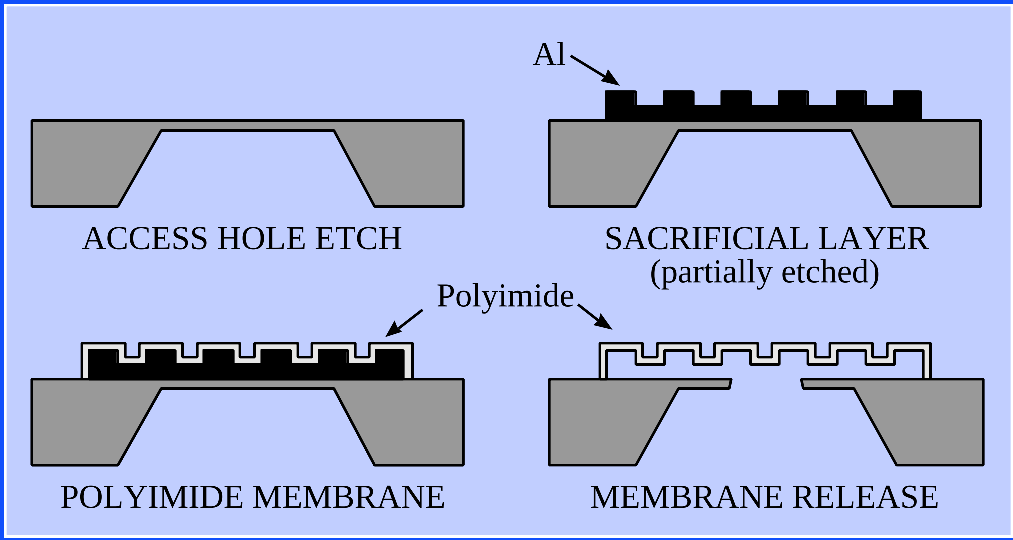




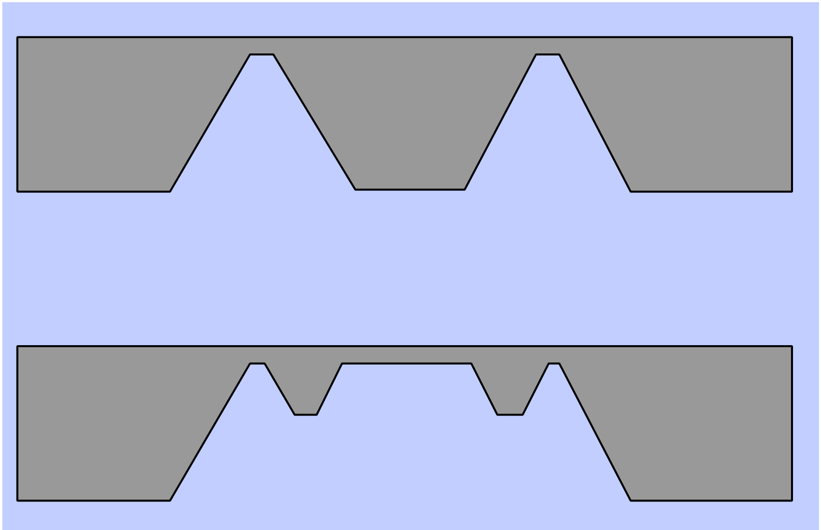


Courtesy Dr. Lj. Ristic, Motorola, Inc.

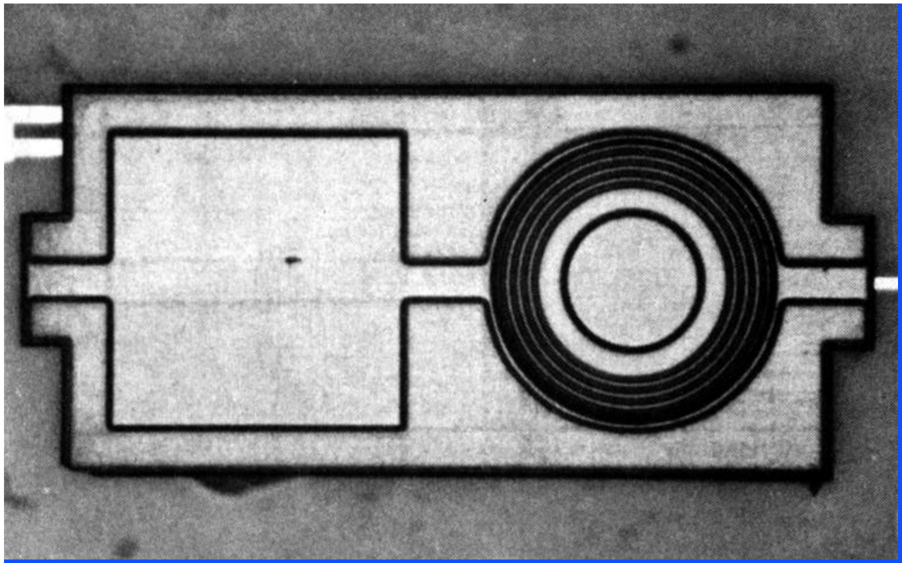
CORRUGATIONS AND BOSSES

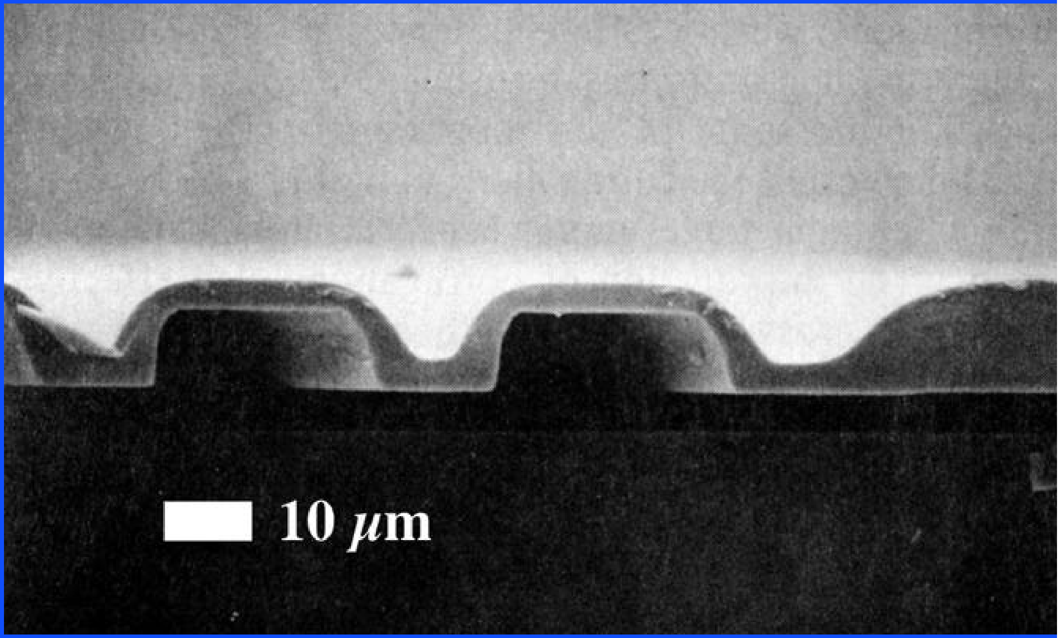


Reference: van Mullem, C. J., Gabriel, K. J., and Fujita, H., "Large Deflection Performance of Surface Micromachined Corrugated Diaphragms," Proceedings of the International Conference on Solid-State Sensors and Actuators, Transducers '91, San Francisco, CA, June 24 - 27, 1991, pp. 1014 - 1017.

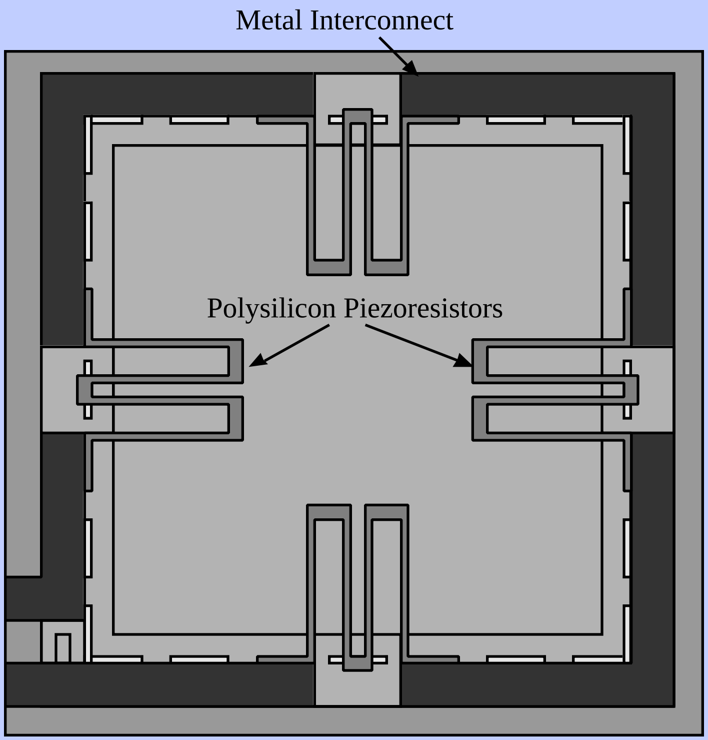


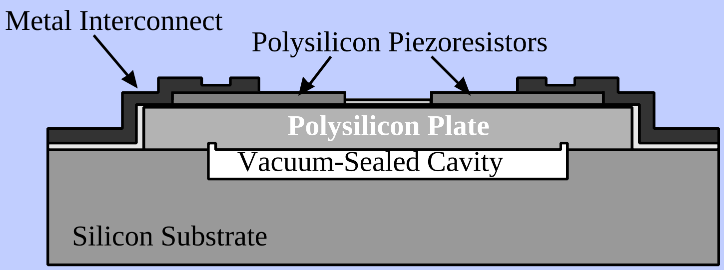
Reference: Bryzek, J., Petersen, K., Mallon, J. R., Christel, L., and Pourahmadi, F., "Silicon Sensors and Microstructures," Lucas NovaSensor, 1055 Mission Court, Fremont, CA, 1991.





Source: Wise Laboratory, University of Michigan.

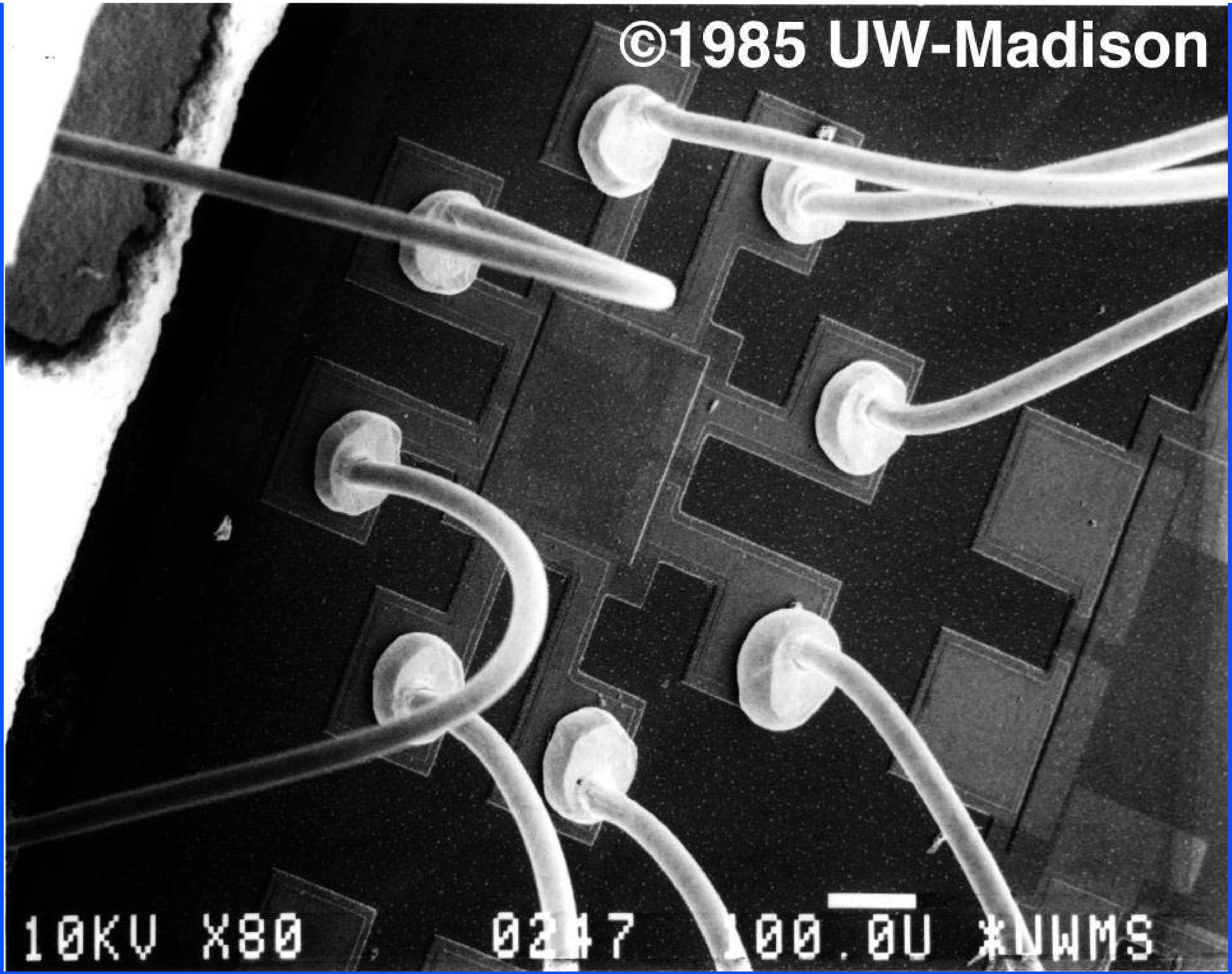




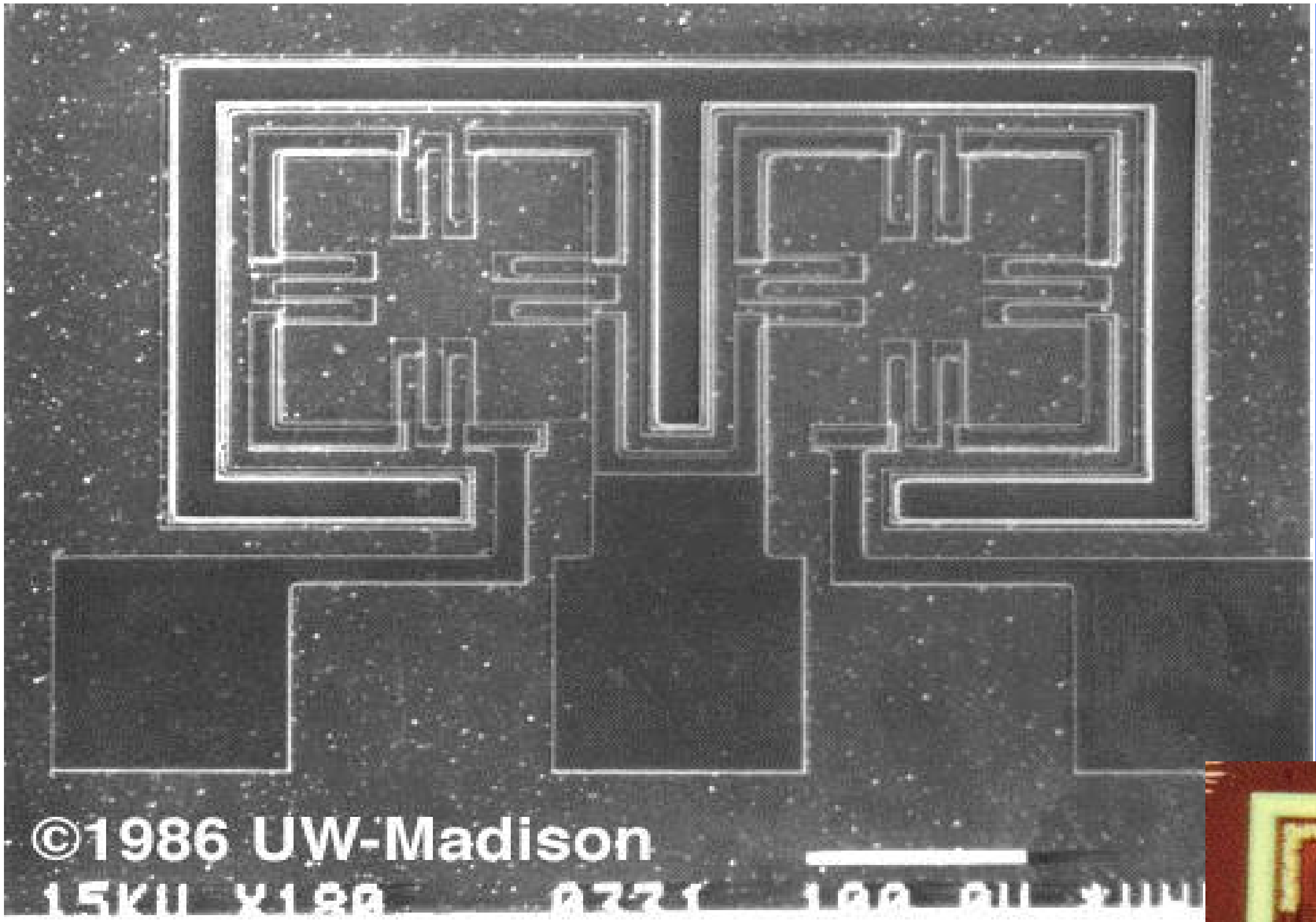
SURFACE MICROMACHINED PRESSURE SENSORS

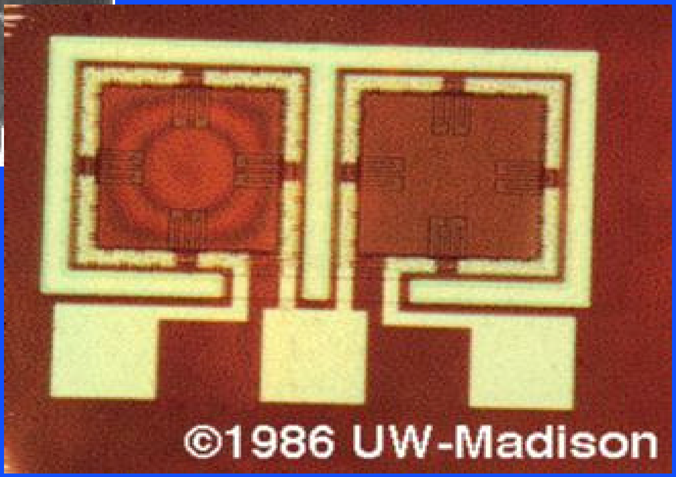
- To obtain "flush" pressure sensors, oxide was thermally grown in cavity regions (≈ 2.3 X less dense than silicon), stripped, and grown again.
- The re-grown oxide was flush with the surface, providing the sacrificial layer.
- Silicon nitride films were used above a polysilicon plate to sandwich implanted polysilicon strain gauges.

Reference: Guckel, H., "Surface Micromachined Pressure Transducers," Sensors and Actuators A, vol. 28, 1991, pp. 133 - 146.



Courtesy of Prof. Henry Guckel http://mems.engr.wisc.edu/images/





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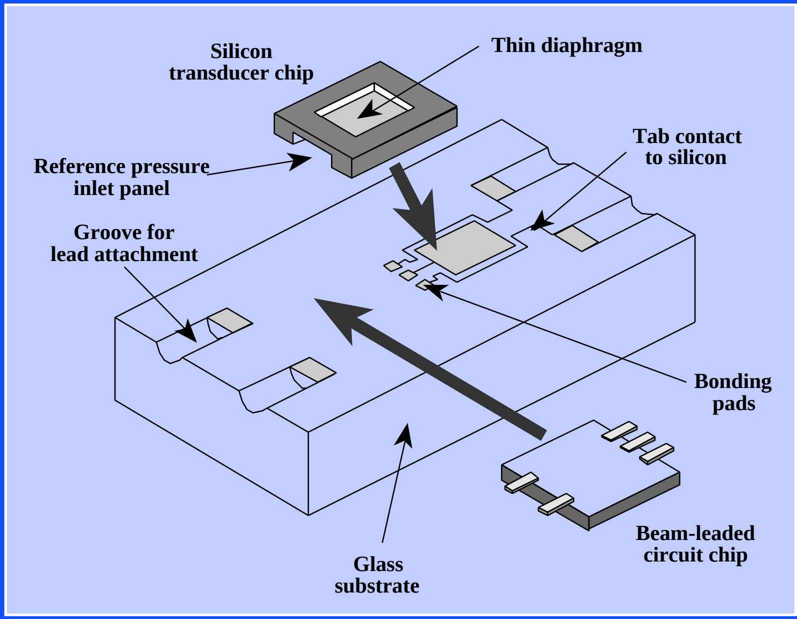
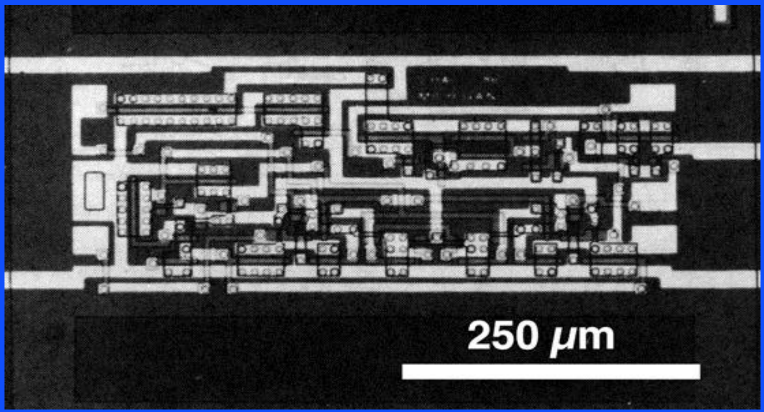
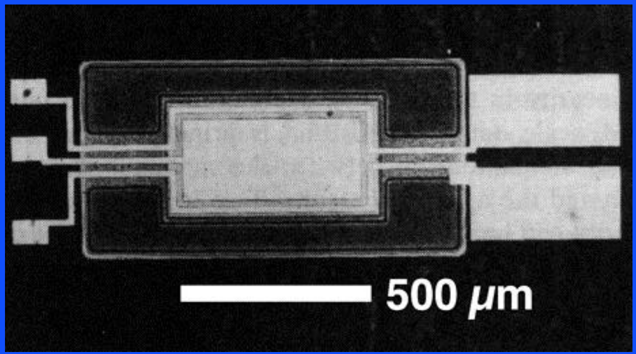
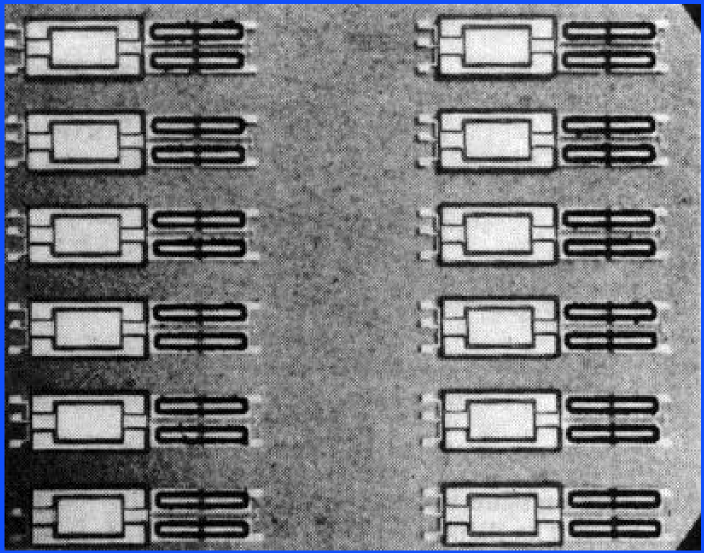
CATHETER-TIP PRESSURE SENSOR

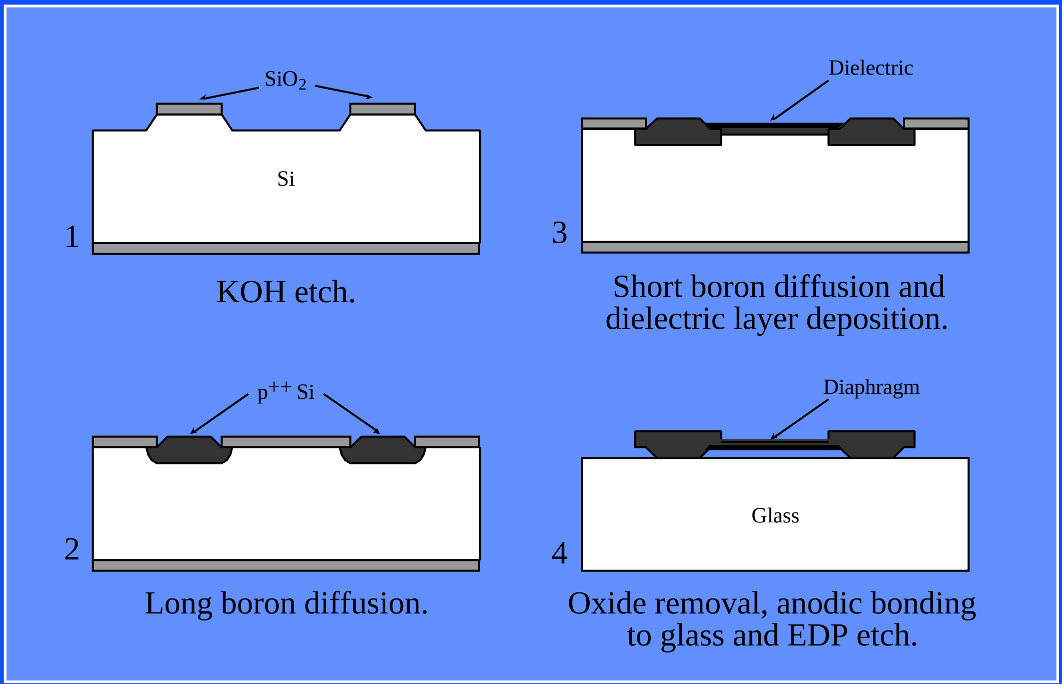




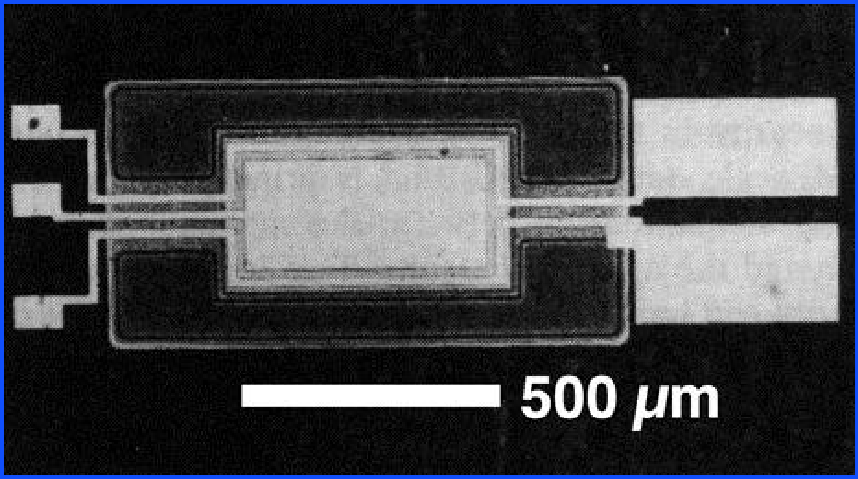




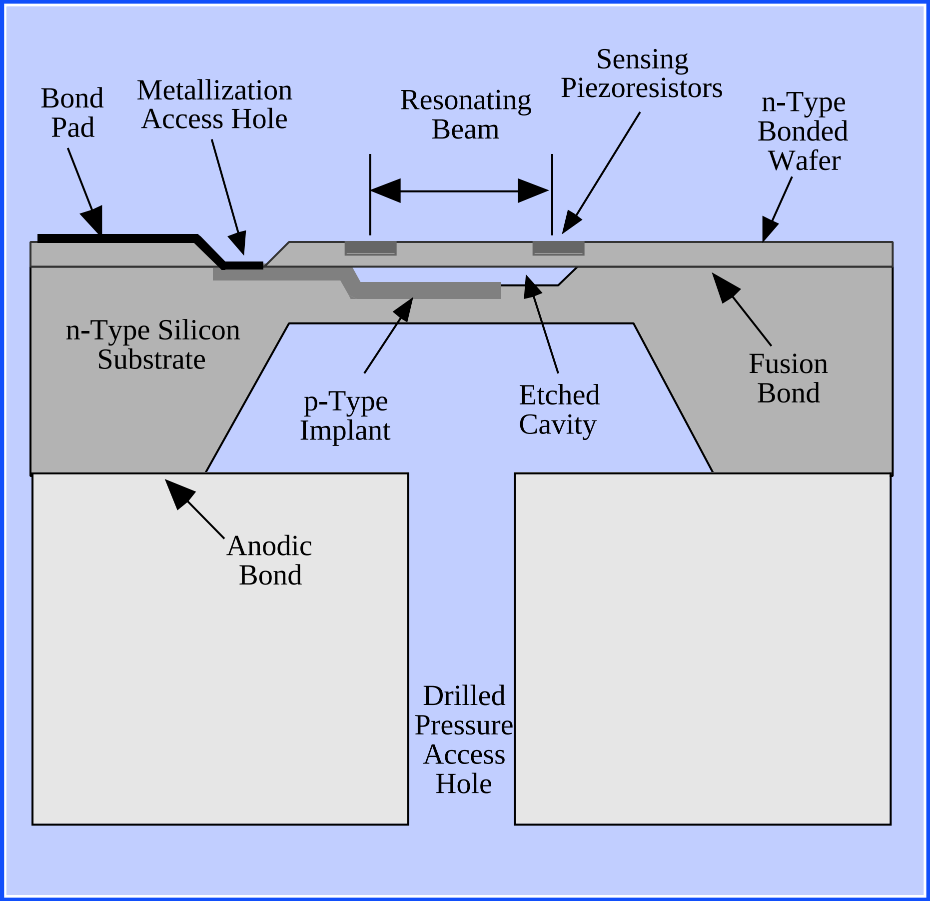
Source: Chau, H.-L. and Wise, K. D., “An Ultraminiature Solid-State Pressure Sensor for a Cardiovascular Catheter,” IEEE Transactions on Electron Devices, vol. 35, no. 12, Dec. 1988, pp. 2355 - 2362.



Chau, H.-L. and Wise, K. D., "An Ultraminiature Solid-State Pressure Sensor for a Cardiovascular Catheter," IEEE Transactions on Electron Devices, vol. 35, no. 12, Dec. 1988, pp. 2355 - 2362.



RESONANT PRESSURE SENSORS



Reference: Petersen, K., et al. "Resonant Beam Pressure Sensor Fabricated With Silicon Fusion Bonding," Proceedings of Transducers '91, June 24 - 27, 1991, San Francisco, CA, pp. 177 - 180.

- **Beam excited electrostatically and sensed piezoresistively.**

Process:

1) etch shallow pit in an n-type substrate

2) diffuse p-type deflection electrode

3) fusion bond second n-type wafer over the surface

4) grind and polish top wafer down to 6 µm

5) form a passivation layer on the top wafer

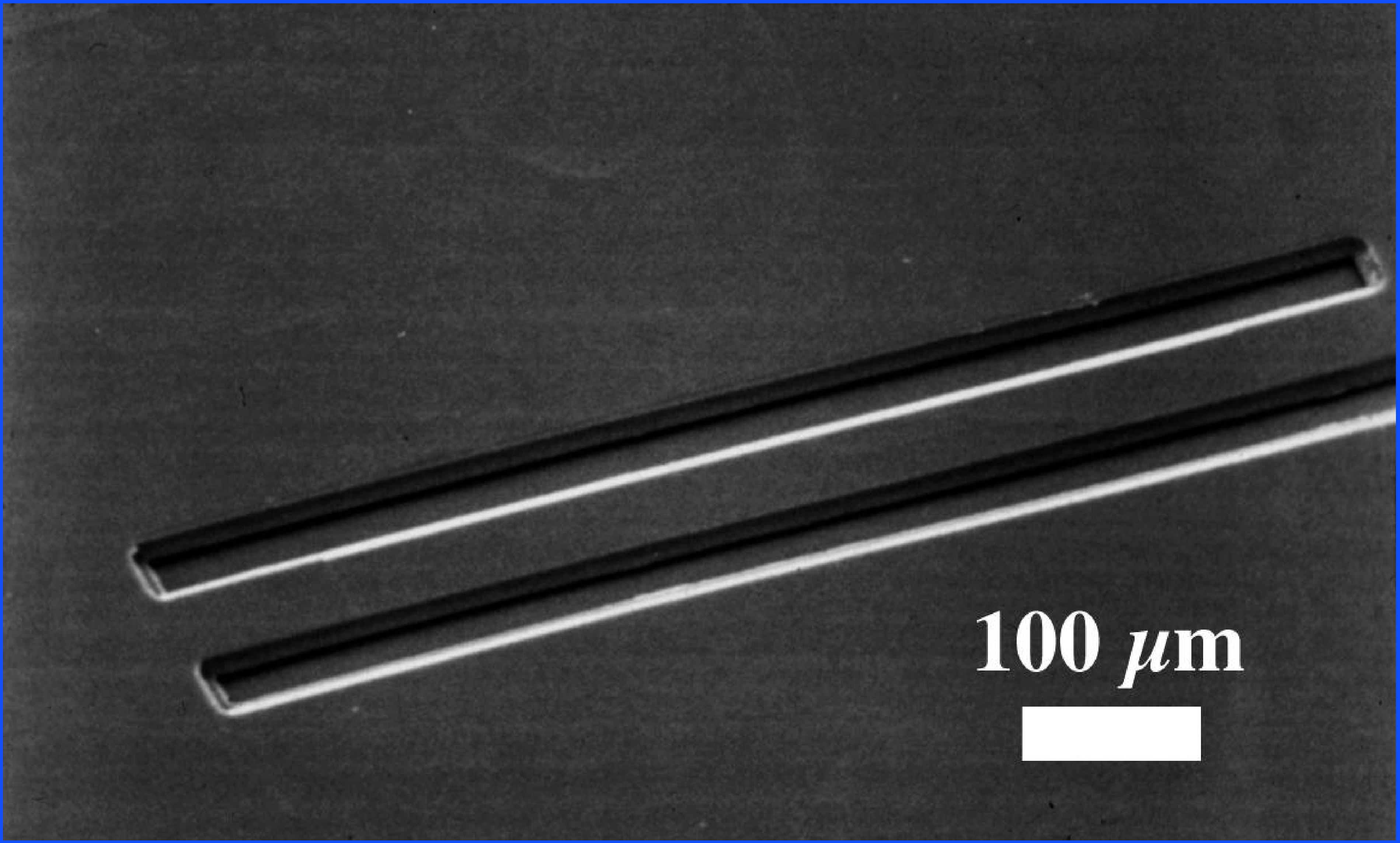
6) implant sensing piezoresistors

7) etch contact holes (to allow metallization in step 8 to contact the underlying deflection electrode)

8) deposit and pattern interconnect and bond-pad metal

9) etch diaphragm into the underlying wafer

10) etch two slots next to the beam to release it over the buried cavity

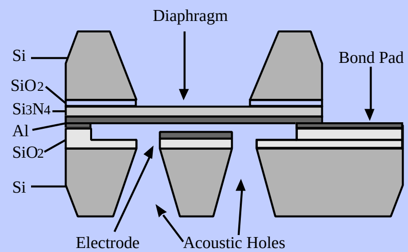


Courtesy Lucas NovaSensor.

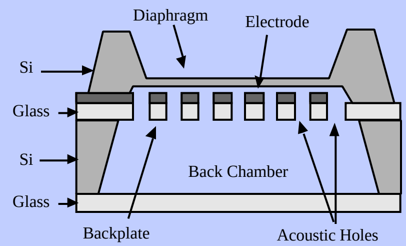
MICROMACHINED MICROPHONES

- There are many applications where miniaturized microphones (essentially sensitive AC pressure sensors) can be useful (hearing aids, surveillance, etc.).
- Excellent quality conventional devices exist and are very inexpensive, so competition is difficult.
- Most available transduction mechanisms have been utilized.
- Piezoresistive designs offer very low sensitivities (tens of µV/Pa), but low output impedance.
- Capacitive designs offer large sensitivities but low output impedances (need buffers).
- Piezoelectric designs to date have shown moderate sensitivities and high noise levels.

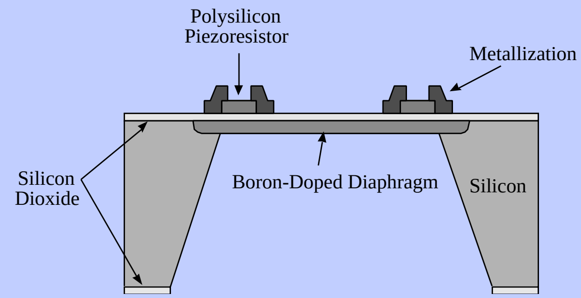
MICROMACHINED MICROPHONES

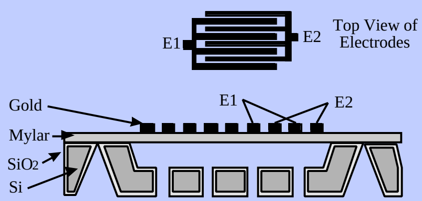


After Hohm, (1986)

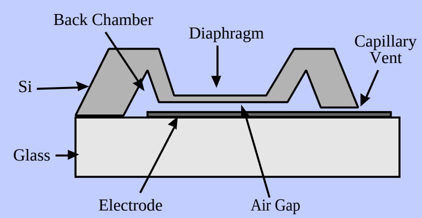


After Berquist and Rudolf, (1990)

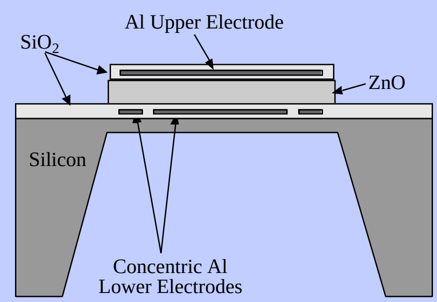


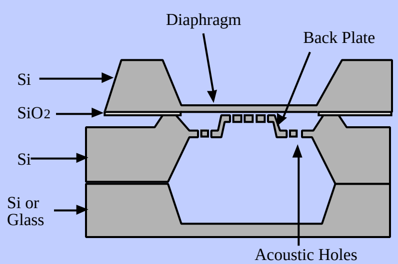


After van der Donk, (1992)

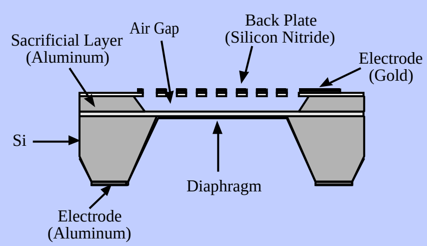


After Bourouina, et al., (1992)

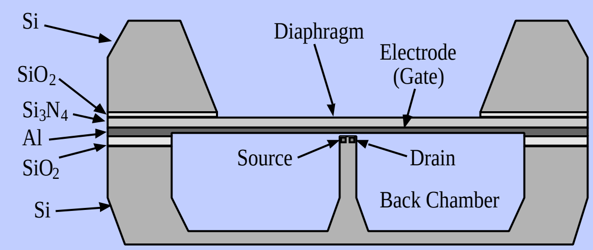




After Berqvist, et al., (1991)



After Scheeper, et al., (1992)

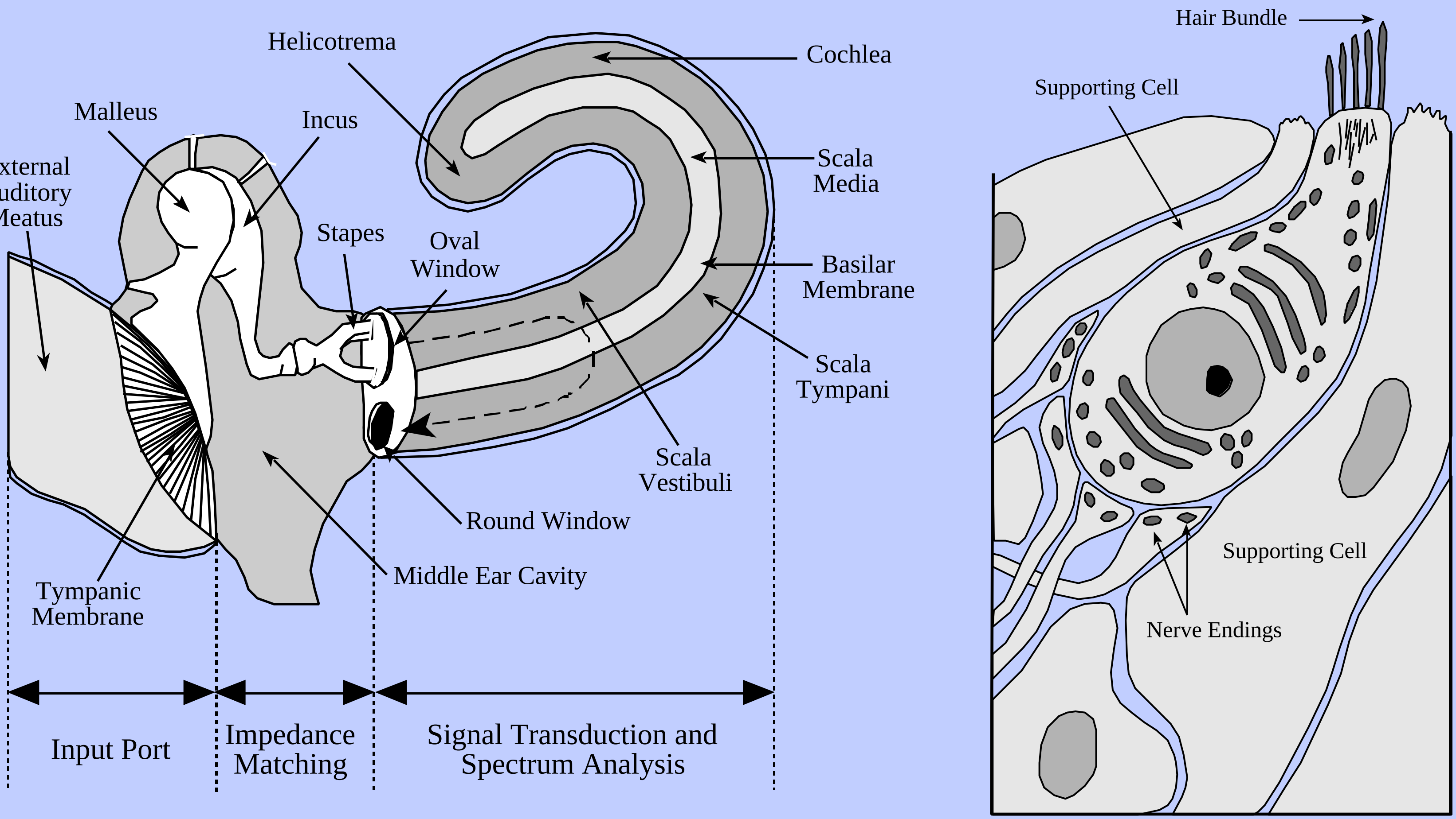


Reference: Scheeper, P., van der Donk, A., Olthuis, W., and Bergveld, P., "A Review of Silicon Microphones," Sensors and Actuators A, vol. 44, 1994, pp. 1 - 11.

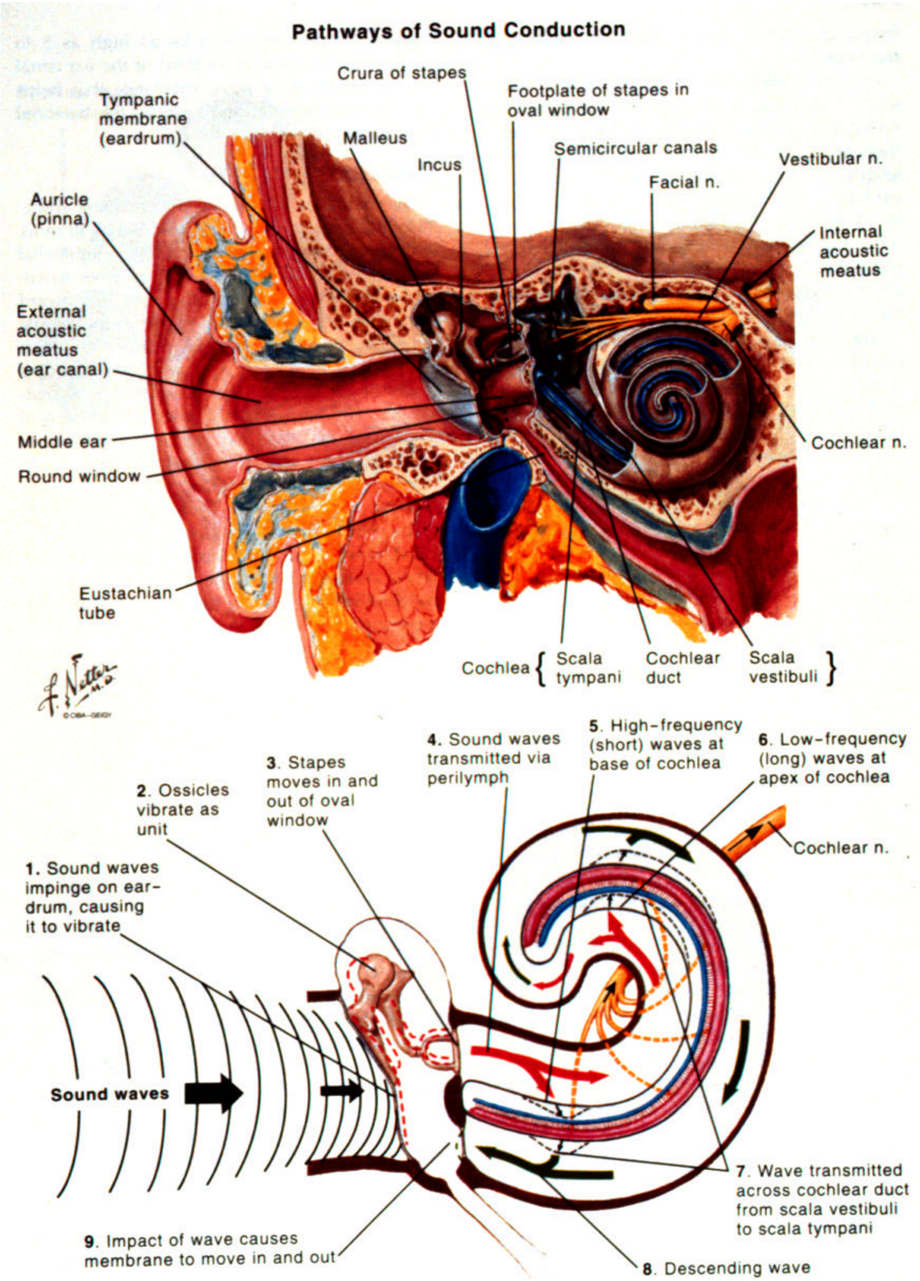
BIOLOGICAL MECHANICAL TRANSDUCERS

- The cochlea (inner ear) is a mechanical spectrum analyzer.
- Sound is coupled through the eardrum through the inner ear bones (malleus, incus and stapes) and to the oval window of the cochlea.
- High frequencies are sensed at the narrow, stiff end of the cochlea near the oval window, with the wider, more compliant distal regions sensing lower frequencies.
- Tactile sensors in the skin are capable of providing information about discriminative touch (shape, size, texture), proprioception (position), nociception (pain) and temperature.
- Several types of specialized receptors contribute to this.

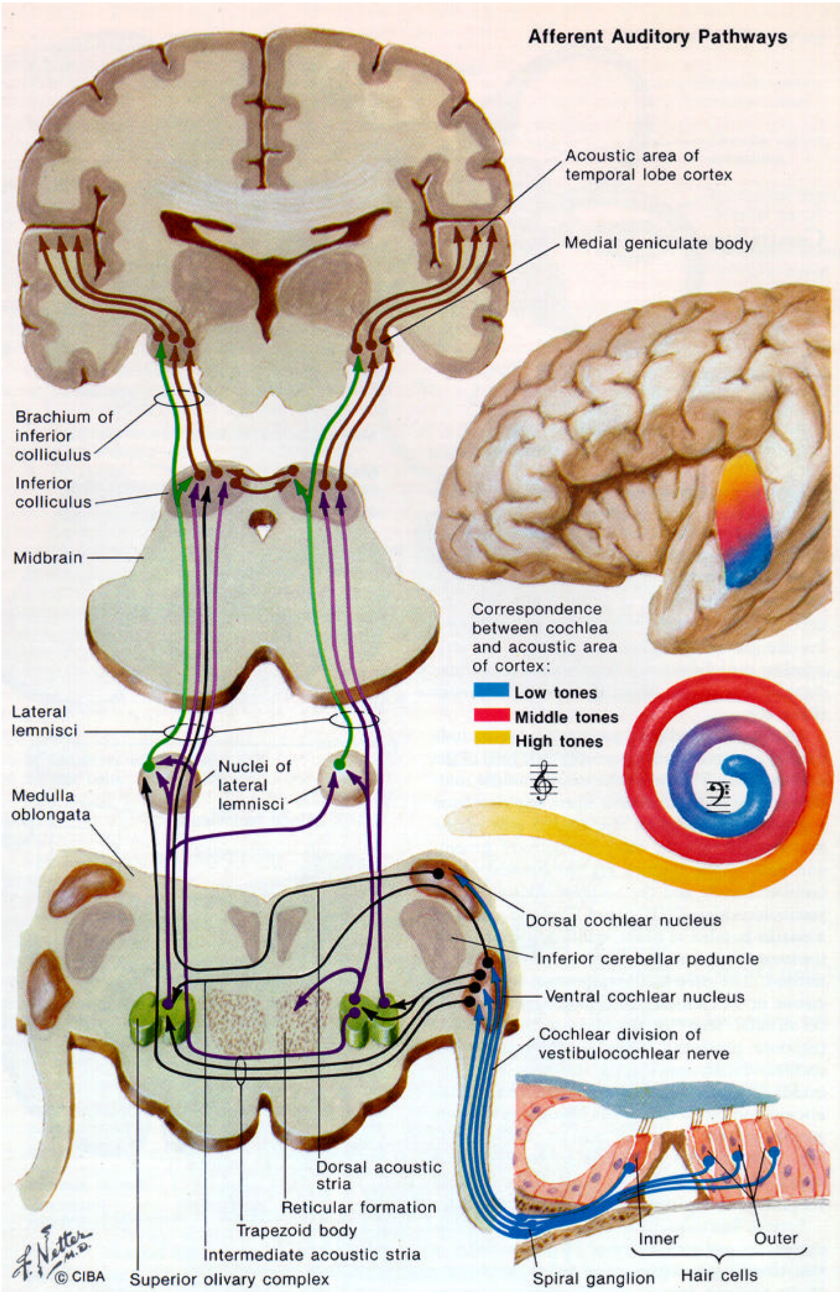
BIOLOGICAL ACOUSTIC SENSORS

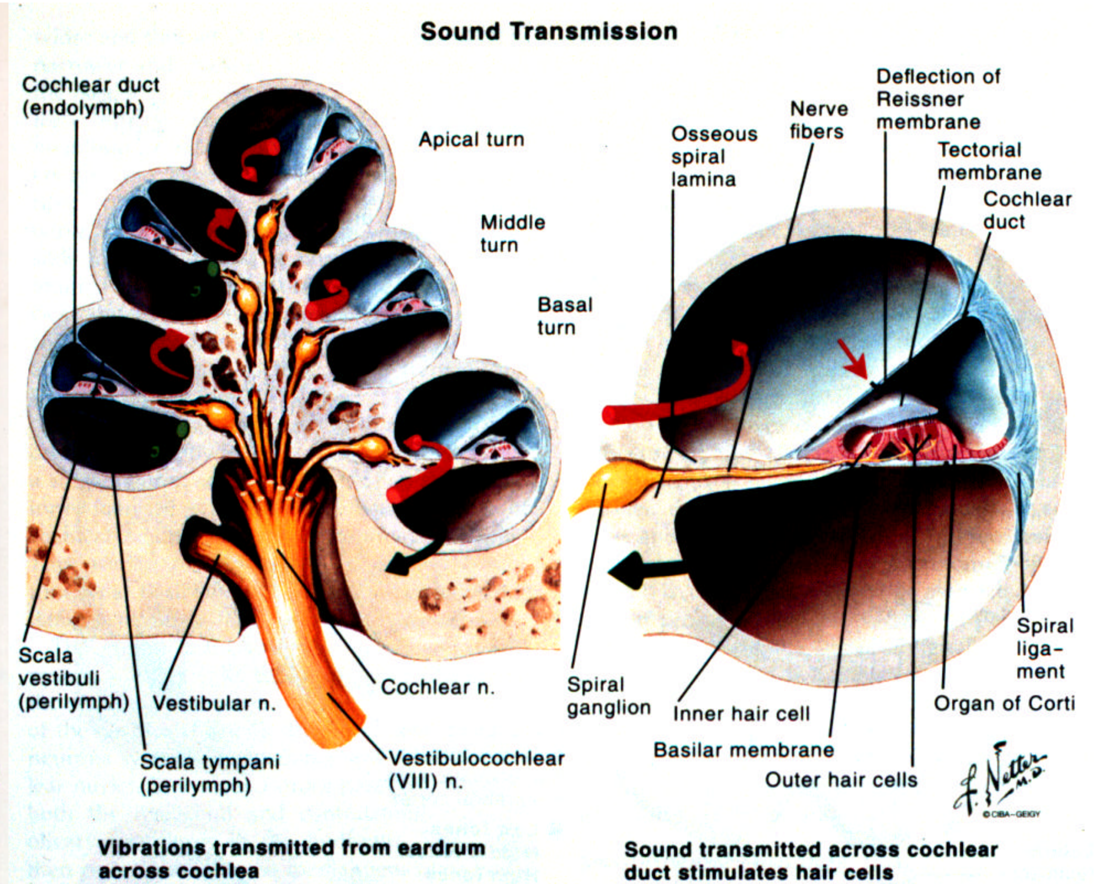


Reference: Kelly, J. P., "Hearing," Chapter 32 in "Principles of Neural Science," Third Edition, Kandel, E. R., Schwartz, J. H., and Jessell, T. M., [eds.], Elsevier, New York, NY, 1991, pp. 481 - 499.



Source: Netter, F., "The CIBA Collection of Medical Illustrations: Volume 1, Nervous System, Part 1, Anatomy and Physiology," CIBA-GEIGY Corp., 1983.



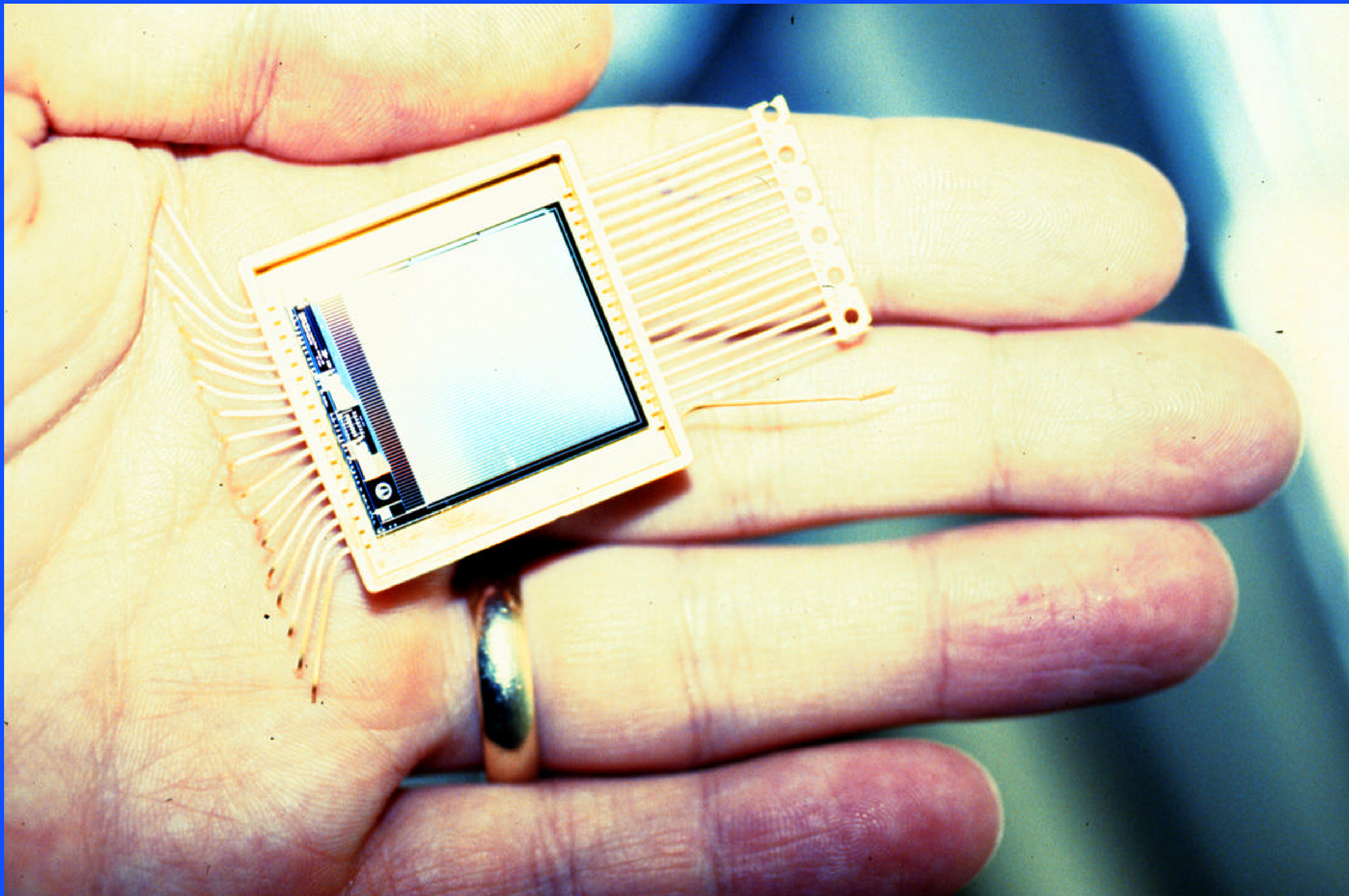


Source: Netter, F., "The CIBA Collection of Medical Illustrations: Volume 1, Nervous System, Part 1, Anatomy and Physiology," CIBA-GEIGY Corp., 1983.

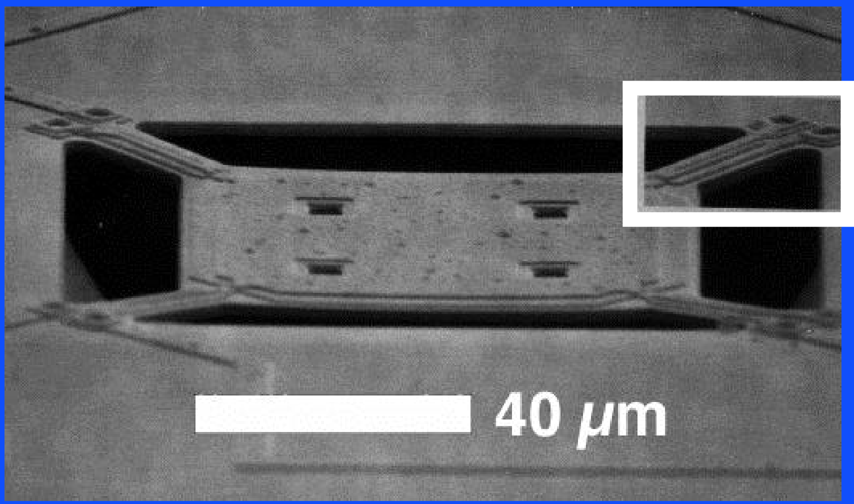
TACTILE SENSORS

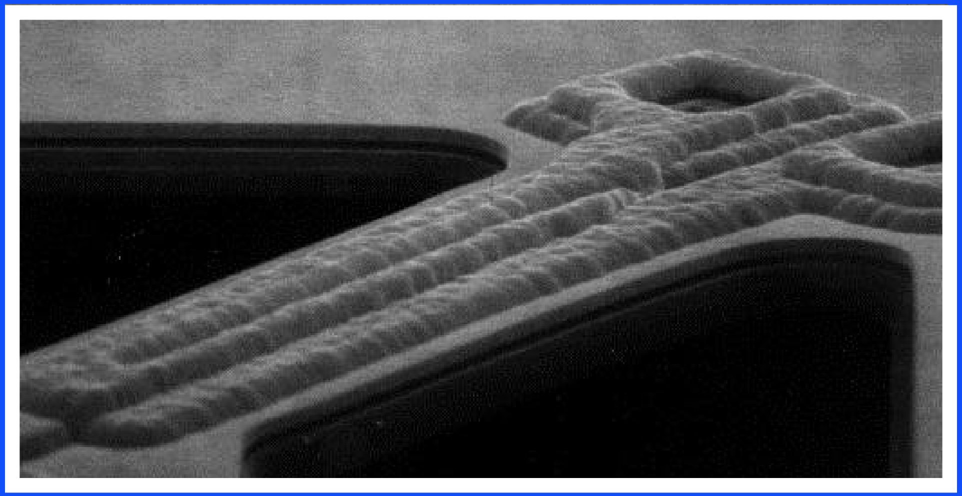
- Tactile sensors can be applied in robotics (end effectors) and research into dextrous manipulation.
- Many different transduction mechanisms have been utilized.
- Few devices have sensed shear forces (very important in object manipulation).


11 1 2
10 4
9 5
8 7 6



SHUTTLE PLATE TACTILE SENSOR

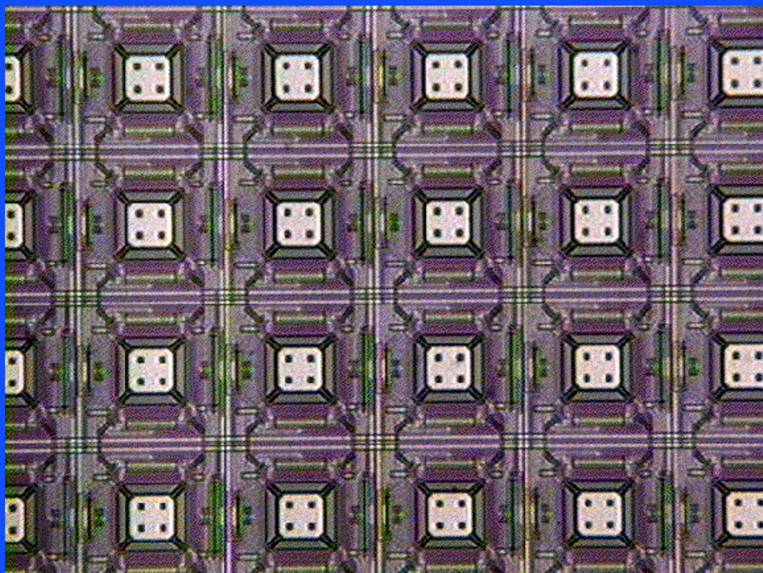


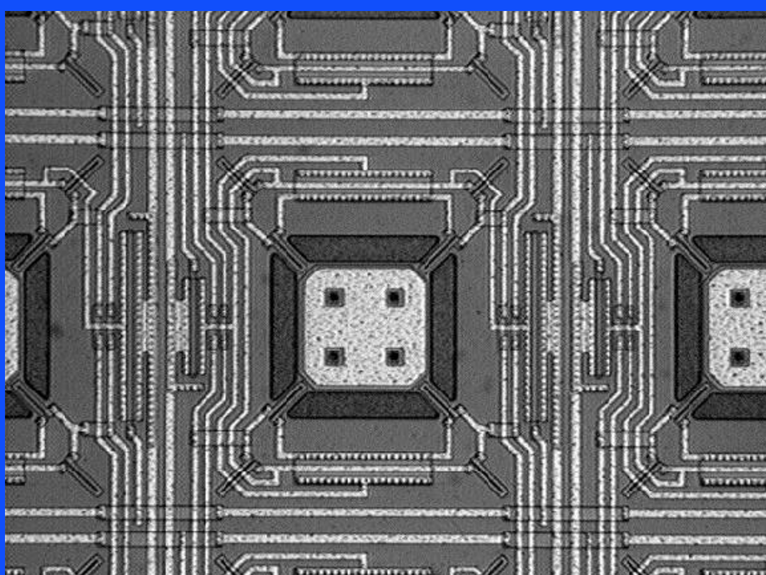


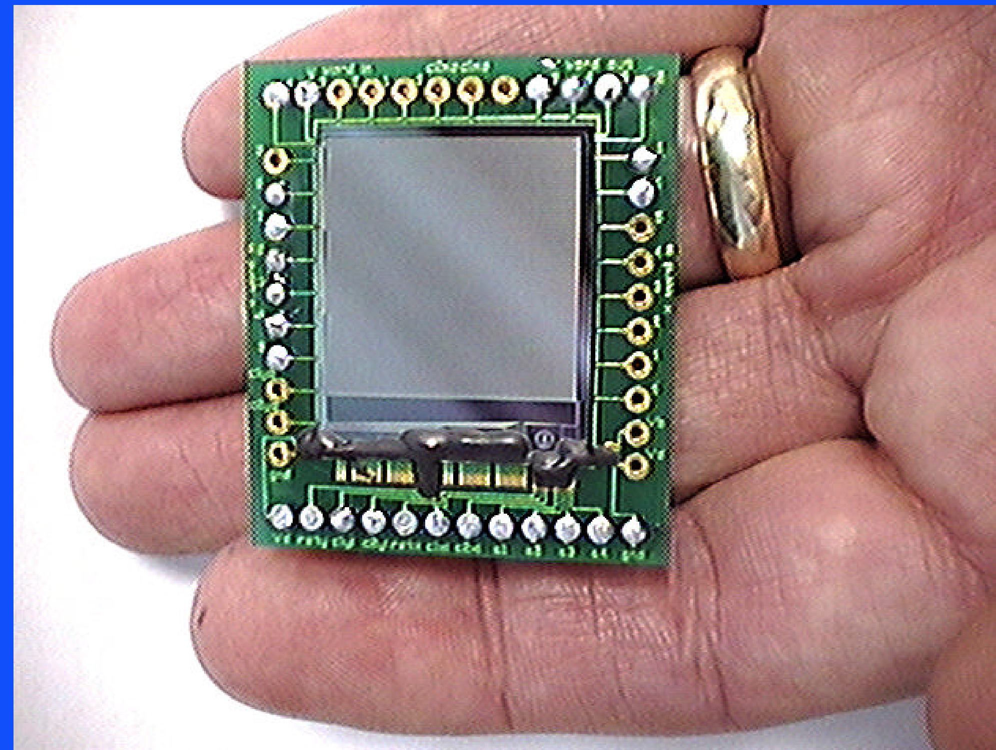
- Shuttle plate with four piezoresistive strain gauges can sense shear and normal forces.

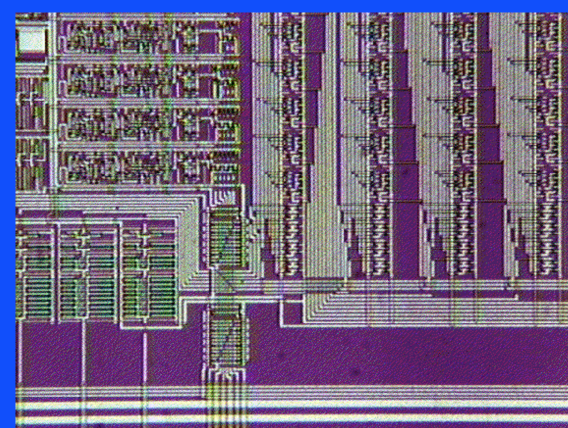
- TMAH undercut of oxide membranes is CMOS compatible.

Reference: Kane, B. J., Cutkosky, M. R., and Kovacs, G. T. A., "CMOS-Compatible Traction Stress Sensor for Use in High-Resolution Tactile Imaging," Sensors and Actuators A, vol. A54, 1996, pp. 511 - 516.

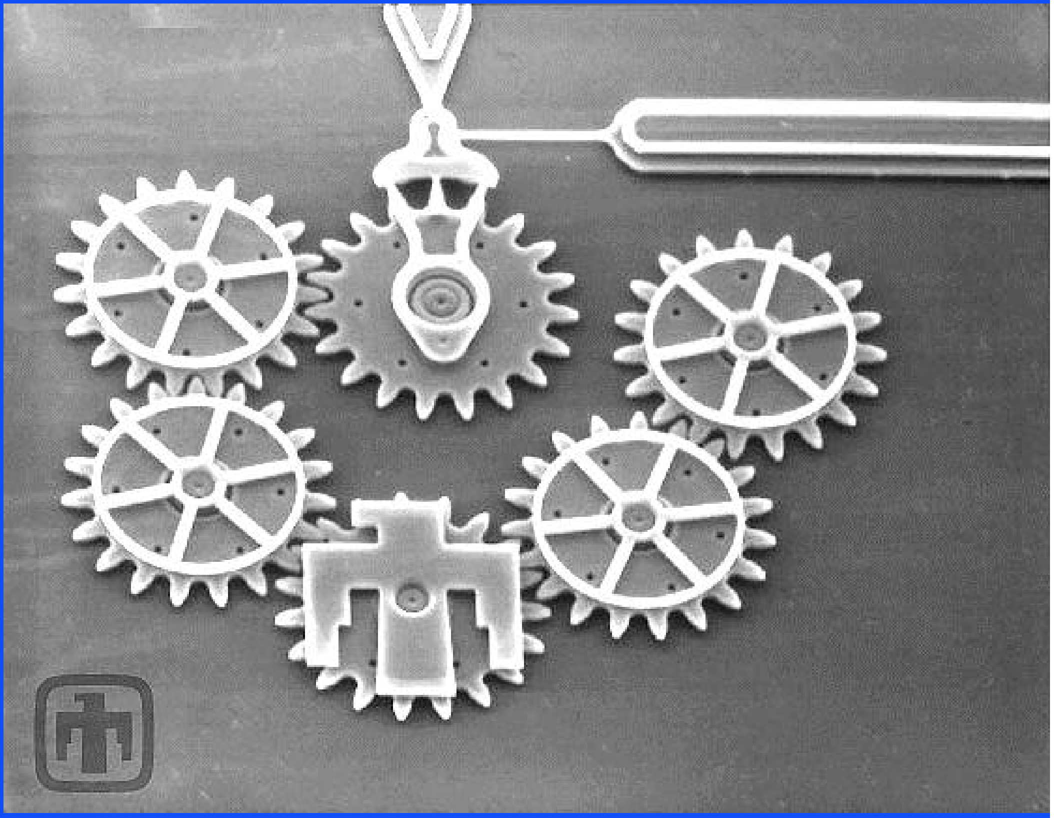




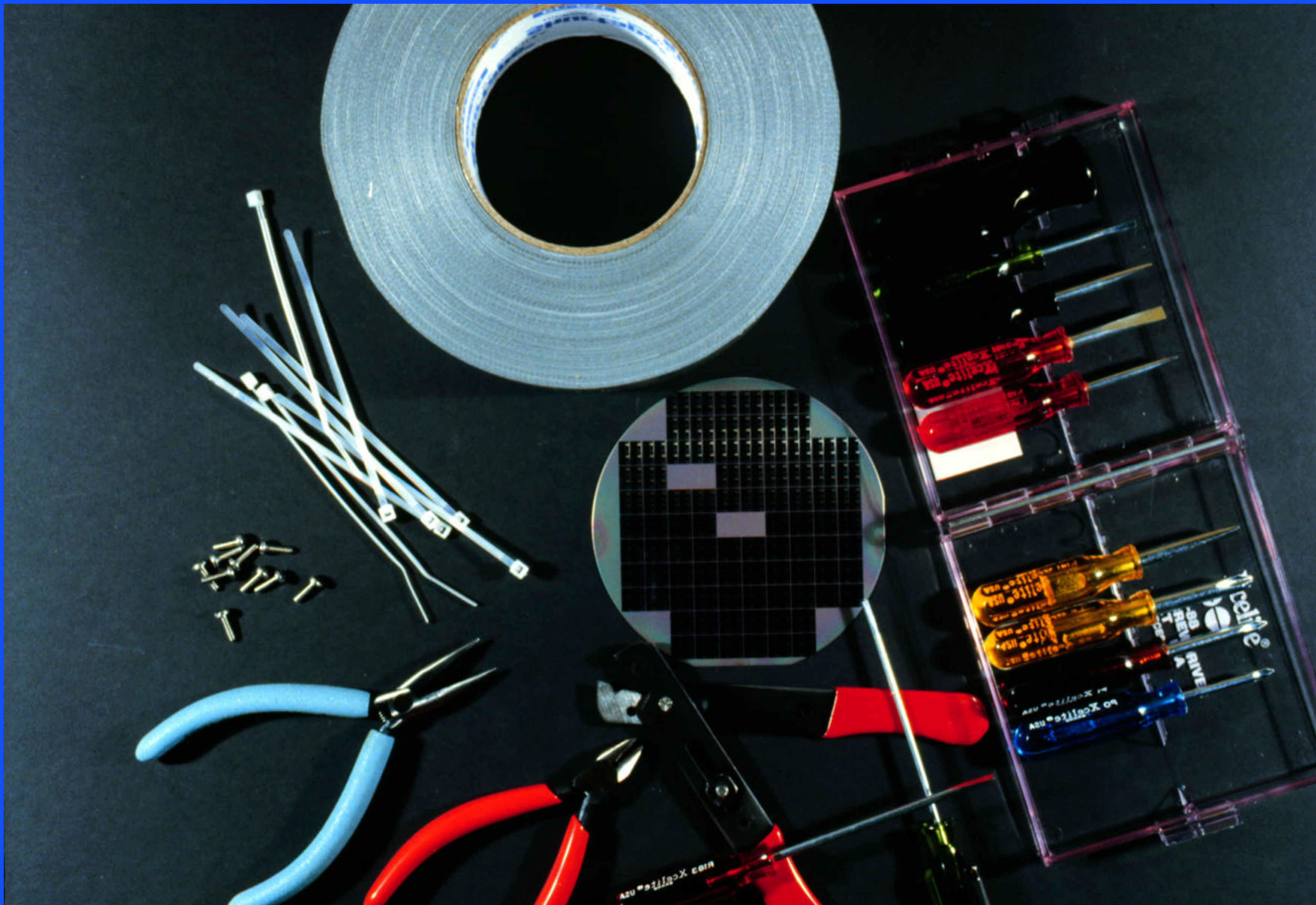




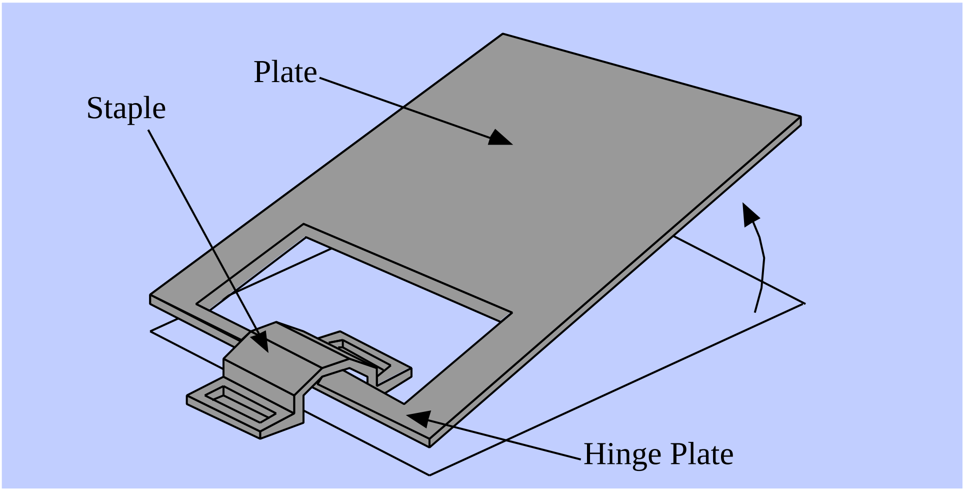
Micromechanisms

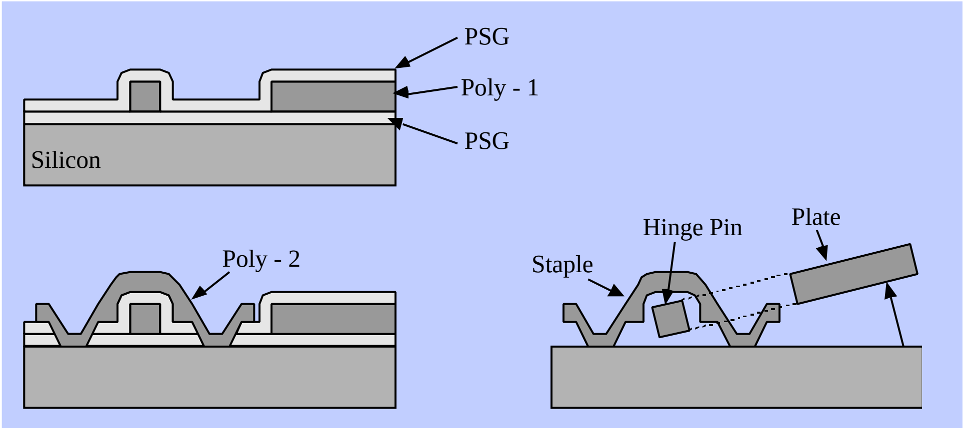


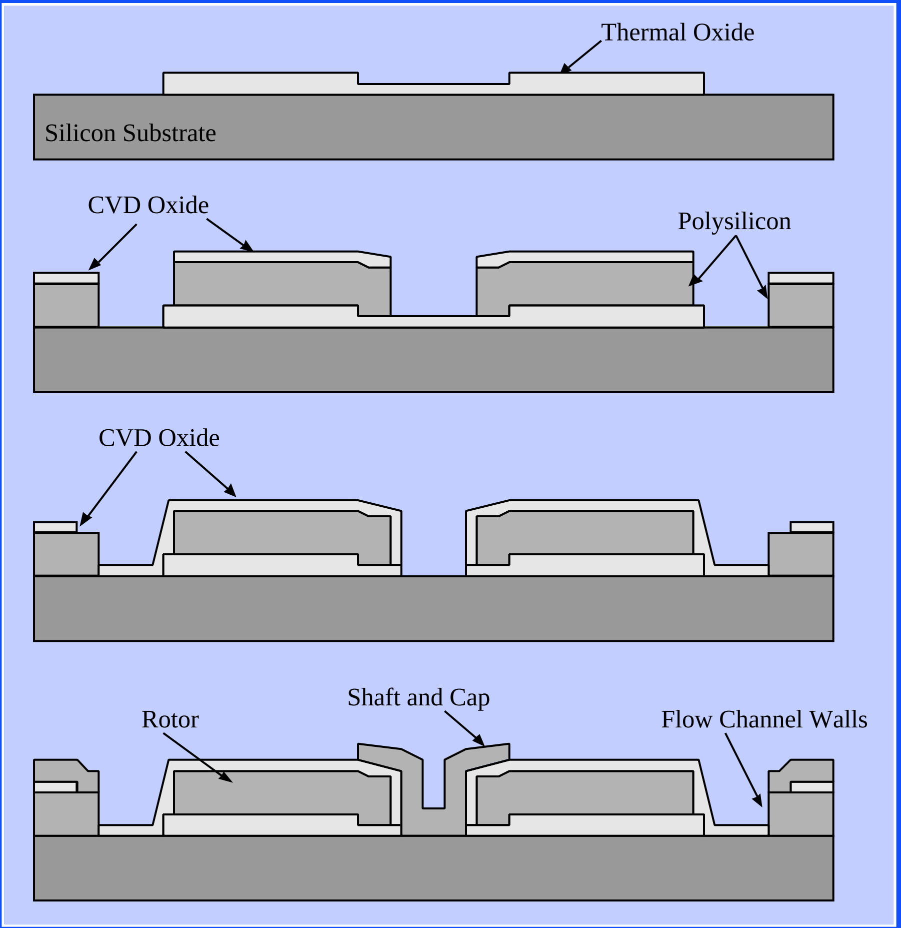
http://www.mdl.sandia.gov/Micromachine/images.html



POLYSILICON MECHANISMS

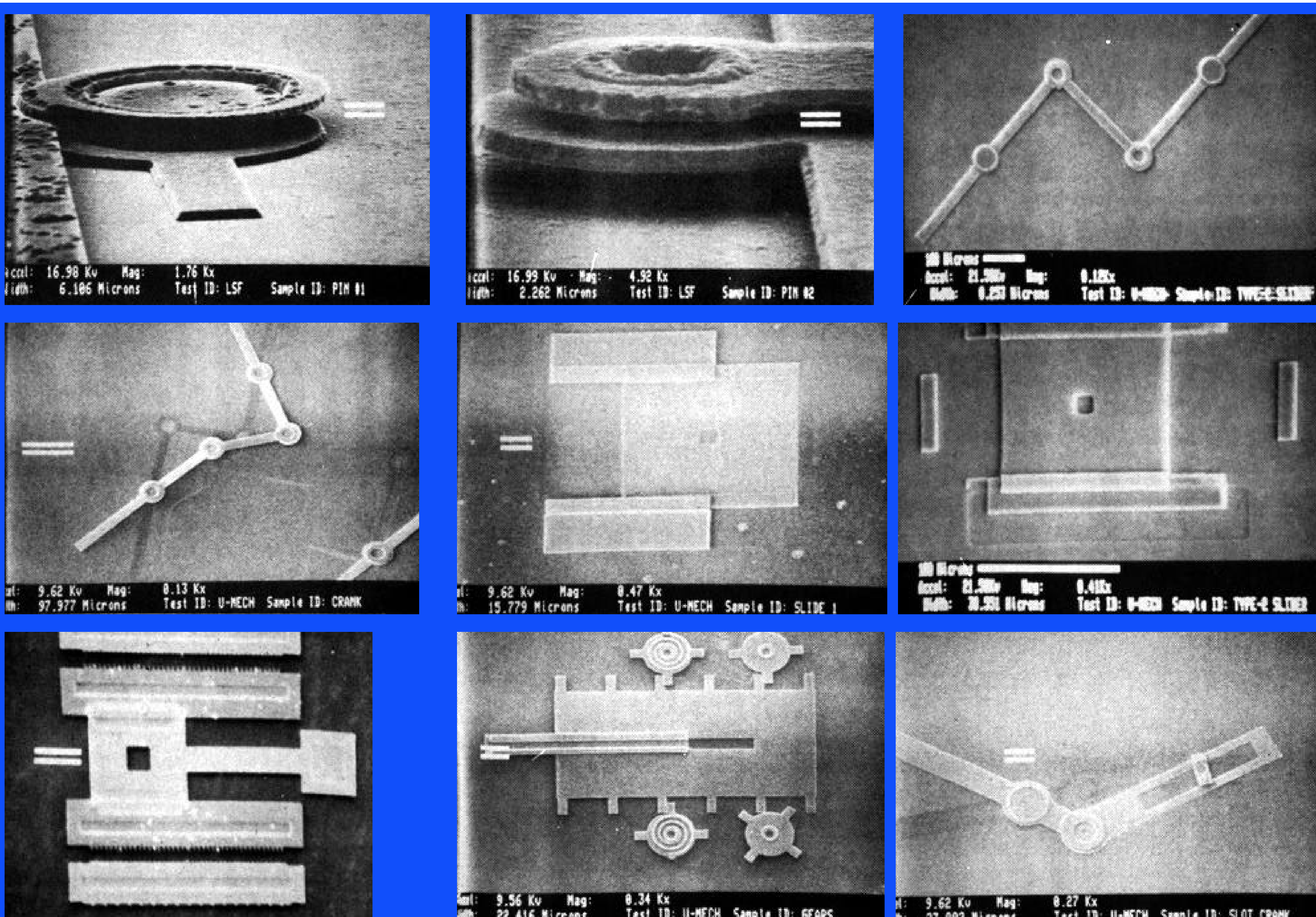




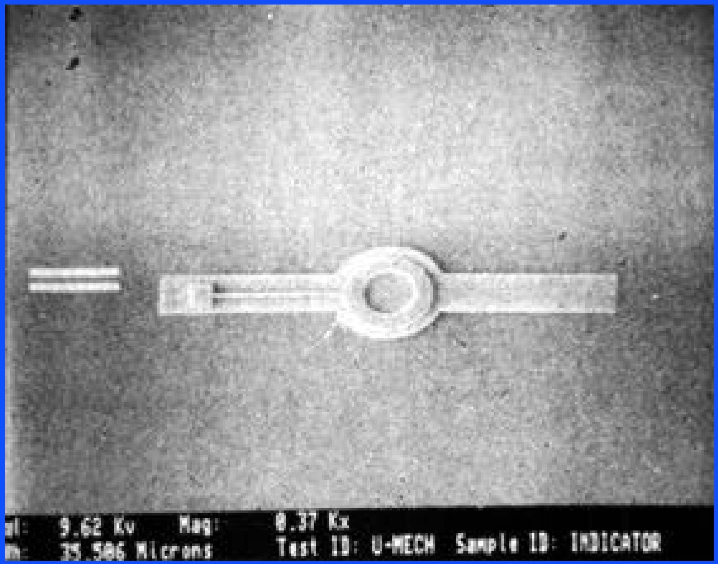


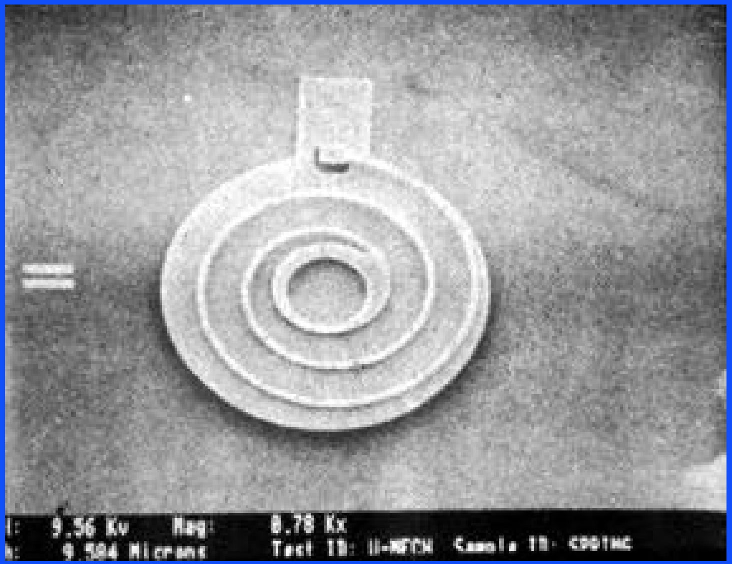
Reference: Mehregany, M., Gabriel, K. J., and Trimmer, W. S. N., "Integrated Fabrication of Polysilicon Mechanisms," IEEE Transactions on Electron Devices, vol. 35, no. 6, June 1988, pp. 719 - 723.

Reference: Pister, K. S. J., Judy, M. W., Burgett, S. R., and Fearing, R. S., "Microfabricated Hinges." Sensors and Actuators A, vol. A33, no. 3, June 1992, pp. 249 - 256.

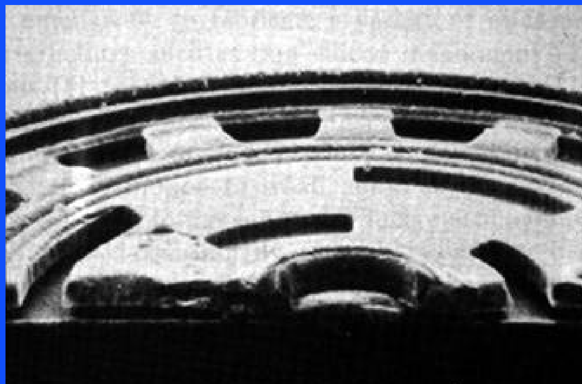
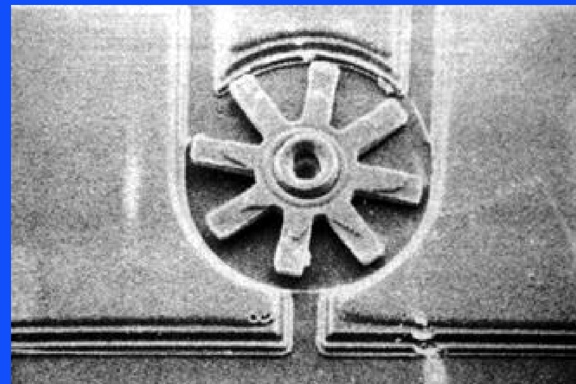
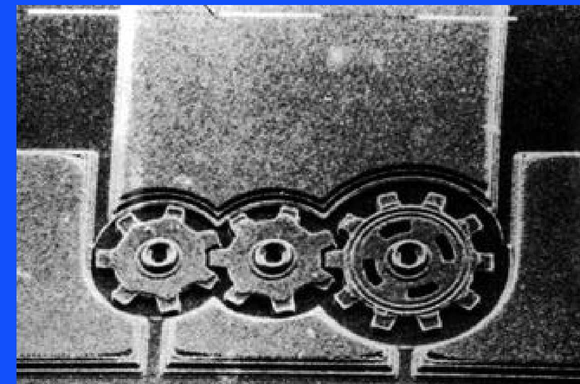
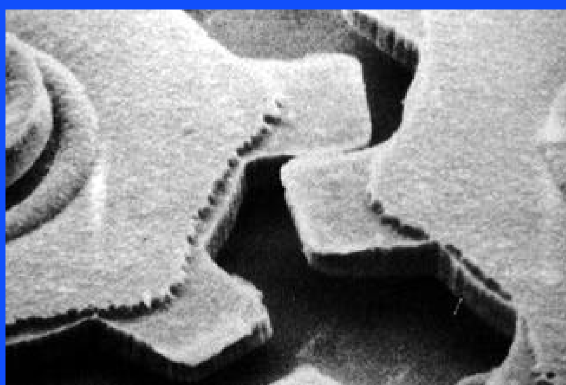
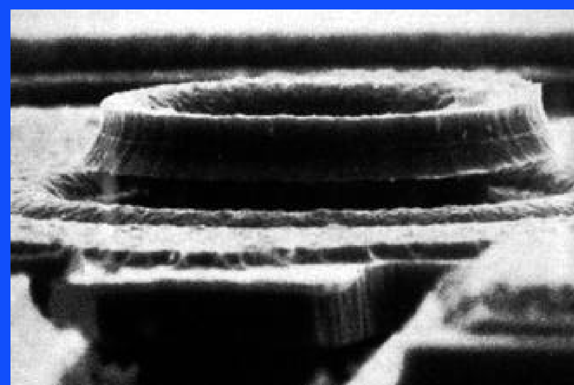


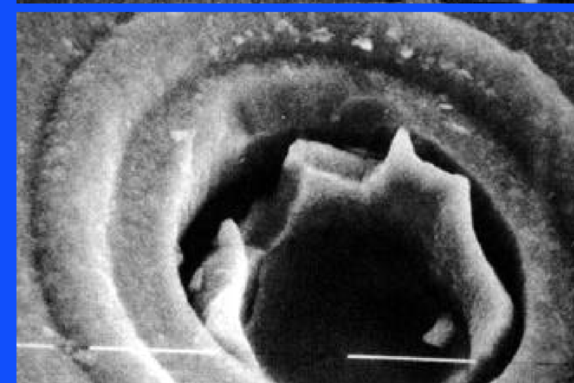
Source: Fan, L.-S., Tai, Y.-C., and Muller, R. S., "Integrated Movable Micromechanical Structures for Sensors and Actuators," IEEE Transactions on Electron Devices, vol. 35, no. 6, June 1988, pp. 724 - 730.



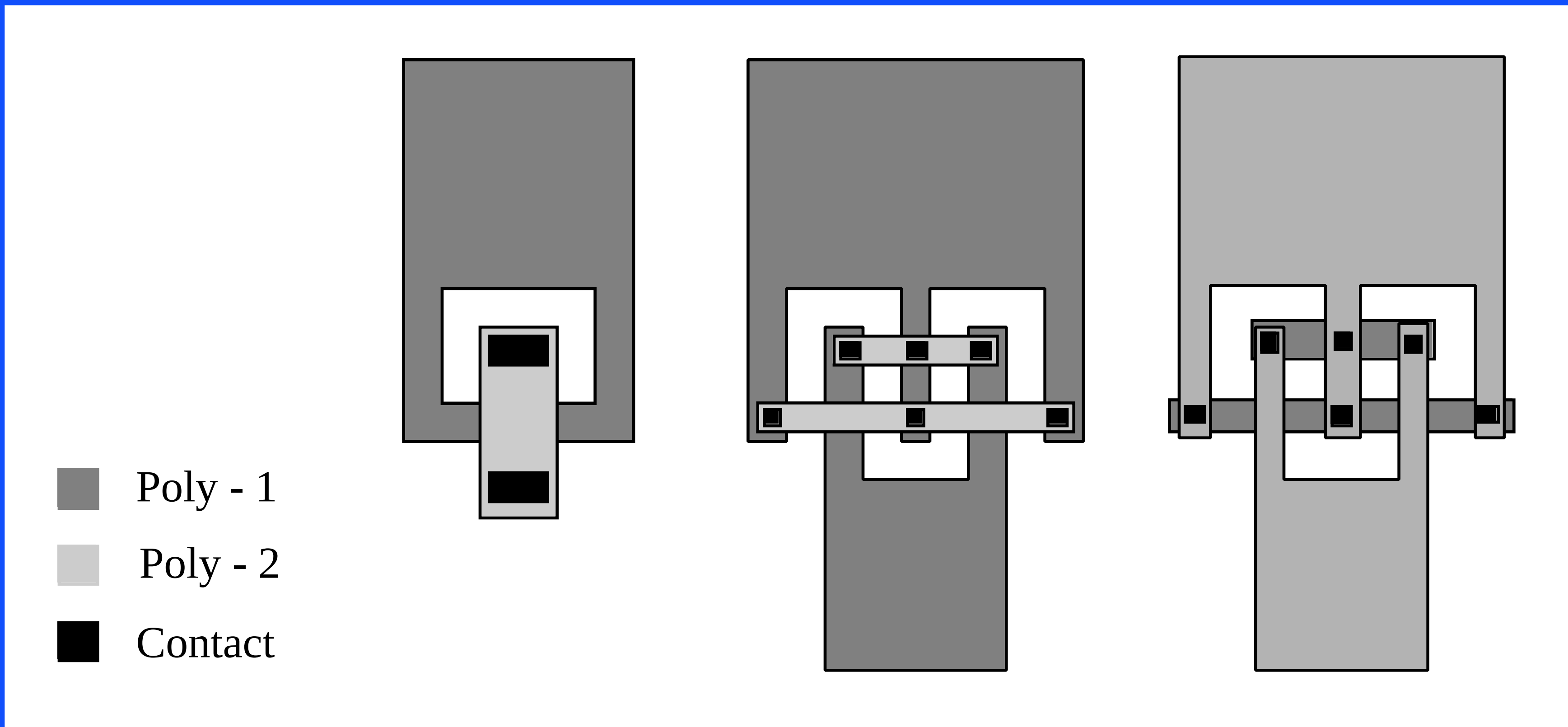


Source: Fan, L.-S., Tai, Y.-C., and Muller, R. S., “Integrated Movable Micromechanical Structures for Sensors and Actuators,” IEEE Transactions on Electron Devices, vol. 35, no. 6, June 1988, pp. 724 - 730.

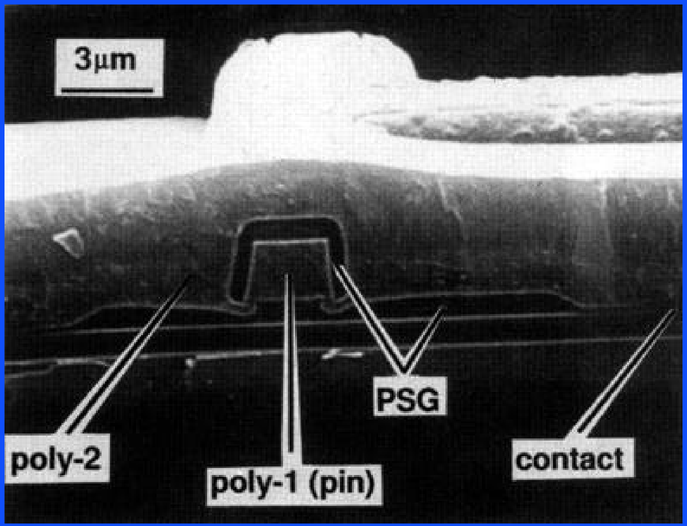






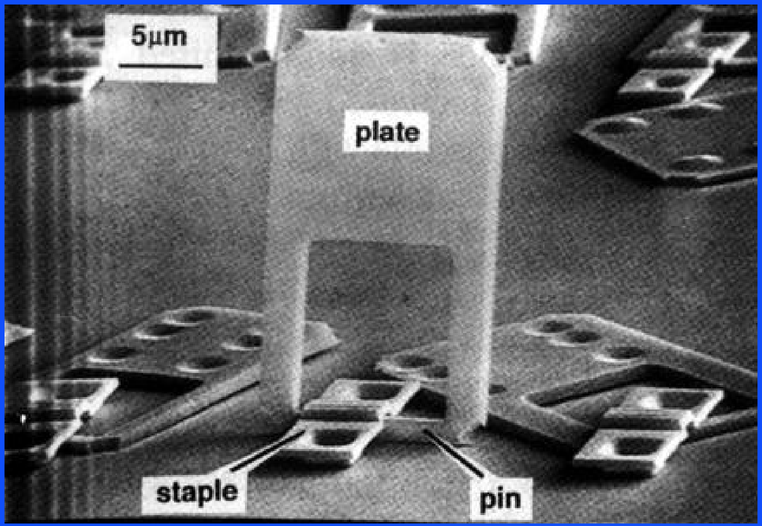


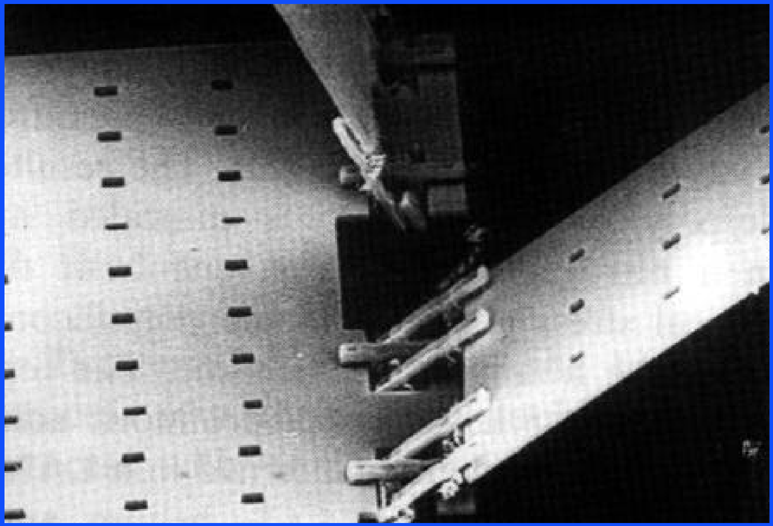
Source: Mehregany, M., Gabriel, K. J., and Trimmer, W. S. N., “Integrated Fabrication of Polysilicon Mechanisms,” IEEE Transactions on Electron Devices, vol. 35, no. 6, June 1988, pp. 719 - 723.

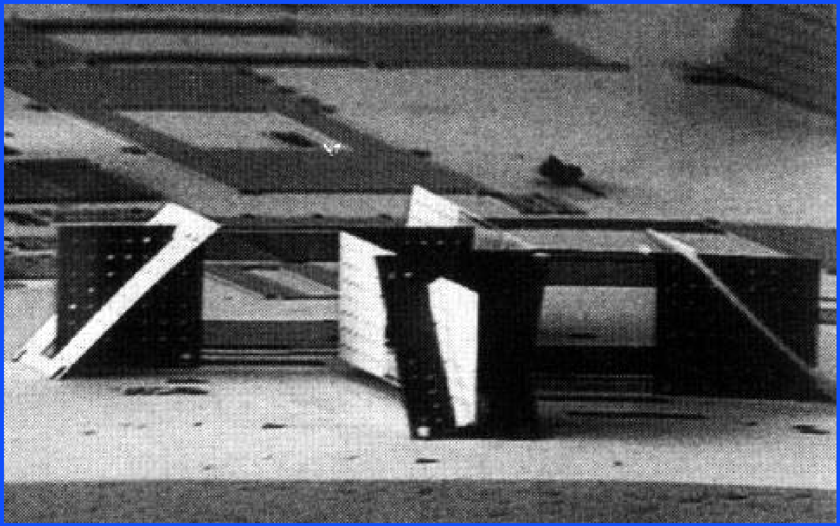


Reference: Pister, K. S. J., Judy, M. W., Burgett, S. R., and Fearing, R. S., "Microfabricated Hinges." Sensors and Actuators A, vol. A33, no. 3, June 1992, pp. 249 - 256.



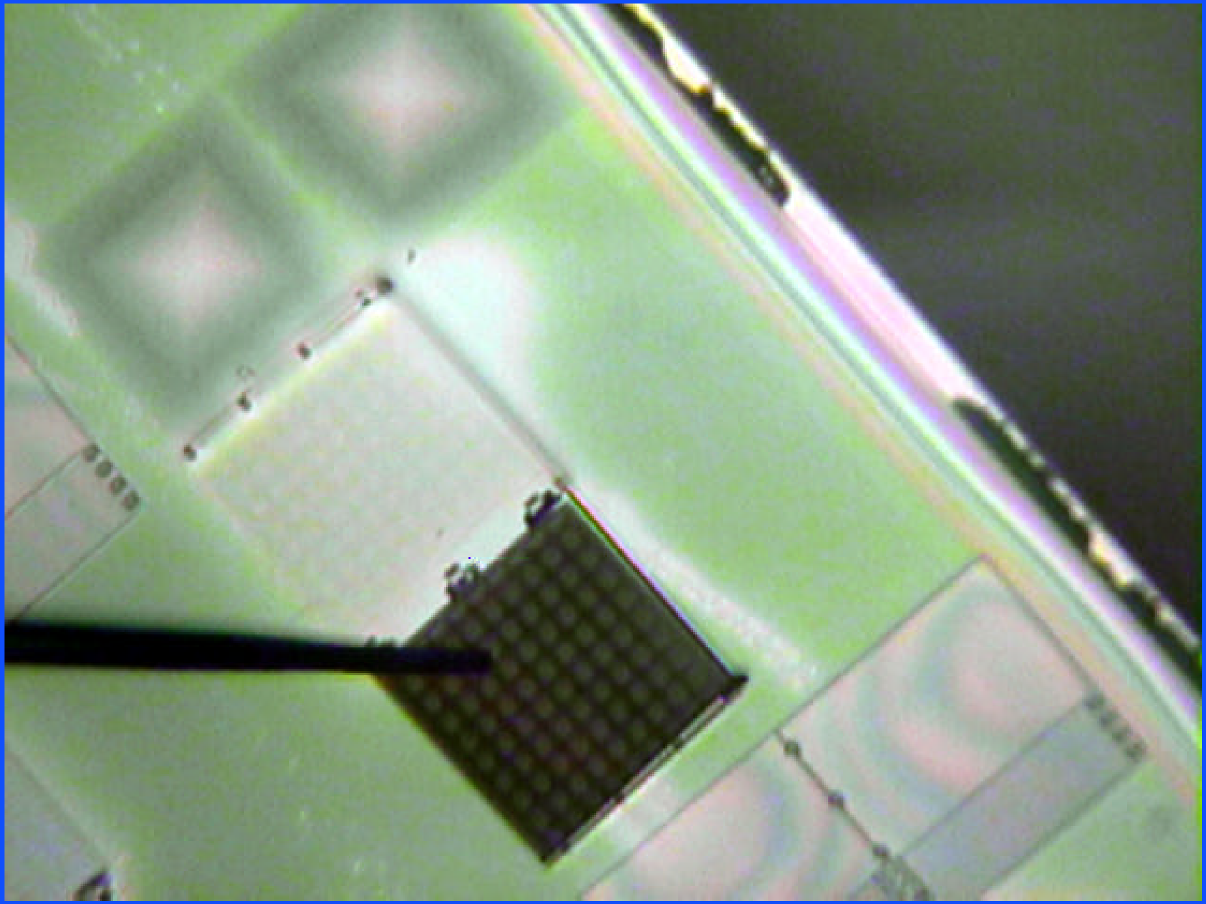






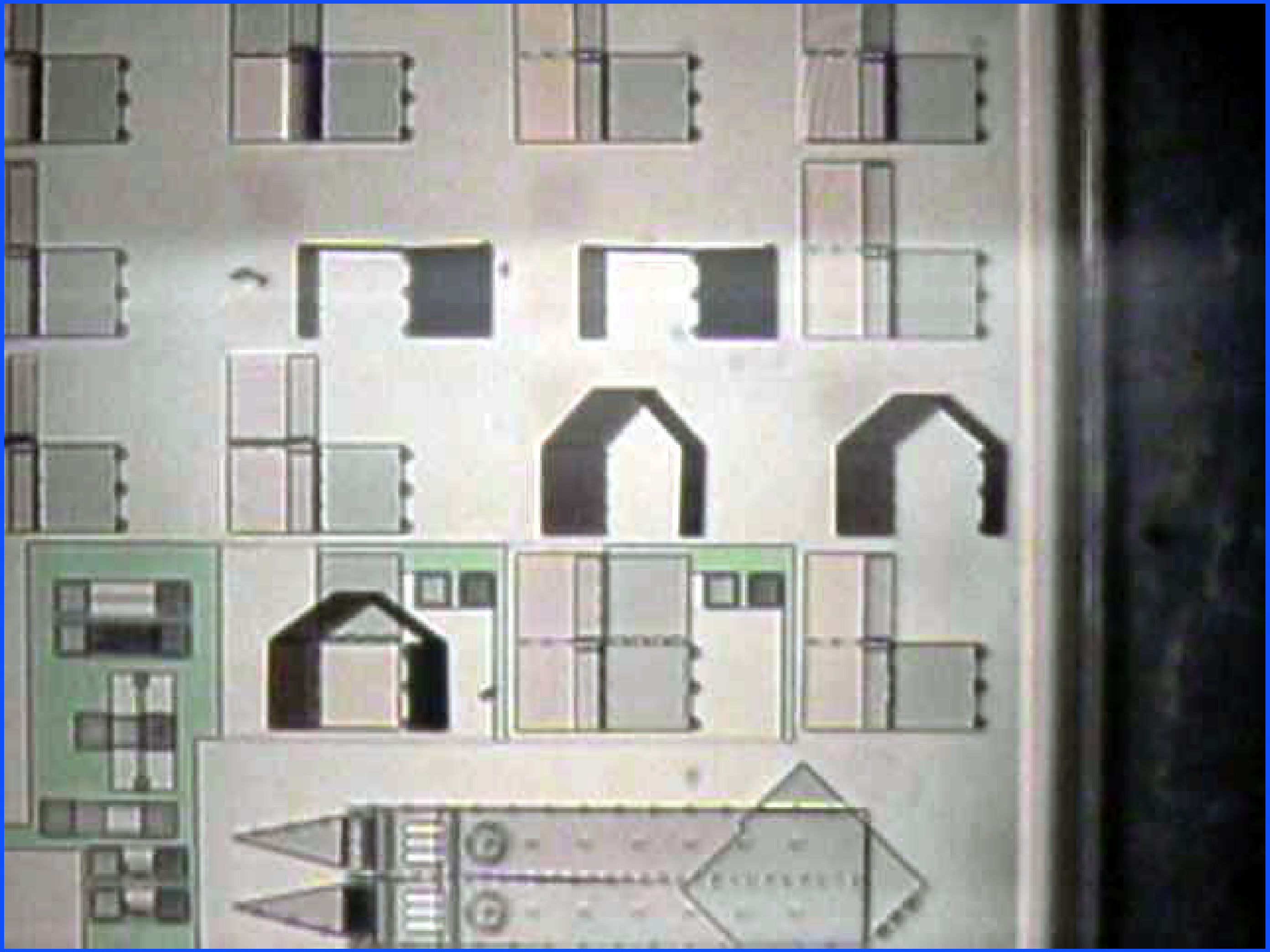
Source: Pister, K. S. J., Judy, M. W., Burgett, S. R., and Fearing, R. S., "Microfabricated Hinges." Sensors and Actuators, vol. A33, no. 3, June 1992, pp. 249 - 256.

HINGED STRUCTURE ASSEMBLY

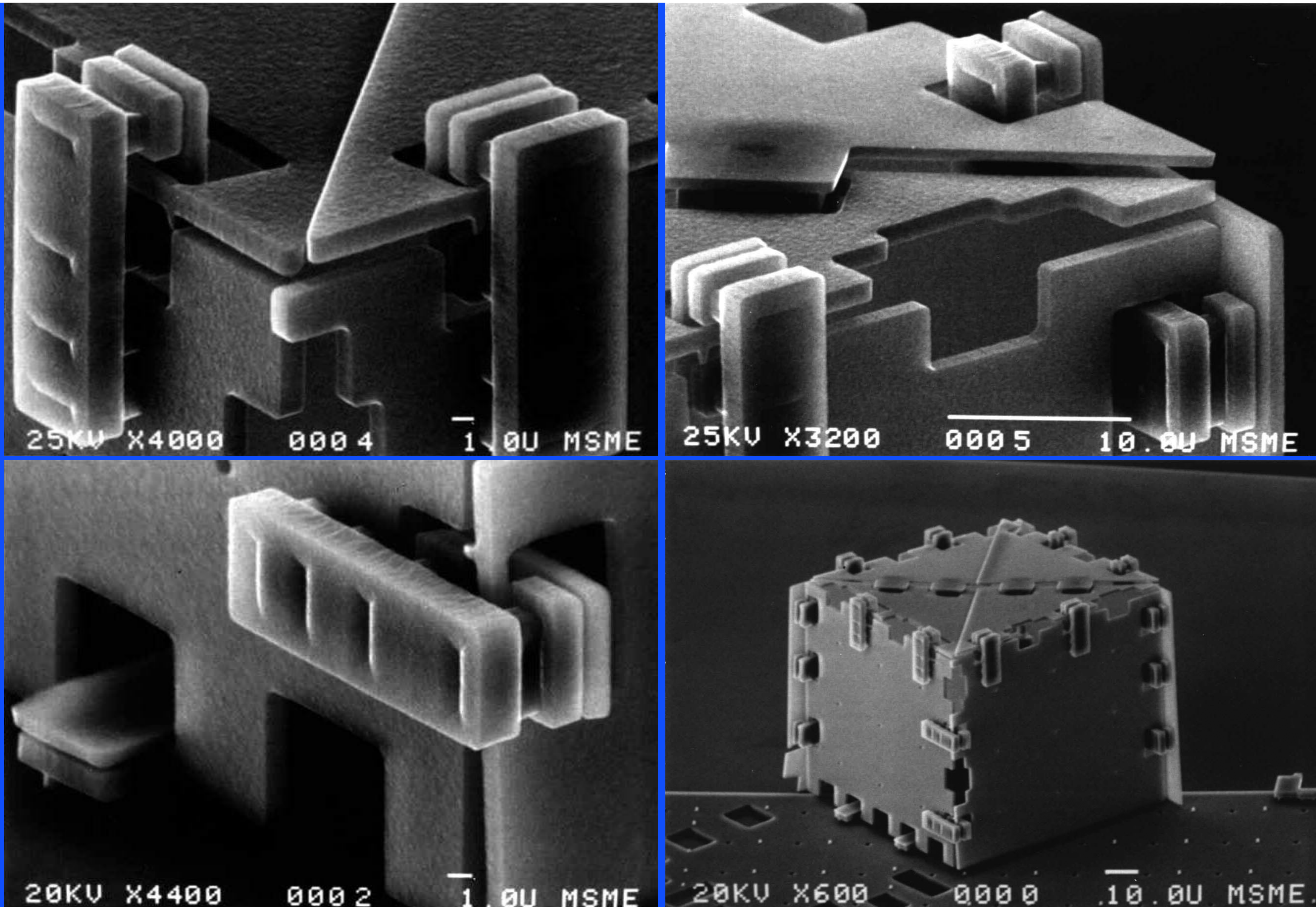


Courtesy E. Hui, U. C. Berkeley.

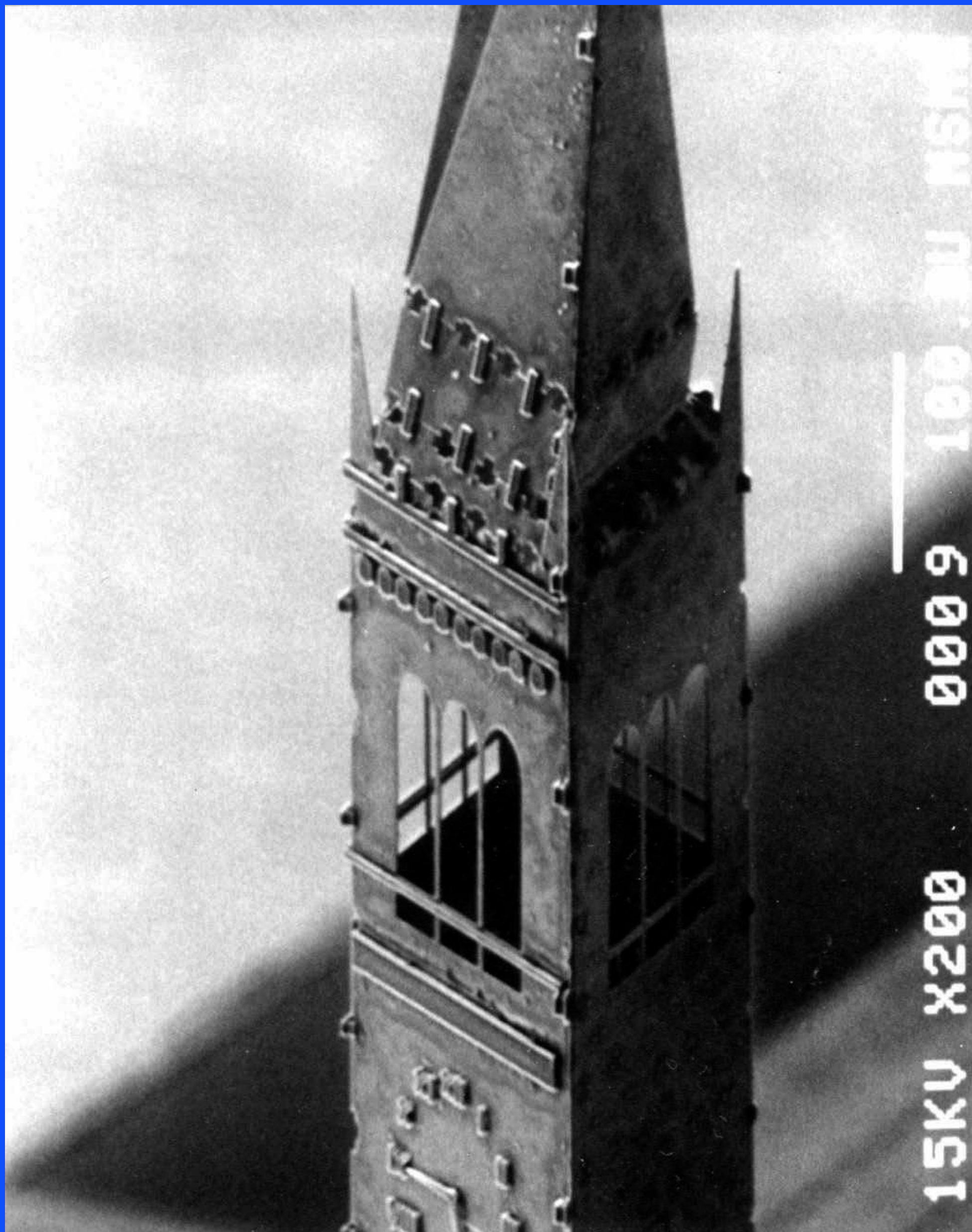
FLUIDIC ASSEMBLY



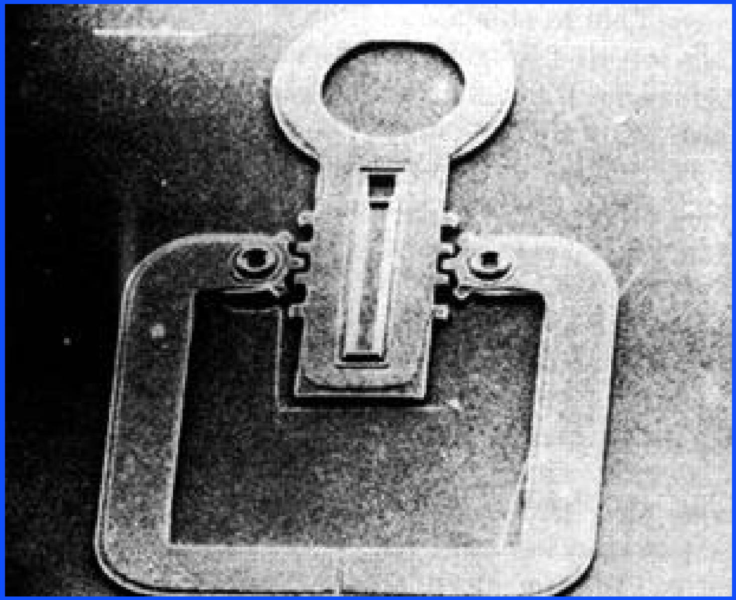
Courtesy E. Hui, U. C. Berkeley.

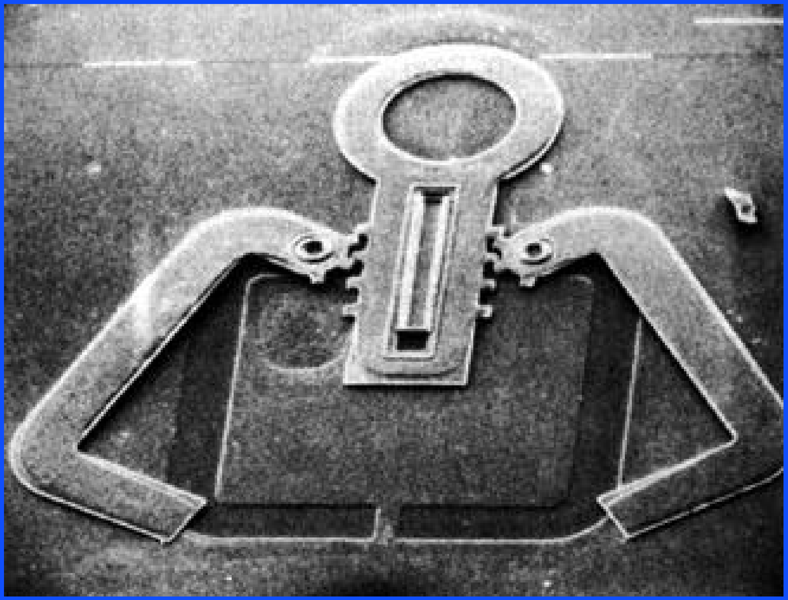


This "pop-up" closed box was assembled in a single flipping step, using tweezers provided by MEMS Precision Instruments. Designed by Elliot Hui in the Sandia SUMMiT 4-level process. 7/22/99 Courtesy E. Hui, U. C. Berkeley.

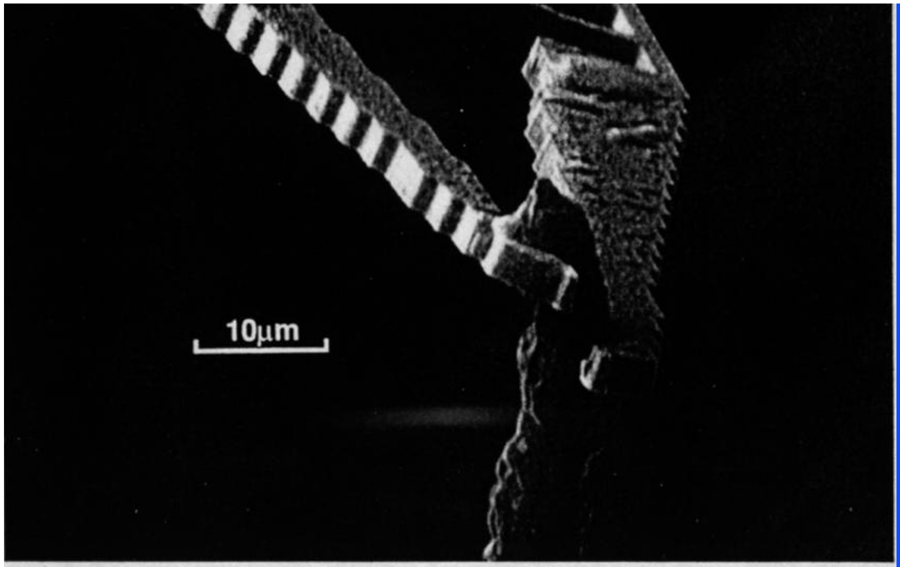


Courtesy E. Hui, U. C. Berkeley.

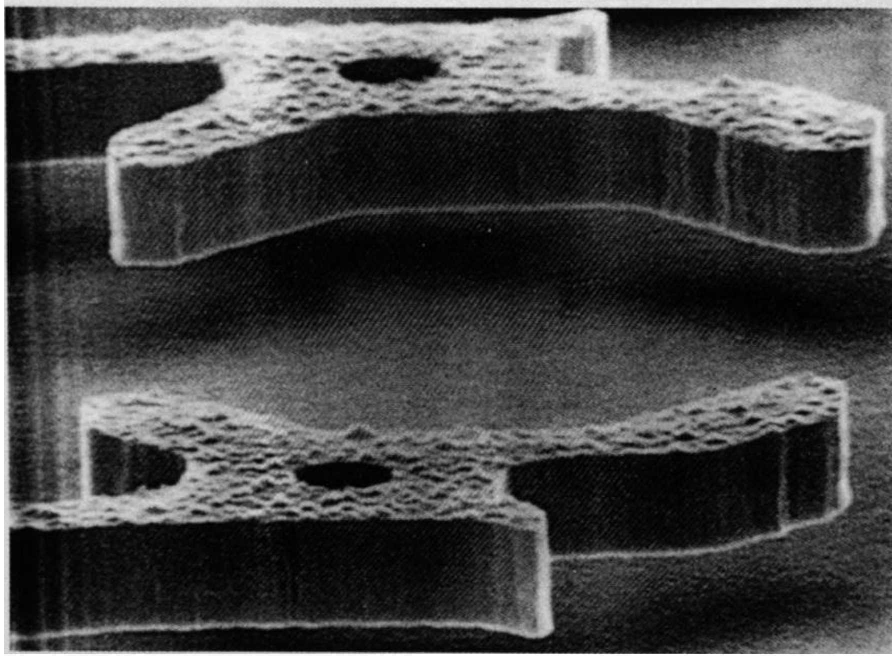


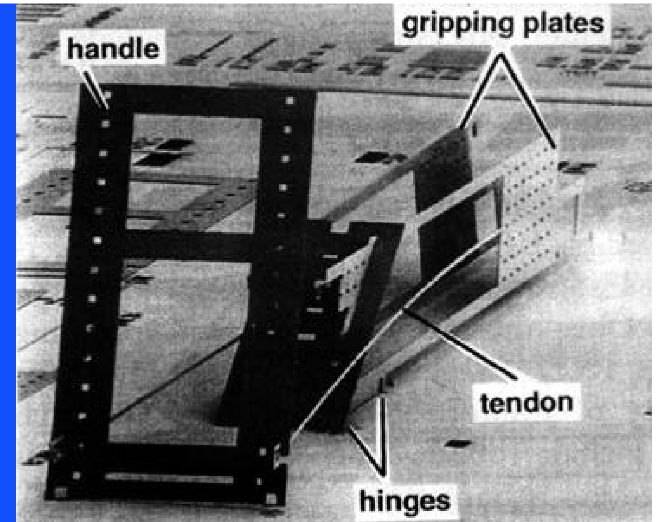


Source: Mehregany, M., Gabriel, K. J., and Trimmer, W. S. N., “Integrated Fabrication of Polysilicon Mechanisms,” IEEE Transactions on Electron Devices, vol. 35, no. 6, June 1988, pp. 719 - 723.



Microgripper. This scanning electron micrograph shows a microgripper made by Chang-Jin Kim, Albert Pisano, and Richard Muller of the Berkeley Sensor & Actuator Center. The gripper is holding a euglena, a 7- by 40-micron single-cell protozoa.





Source: Pister, K. S. J., Judy, M. W., Burgett, S. R., and Fearing, R. S., "Microfabricated Hinges." Sensors and Actuators, vol. A33, no. 3, June 1992, pp. 249 - 256.

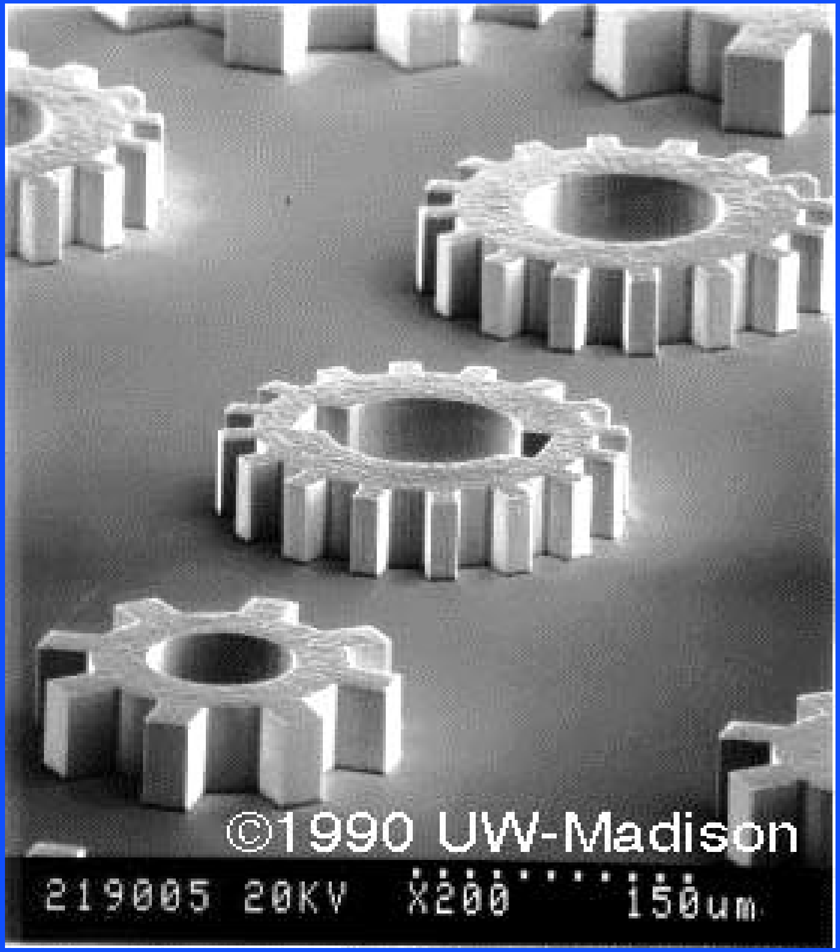
Source: Kim, C.-J., Pisano, A. P., and Muller, R. S., "Silicon-Processed Overhanging Microgripper." Journal Of Microelectromechanical Systems, vol. 1, no. 1, Mar. 1992, pp. 31 - 36.

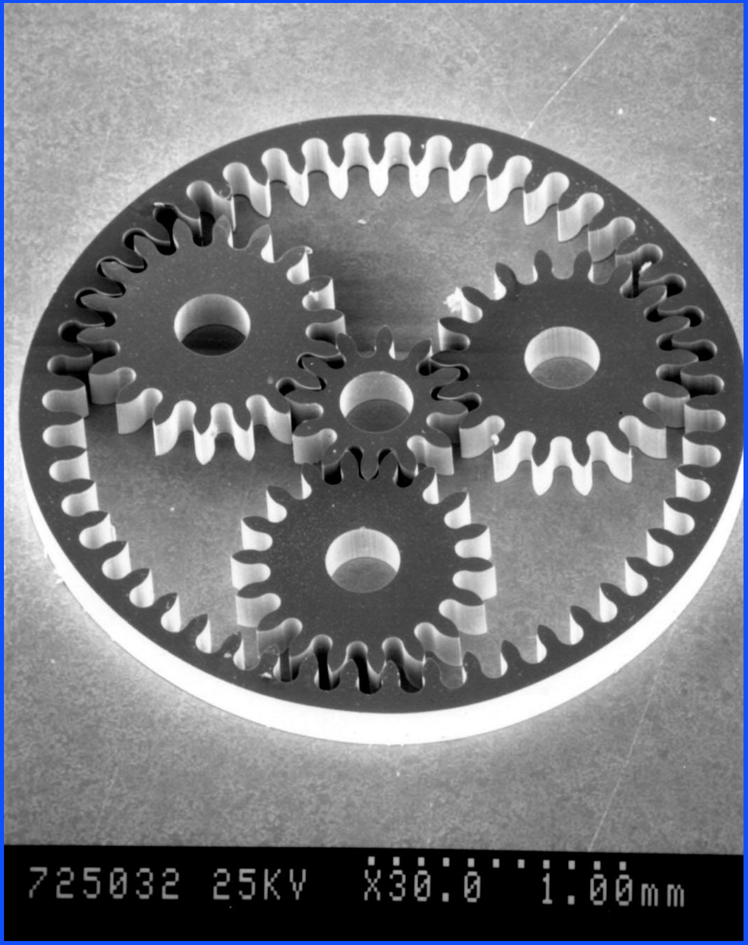
LIGA HOSE CLAMP & SPRING

Courtesy of Prof. Henry Guckel

http://mems.engr.wisc.edu/images/

LIGA GEARS



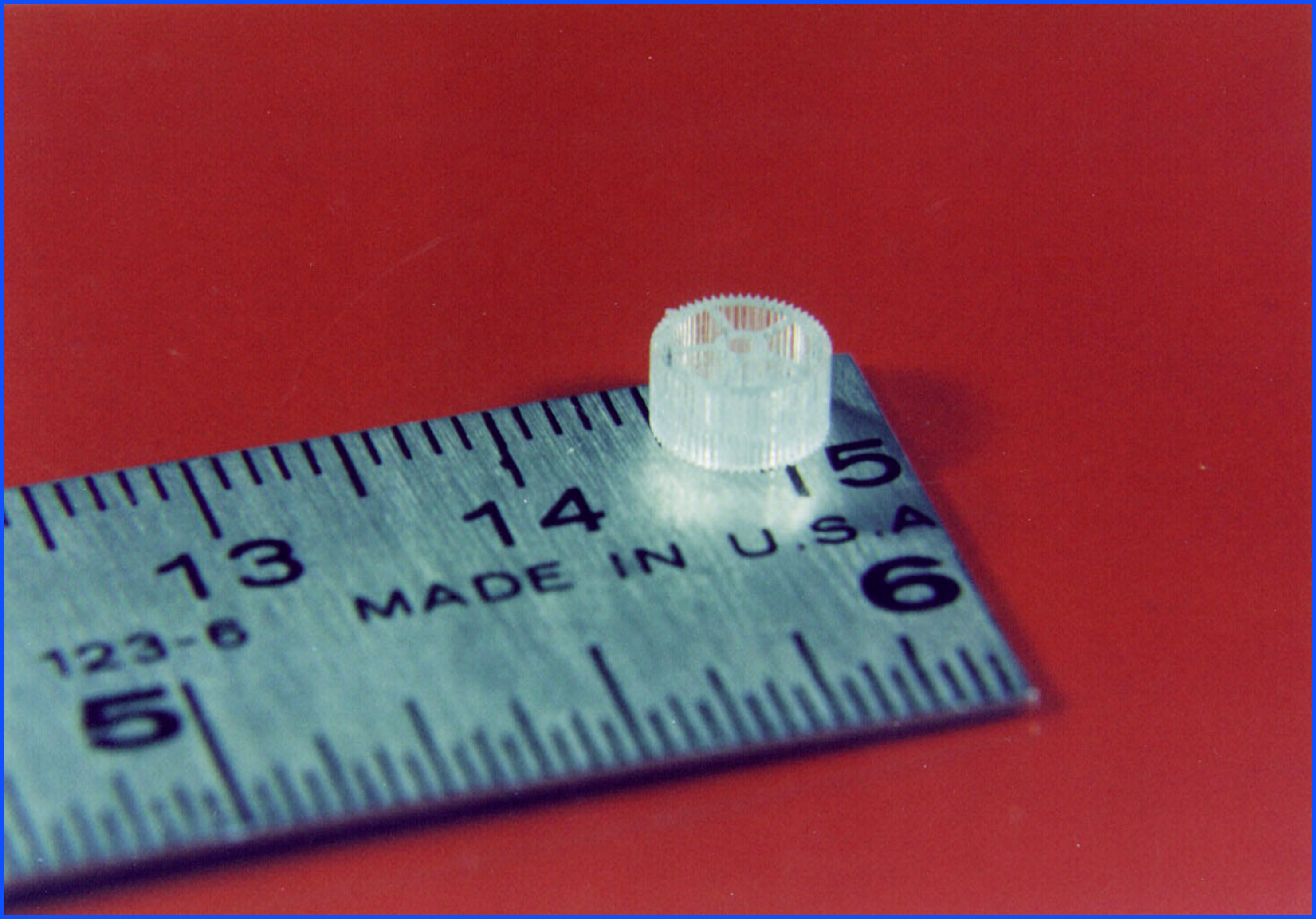


Courtesy of Prof. Henry Guckel

http://mems.engr.wisc.edu/images/

Reference: H. Guckel, "Micromechanics for Actuator and Precision Engineering Applications", Meeting Abstracts, 194th Meeting of the Electrochemical Society, Inc., Vol. (98-2), Abstract No. (1154), Boston, MA, November 1998

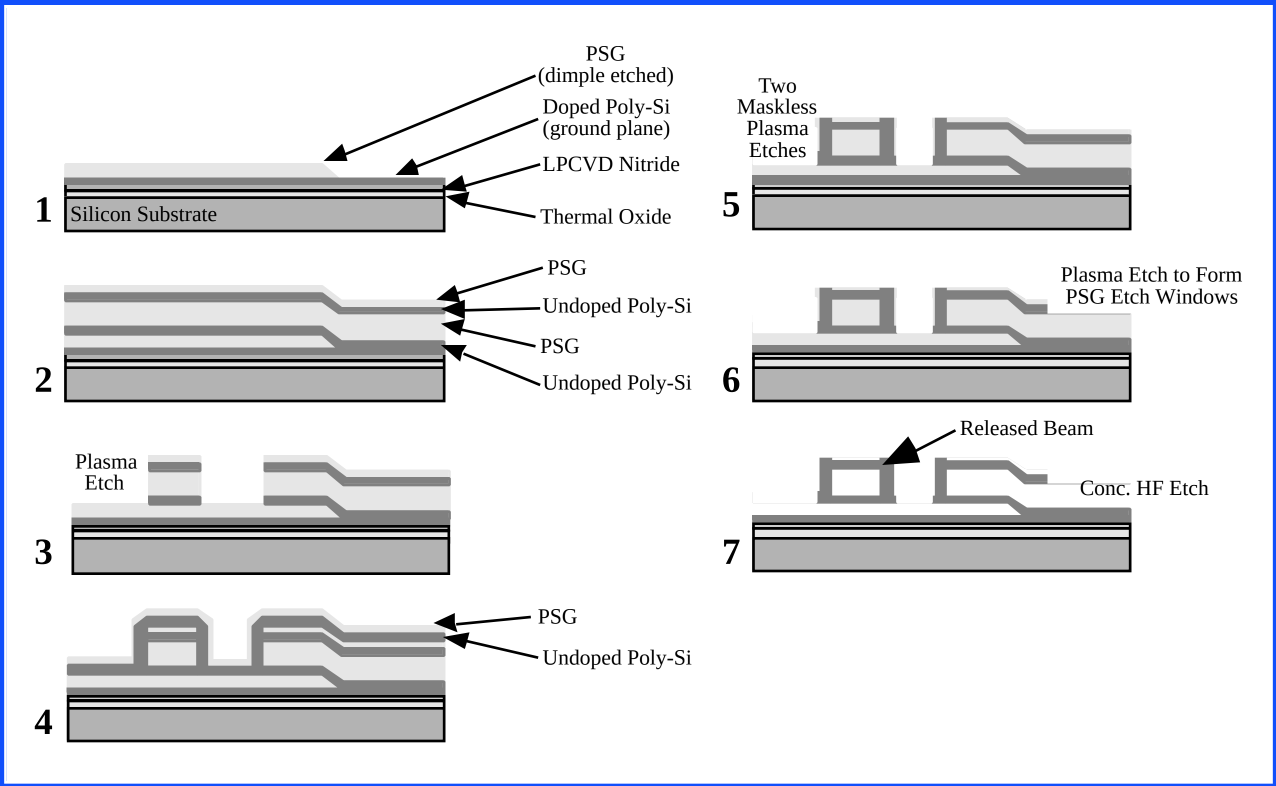
PMMA GEAR



Courtesy of Prof. H. Guckel, University of Wisconsin.

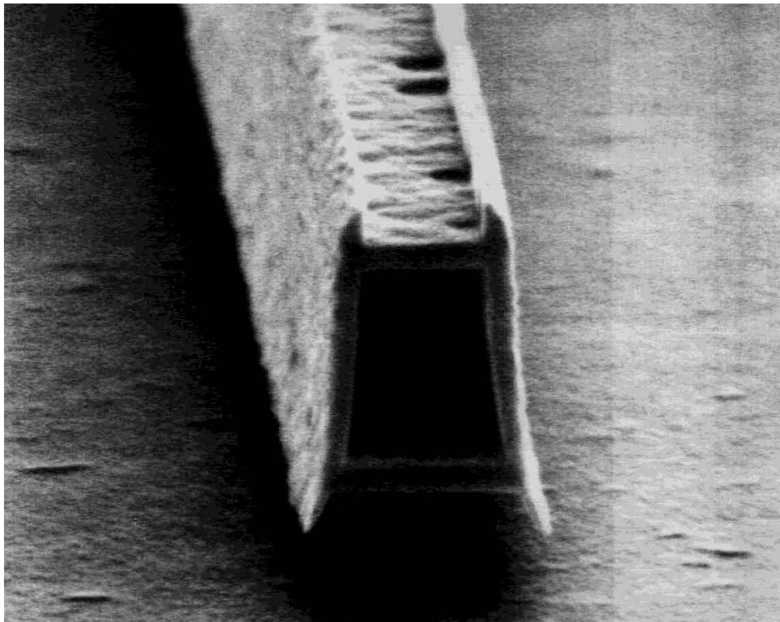
Reference: D.P. Siddons, E.D. Johnson and H. Guckel, "Precision Machining Using Hard X-rays," Synchrotron Radiation News, (7), No. 2, (1994) pp. 16-18.

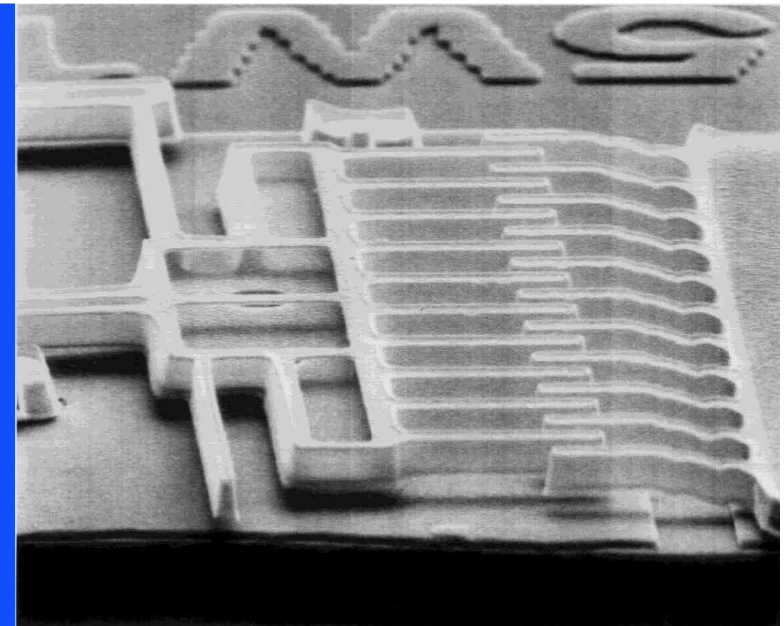
HOLLOW BEAMS IN POLYSILICON

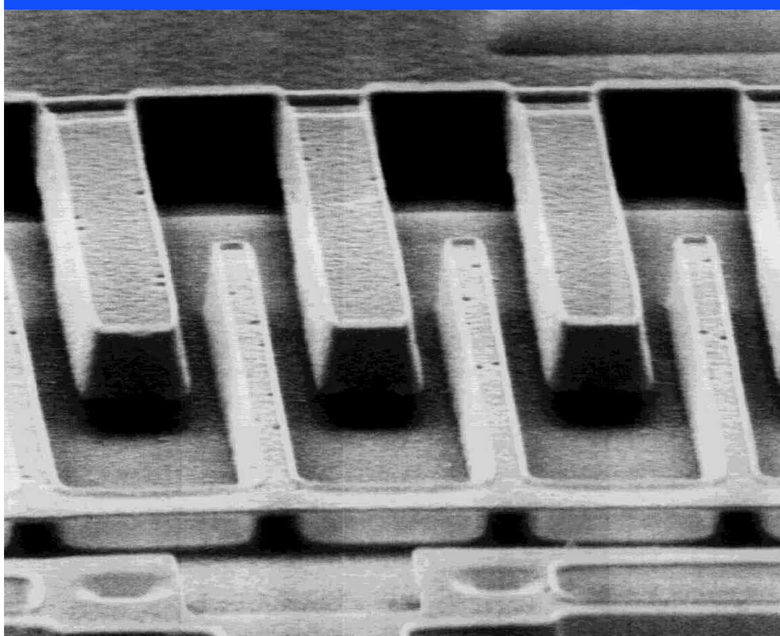


- **Hollow beams of polysilicon can be formed with higher stiffness to mass ratios than solid beams.**
- **A poly-Si sandwich is formed, followed by sidewall deposition using a blanket poly-Si layer.**
- **Access holes for HF etching are created and the structures are released.**

Reference: Judy, M. W., and Howe, R. T., "Polysilicon Hollow Beam Lateral Resonators," Proceedings of the IEEE Microelectromechanical Systems Conference, Fort Lauderdale, FL, Feb. 1993, pp. 265 - 271.



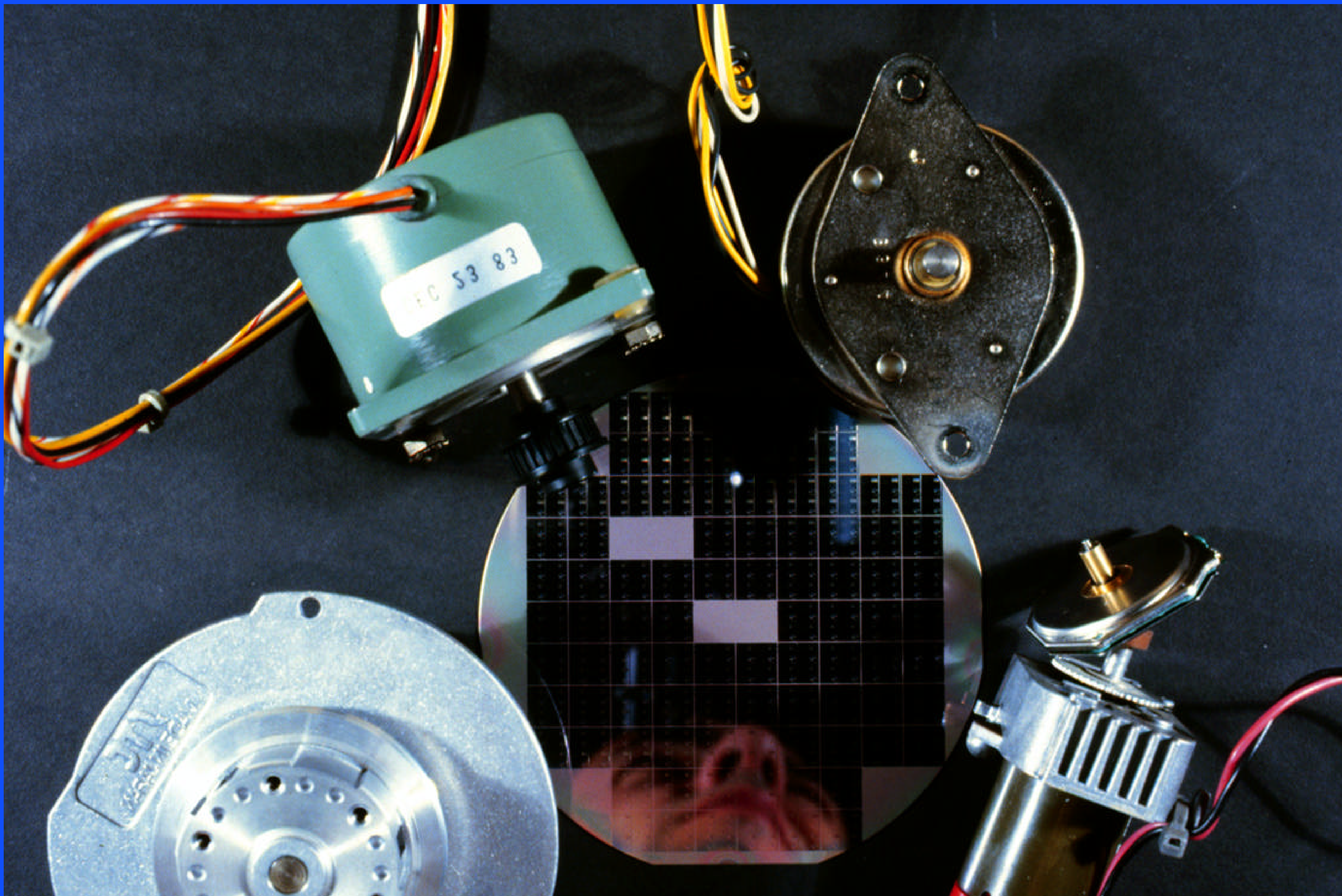




Courtesy Dr. M. Judy, Analog Devices, Inc.

ACTUATION IN MECHANICAL TRANSDUCERS

- There is no "perfect" actuation method.
- Electrostatic actuation can generate large forces using low power but is very nonlinear.
- Piezoelectric actuation provides quite linear (although small) displacements at high forces, but may require high voltages (but low power).
- Thermal expansion/bimorph actuators rely on differential thermal expansion of coupled materials and provides linear, moderate forces at high power levels.
- Thermopneumatic, shape memory alloy, vapor bubble, chemical and other actuation schemes are also possible on a micro scale.


EC 53 83

Type of Actuator	Stress (MPa)	Strain (%)	Strain Rate (Hz)	Power Density (W/kg)	Efficiency
Electrostatic (Macroscopic Composite)	0.04	> 10	> 1	> 10	> 20
Cardiac Muscle (Human)	0.1	> 40	4	> 100	> 35
Polymer (Polyacrylic Acid/Polyvinyl Alcohol)	0.3	> 40	0.1	> 5	30
Skeletal Muscle (Human)	0.35	> 40	5	> 100	> 35
Polymer (Polyaniline)	180	> 2	> 1	> 1000	> 30
Piezoelectric Polymer (PVDF)	3	0.1	> 1	> 100	< 1
Piezoelectric Ceramic	35	0.09	> 10	> 1000	> 30
Magnetostrictive (Terfenol-D)	70	0.2	1	> 1000	< 30
Shape Memory Alloy (NiTi Bulk Fiber)	> 200	> 5	3	> 1000	> 3

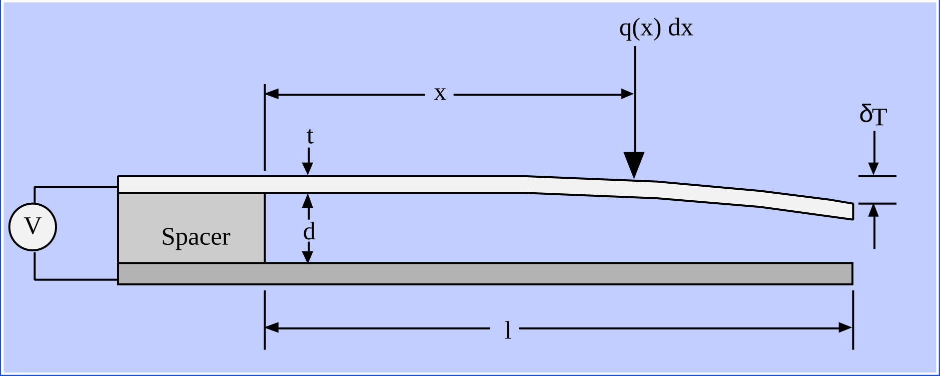
Reference: Hunter, I. W., and Lafontaine, S., "A Comparision of Muscle with Artificial Actuators," Proceedings of the 1992 Solid-State Sensor and Actuator Workshop, Hilton Head Island, South Carolina, June 22 - 25, 1992, pp. 178 - 185.

ACTUATOR PROPERTIES TO COMPARE

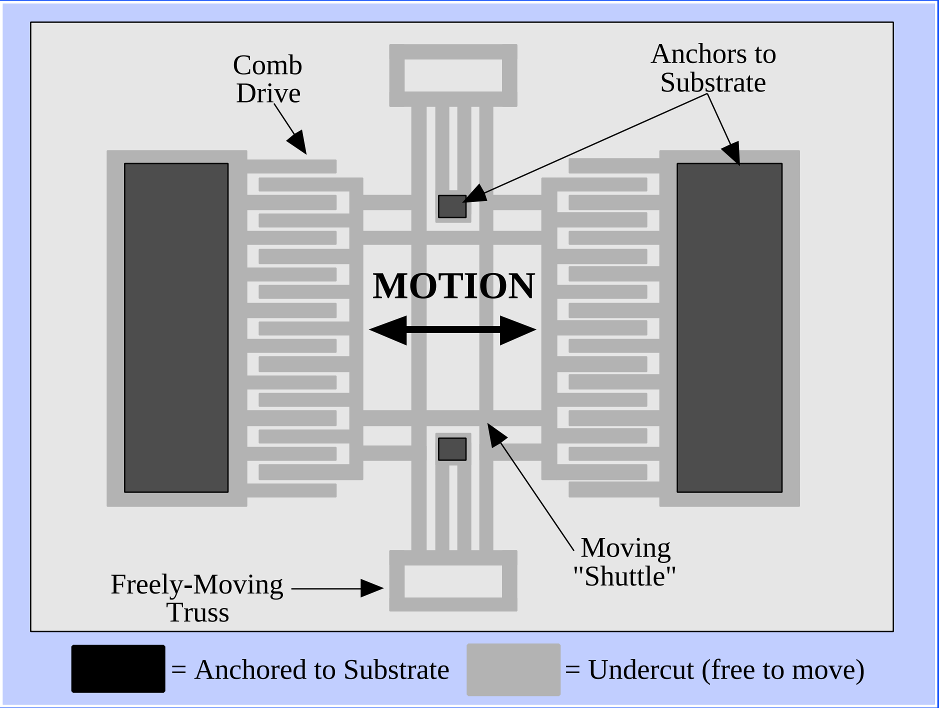
1) Power.
2) Mechanical efficiency.
3) Stress/Strain.
4) Robustness (i.e. resistantance to mechanical and environmental insults).
5) Speed.
6) Power-to-mass ratio.
7) Linearity.
8) Other?

ELECTROSTATIC ACTUATORS

- Electrostatic actuators are very common in micromachined systems due to their simplicity.
- They are highly nonlinear and may require high voltages.

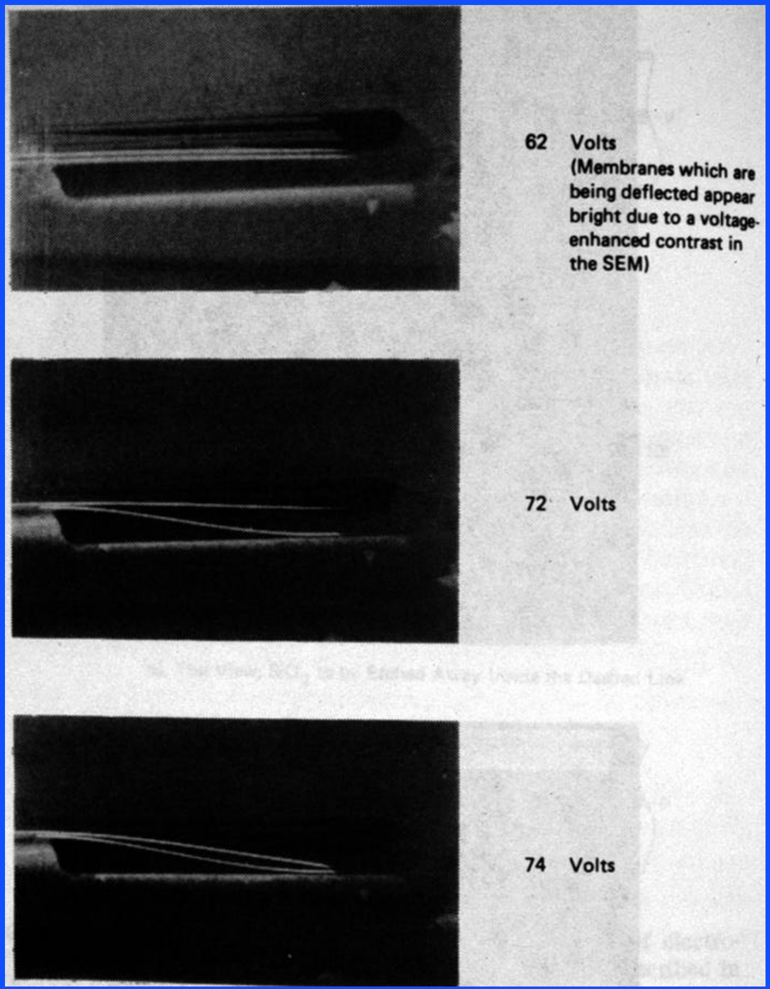


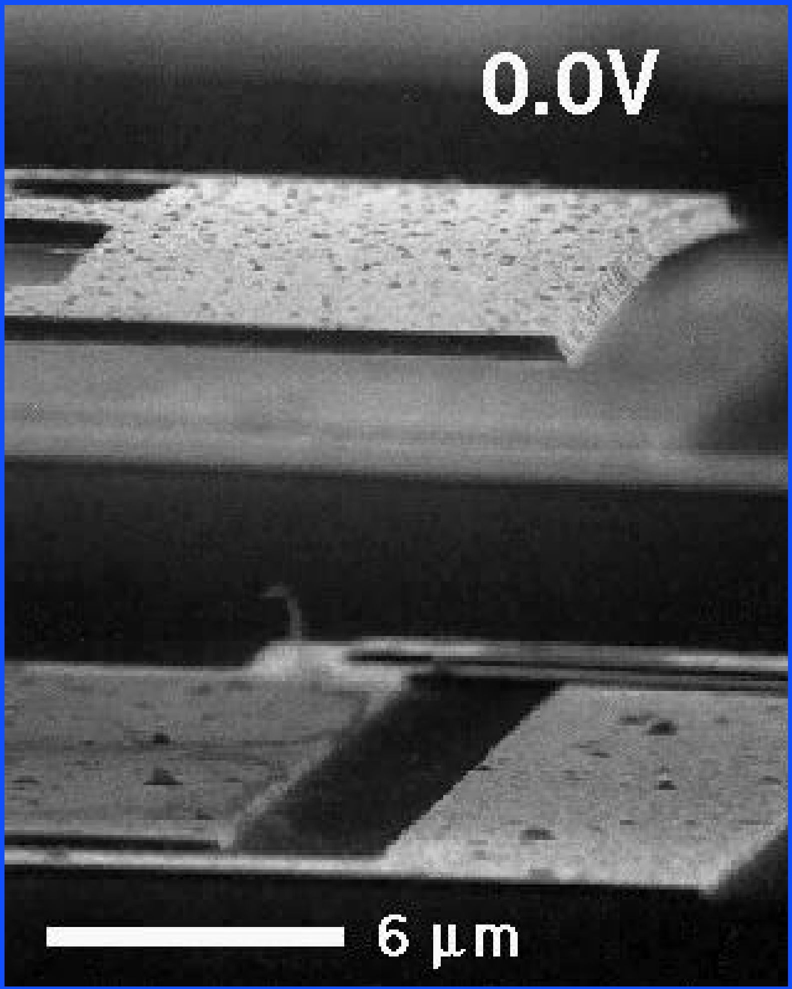
Reference: Petersen, K. E, "Dynamic Micromechanics on Silicon: Techniques and Devices," IEEE Transactions on Electron Devices, vol. ED-25, no. 10, Oct. 1978, pp. 1241 - 1250.



Reference: Judy, M. W., and Howe, R. T., "Polysilicon Hollow Beam Lateral Resonators," Proceedings of the IEEE Microelectromechanical Systems Conference, Fort Lauderdale, FL, Feb. 1993, pp. 265 - 271.

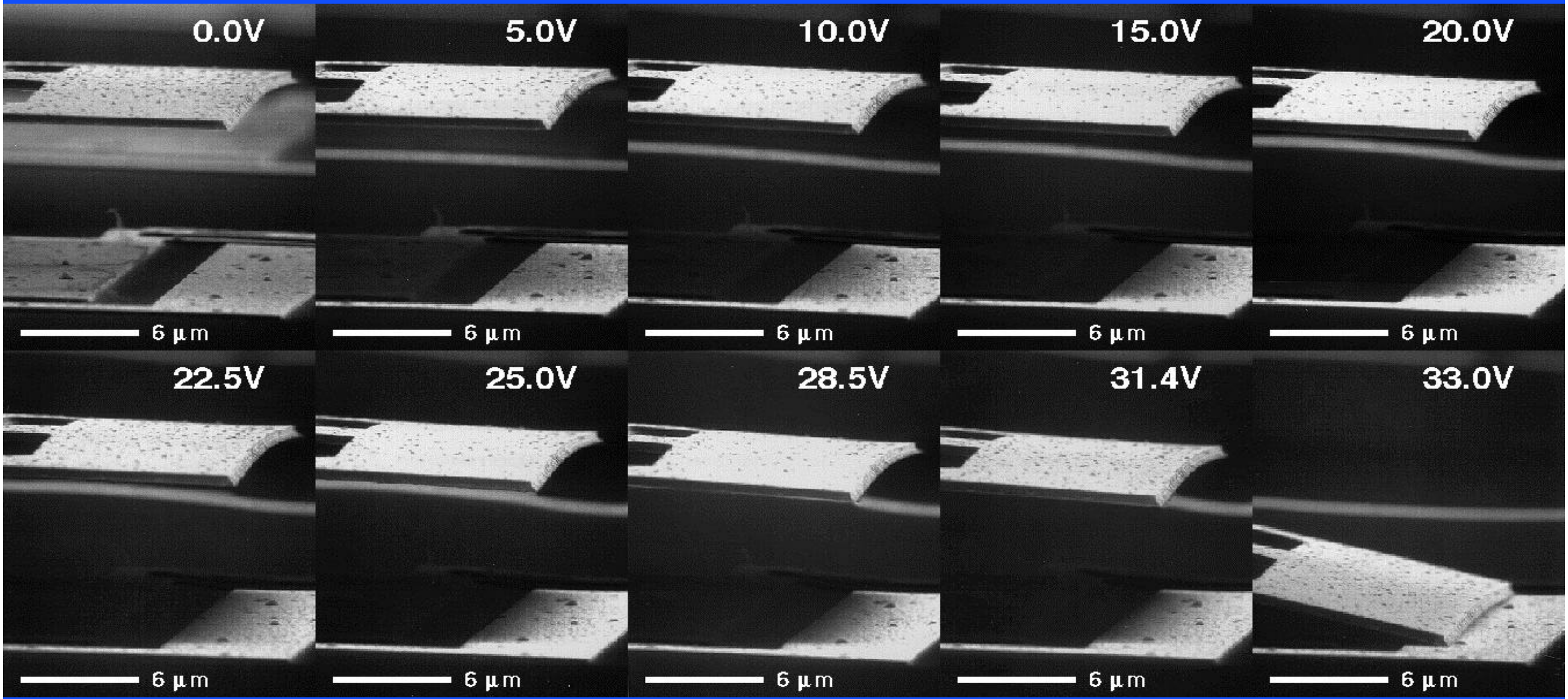
ELECTROSTATIC NONLINEARITY



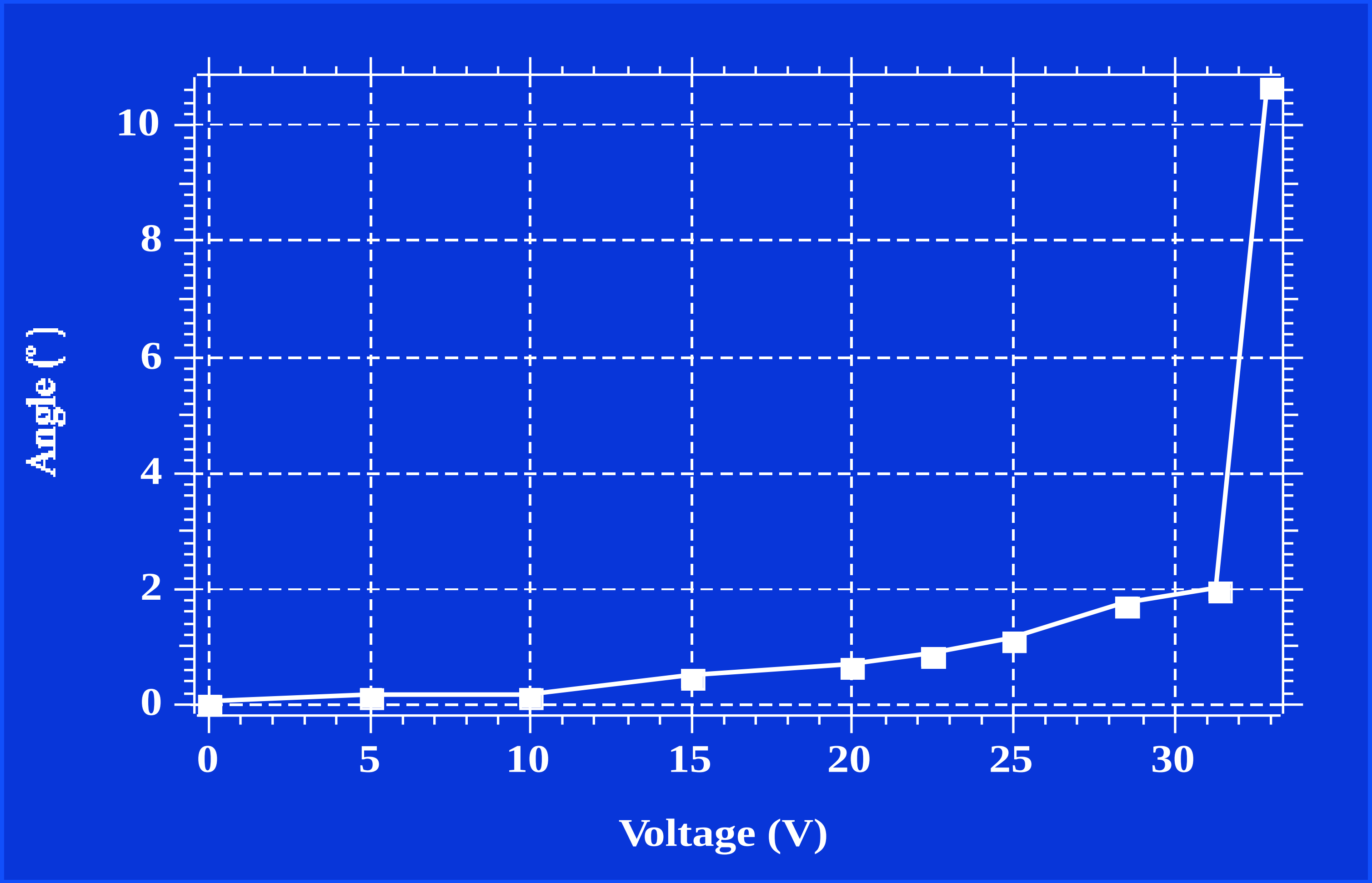


Source (left): Petersen, K. E, “Dynamic Micromechanics on Silicon: Techniques and Devices,” IEEE Transactions on Electron Devices, vol. ED-25, no. 10, Oct. 1978, pp. 1241 - 1250.

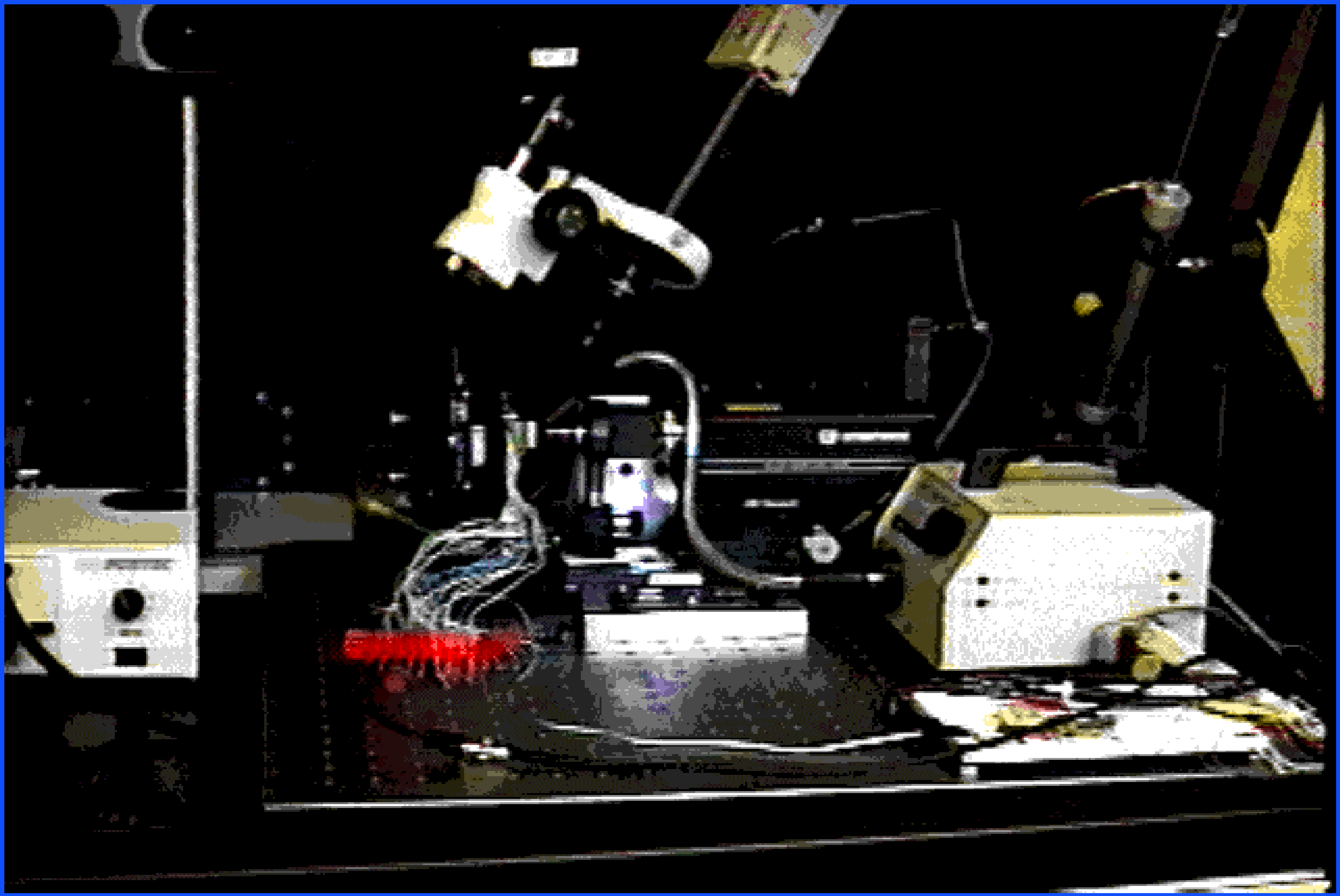
SEM ACTUATION STUDIES



ANGLE VS. VOLTAGE - SEM

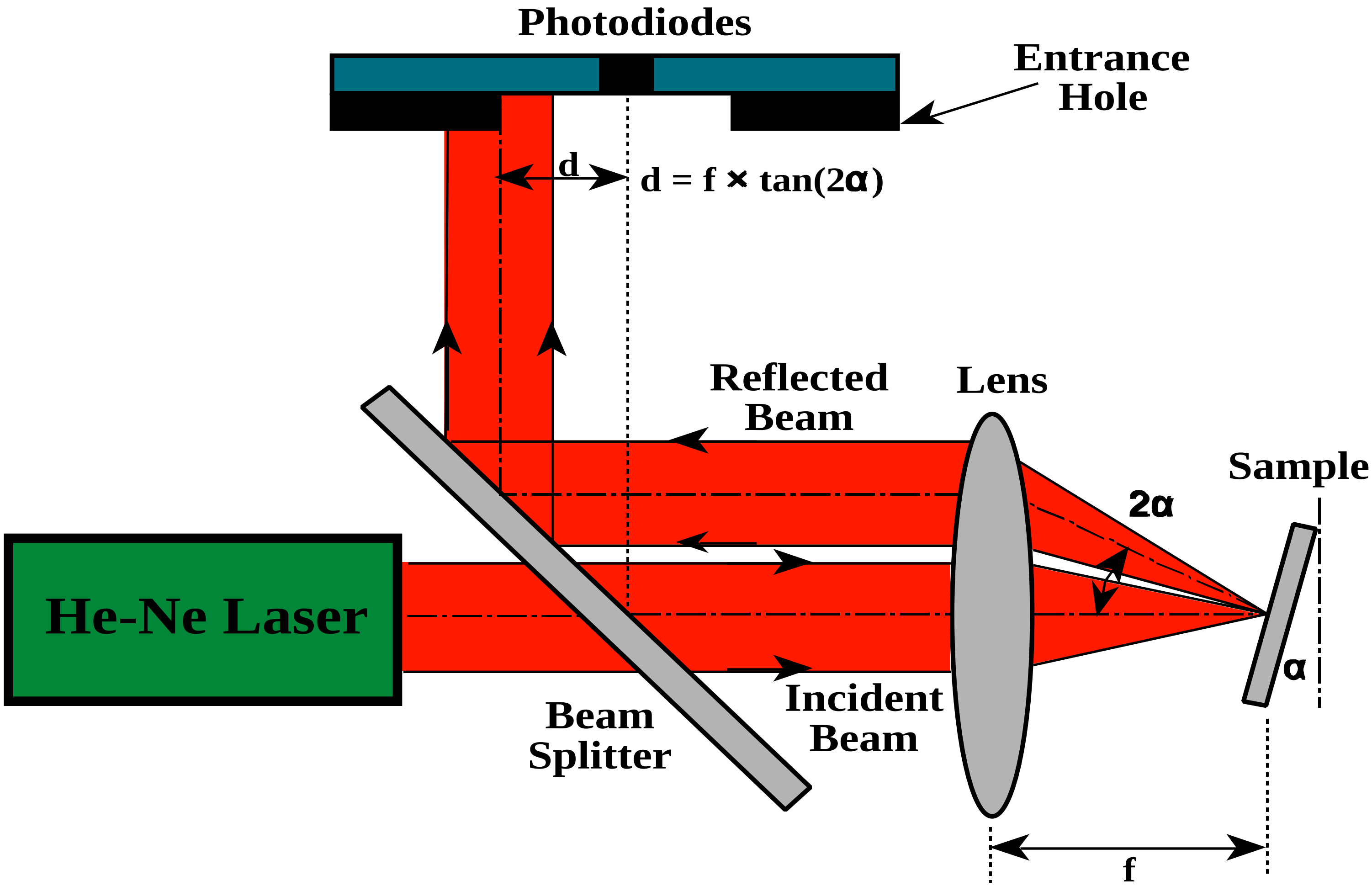


REAL-TIME OPTICAL DEFLECTION MEASUREMENT SYSTEM

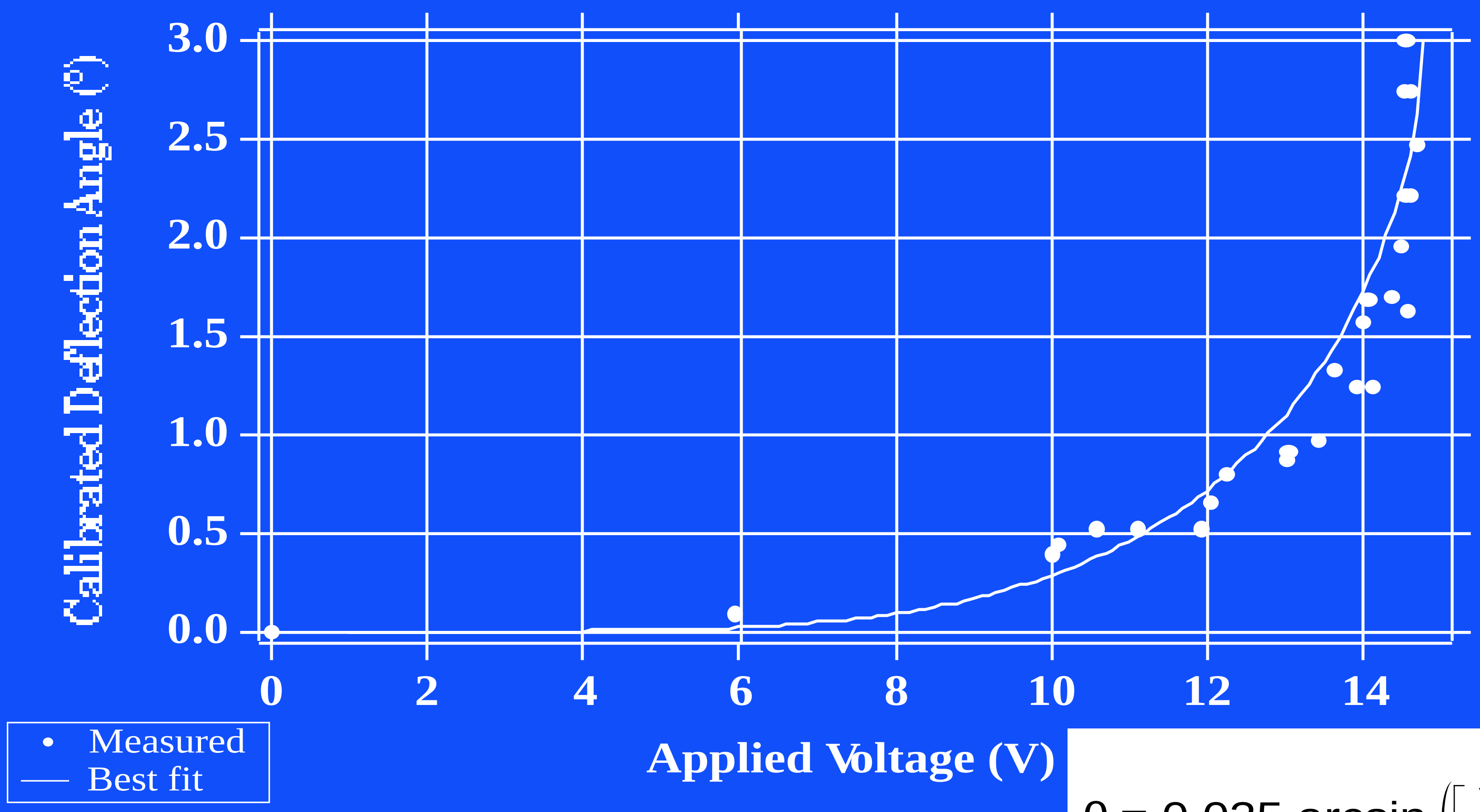


Reference: Honer, K. A., Maluf, N. I., Martinez, E., and Kovacs, G. T. A., "A High-Resolution Laser-Based Deflection Measurement System for Characterizing Aluminum Electrostatic Actuators," Digest of Technical Papers from Transducers '95/Eurosensors IX, Vol. 1, June 25 - 29, 1995, Stockholm, Sweden, pp. 308 - 311.

OPTICAL DEFLECTION MEASUREMENT

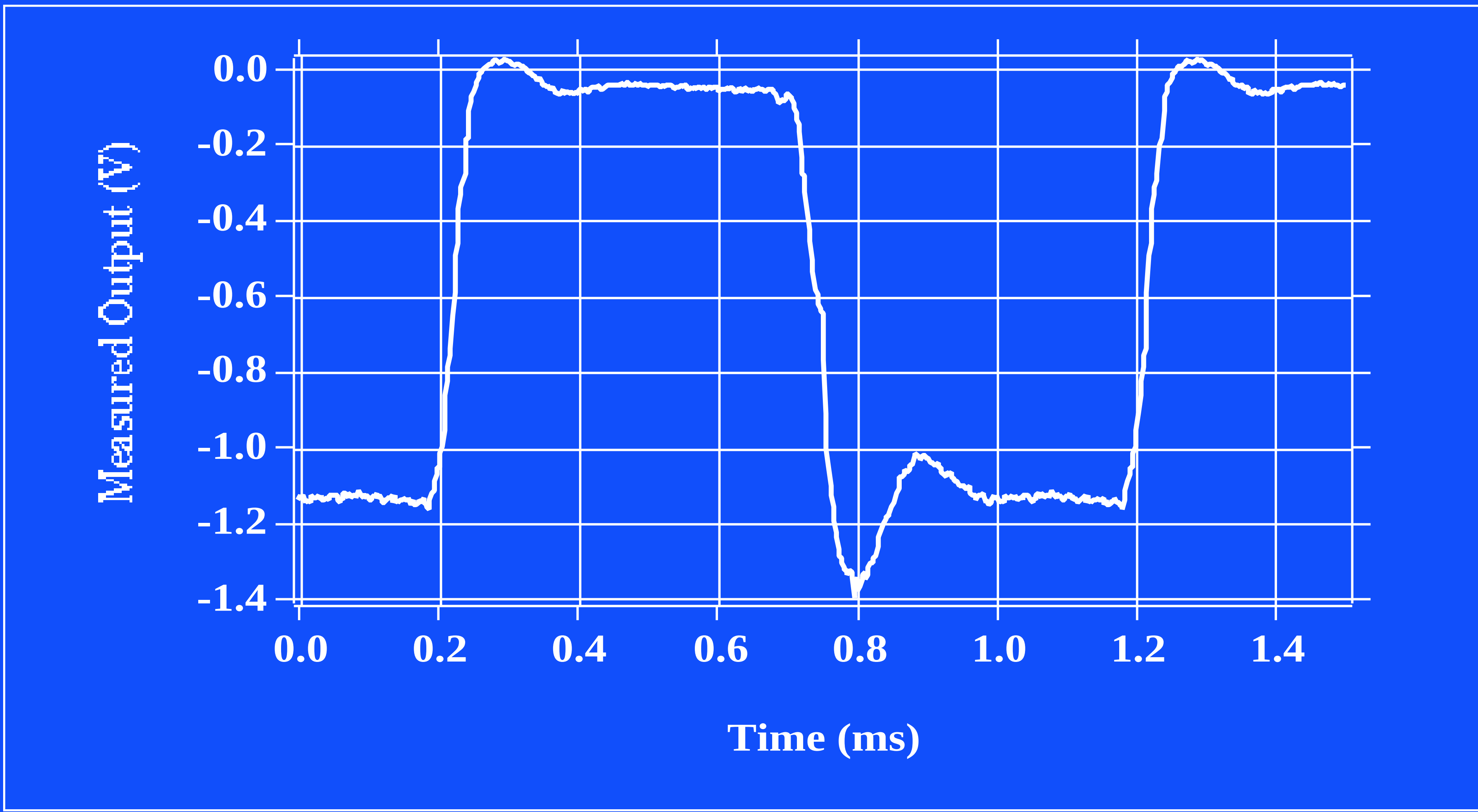


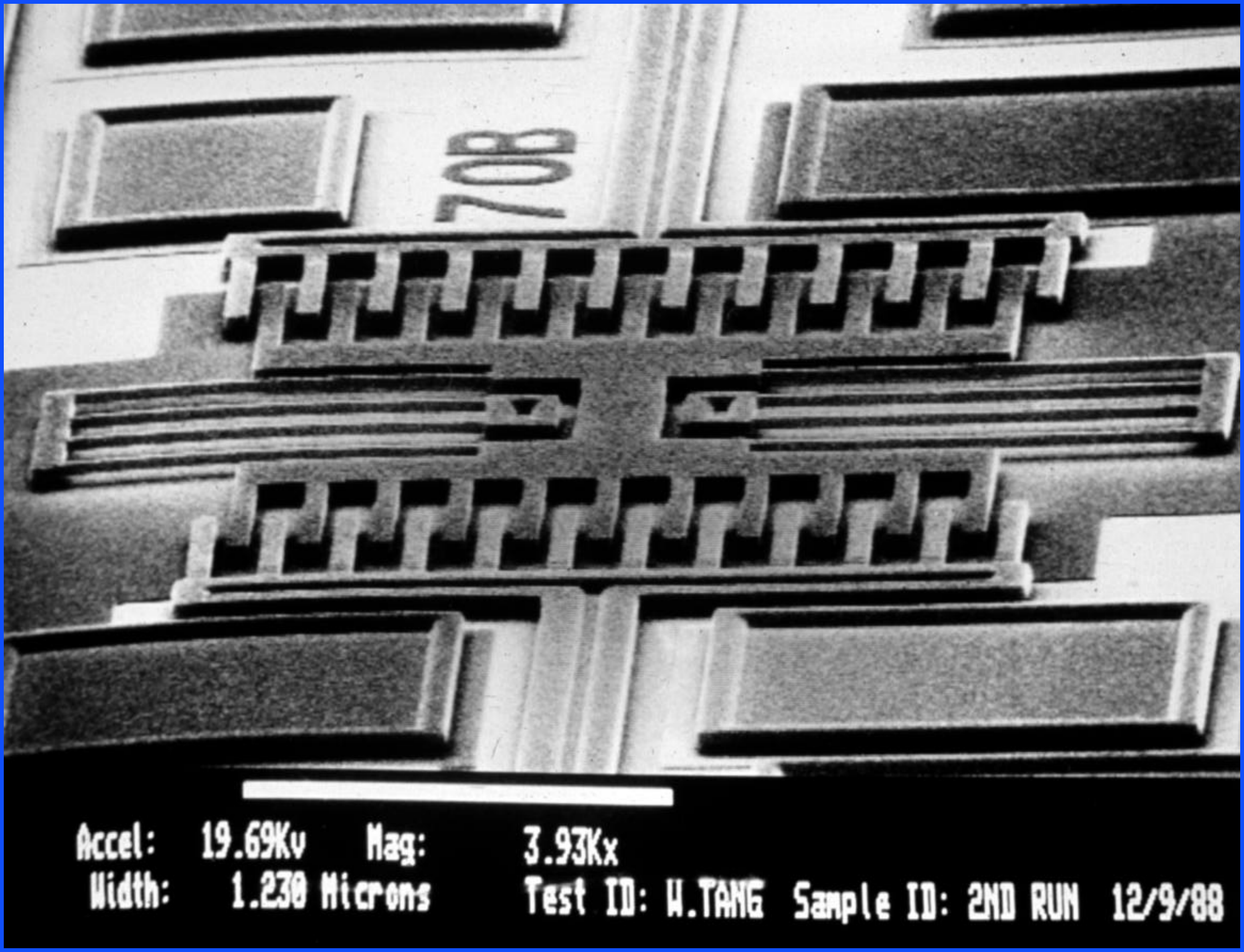
MEASURED θ - V CURVE



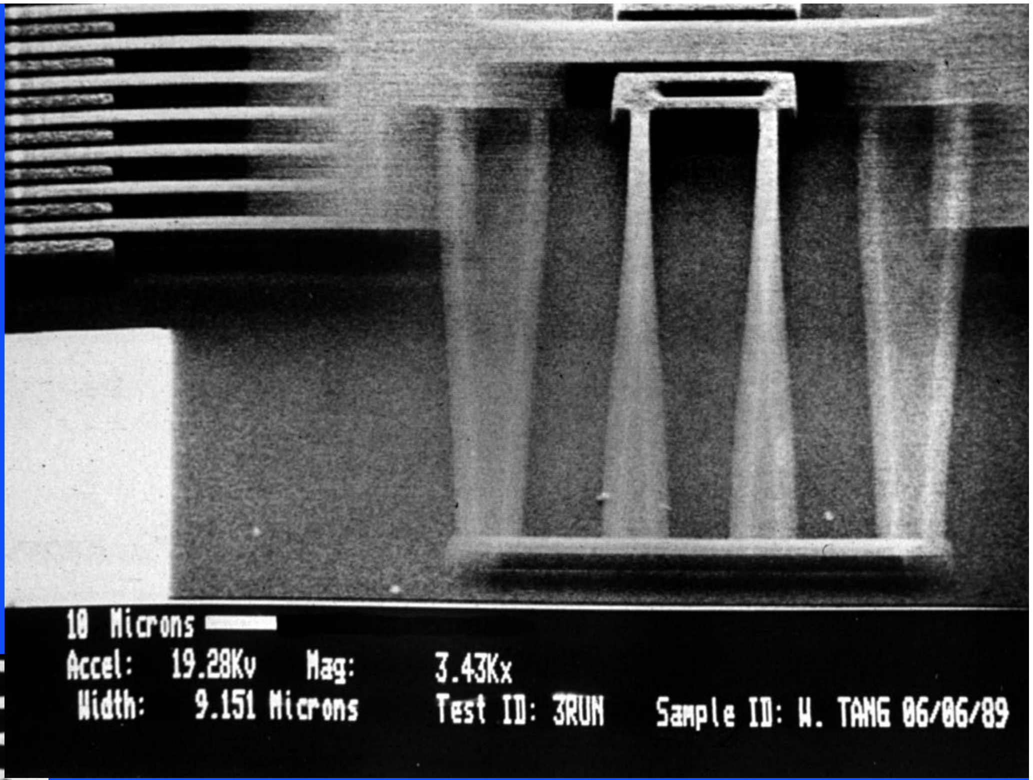
$$\theta = 0.035 \arcsin\left(\left[\frac{V}{15}\right]^4\right)$$

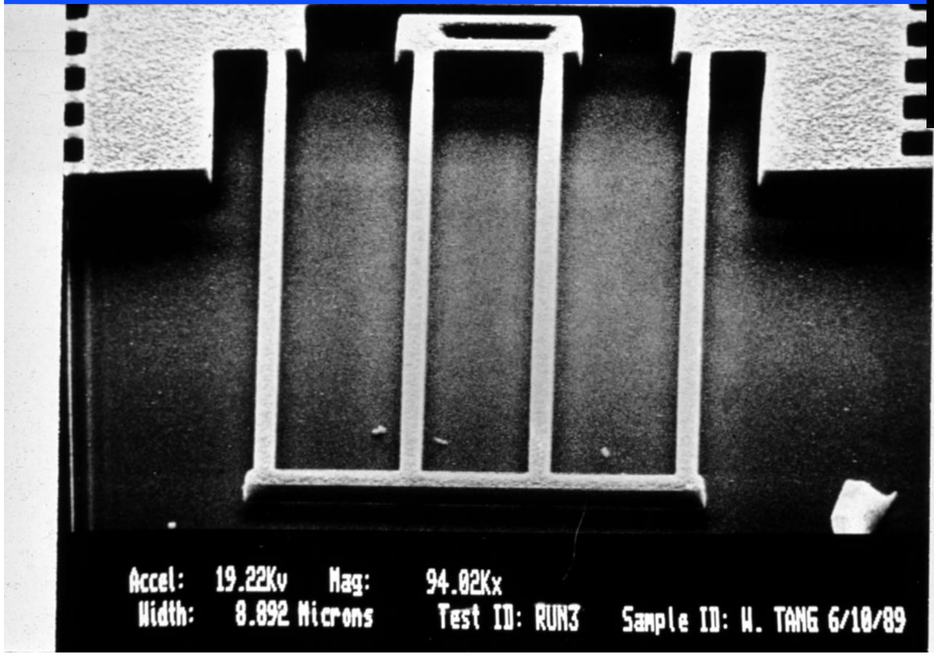
MEASURED TIME-DOMAIN RESPONSE





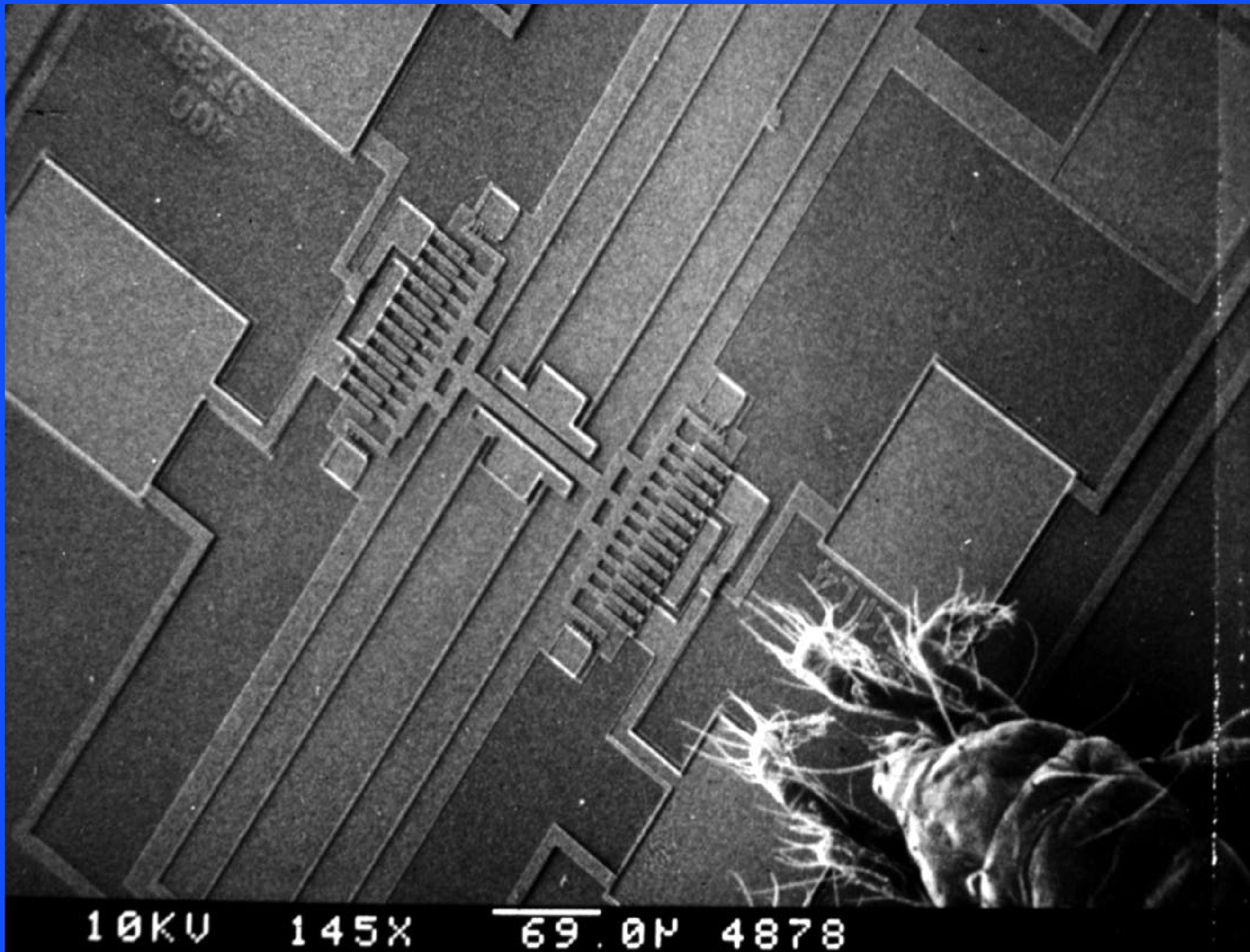
Source: Tang, W. C., Nguyen, H., Judy, M. W., and Howe, R. T., "Electrostatic-Comb Drive of Lateral Polysilicon Resonators," Sensors and Actuators, vol. A21, nos. 1 - 3, Feb. 1990, pp. 328 - 331. Courtesy Prof. R. Howe, U.C. Berkeley.





Source: Tang, W. C., Nguyen, H., Judy, M. W., and Howe, R. T., "Electrostatic-Comb Drive of Lateral Polysilicon Resonators," Sensors and Actuators, vol. A21, nos. 1 - 3, Feb. 1990, pp. 328 - 331.

Courtesy Prof. R. Howe, U.C. Berkeley.



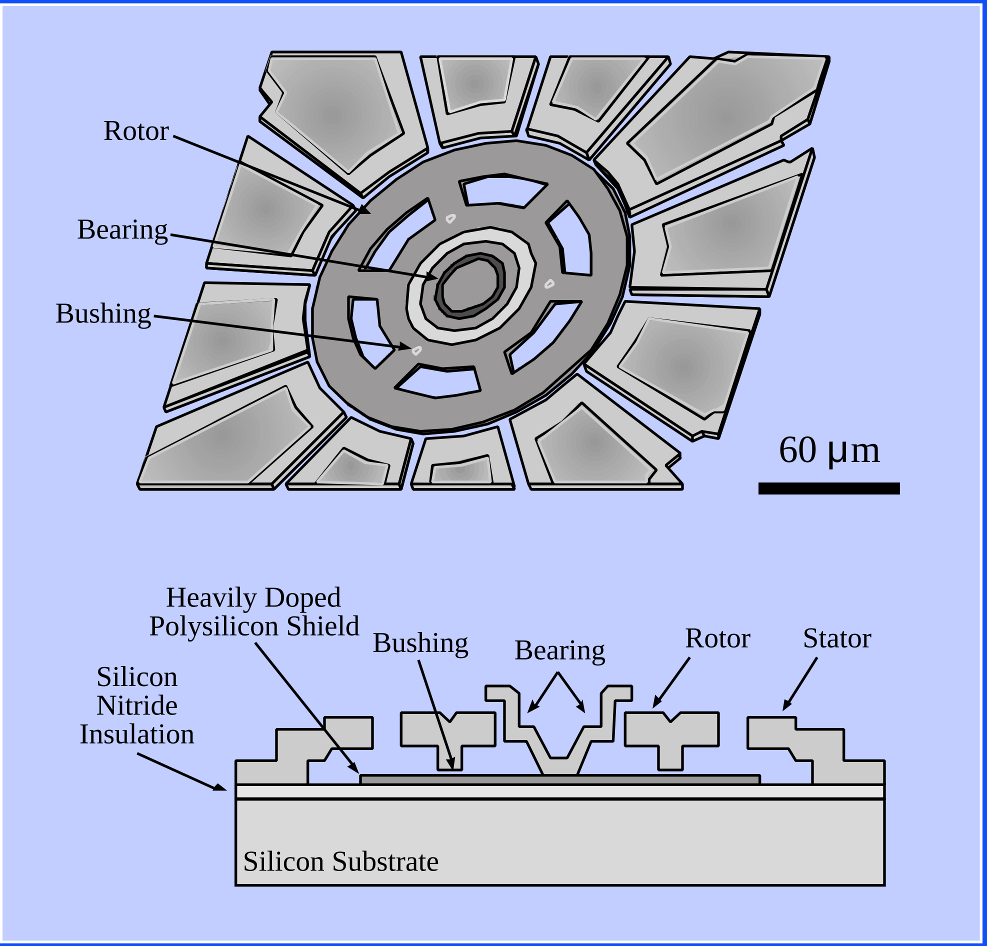
Courtesy Prof. R. Howe, U.C. Berkeley.

ELECTROSTATIC MICROMOTORS

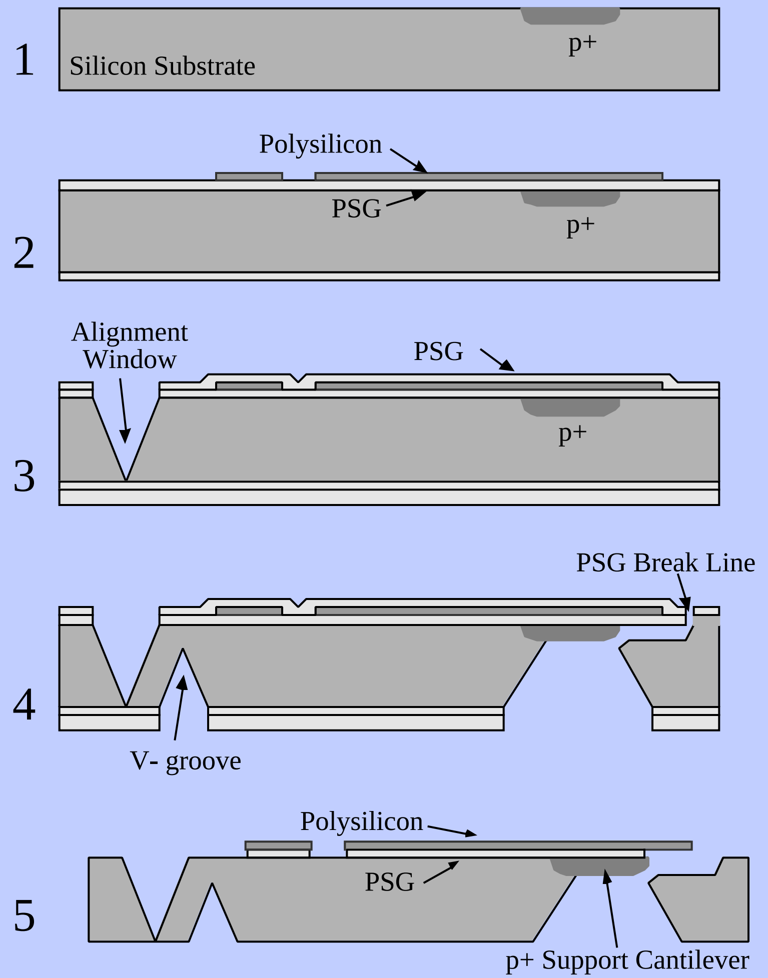
- Despite initial enthusiasm, these devices have not emerged in any products after more than a decade.
- Rotary motors have thus far had limited lifetimes, very high speeds, and limited torques.
- Mehregany, et al., (Case Western) have applied them to optical scanning, and optical applications may be the most practical since the motors only have to move themselves.
- Several groups have also applied linear micromotors ("steppers") to positioning optical components.

ELECTROSTATIC MICROMOTORS

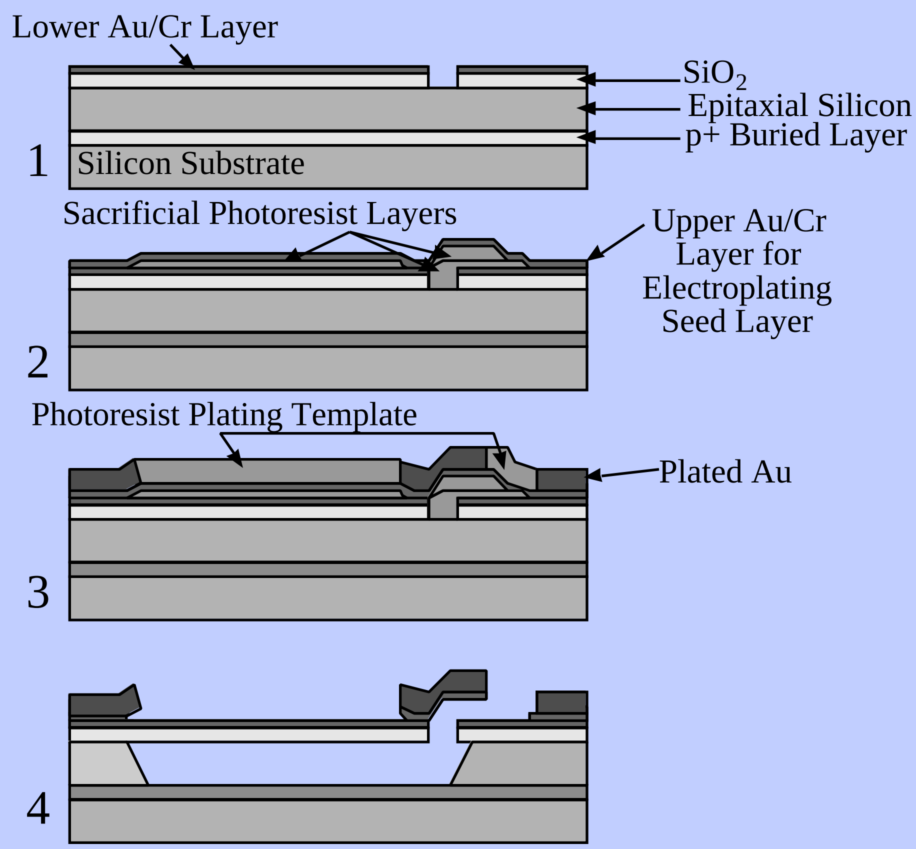
Source (SEM): Mehregany, M., Bart, S. F., Tavrow, L. S., Lang, J. H., Senturia, S. D., and Schlecht, M. F., "A Study of Three Microfabricated Variable-Capacitance Micromotors," Sensors and Actuators, vol. A21, nos. 1 - 3, Feb. 1990, pp. 173 - 179.



OTHER ELECTROSTATIC ACTUATORS



Reference: Kim, C.-J., Pisano, A. P., and Muller, R. S., "Silicon-Processed Overhanging Microgripper." Journal Of Microelectromechanical Systems, vol. 1, no. 1, Mar. 1992, pp. 31 - 36.

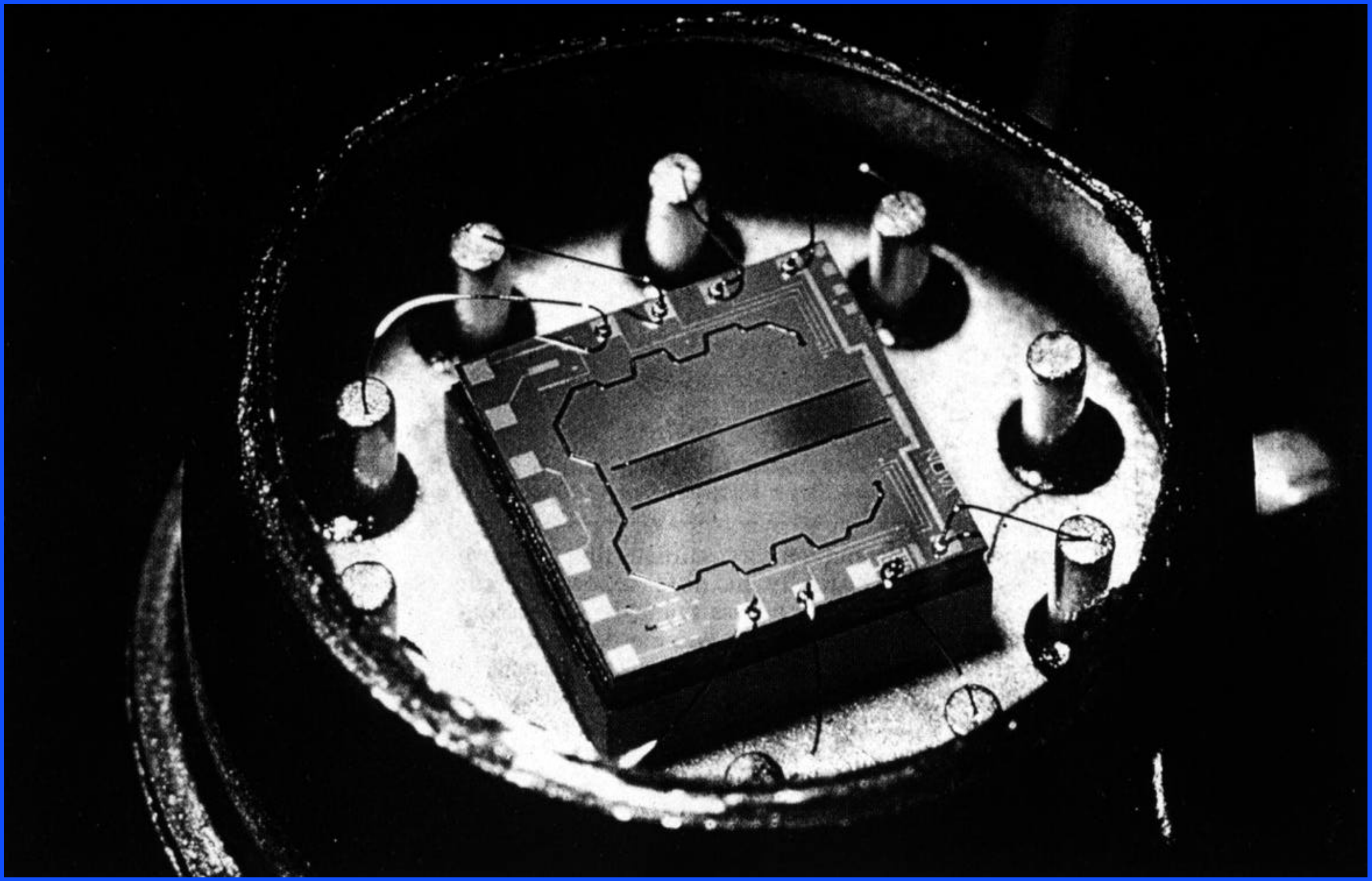


Reference: Petersen, K. E., "Silicon as a Mechanical Material," Proceedings of the IEEE, vol. 70, no. 5, May, 1982, pp. 420 - 457.

THERMAL ACTUATORS

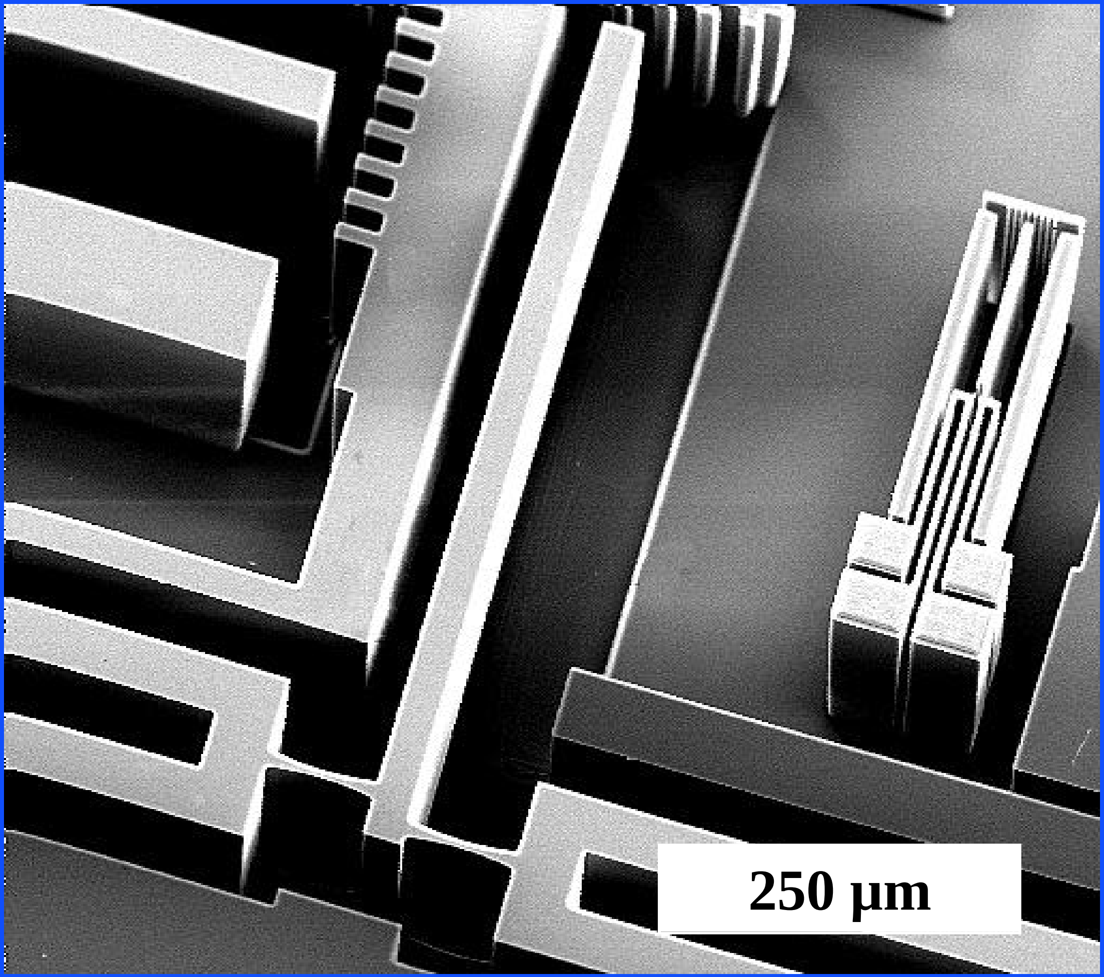
- They require high power, but can generate large forces in a linear fashion (proportional to dissipated power).
- They can be driven using embedded thin film heaters, optically, or using dielectric loss heating.
- Simple “monomorph” devices make use of linear expansion of beams.
- Bimorph devices make use of differential thermal expansion of two bonded layers.
- Phase-change devices make use of bubble formation.

THERMAL SELF-TEST IN ACCELEROMETER



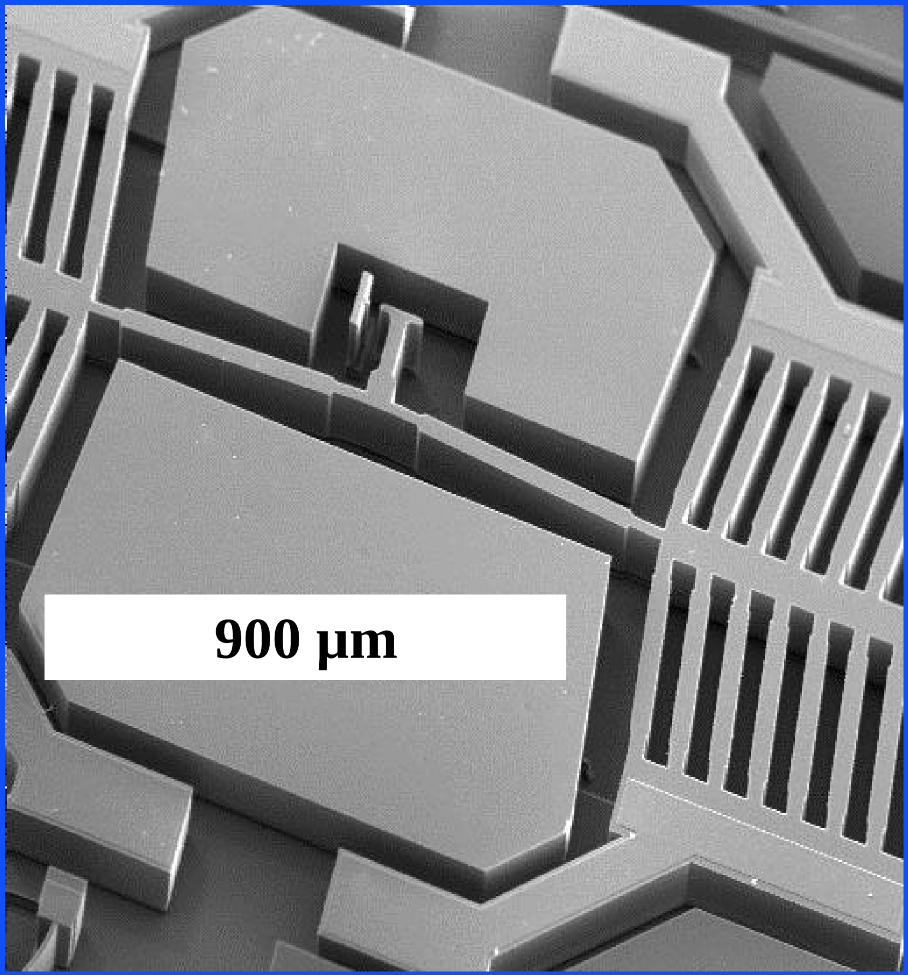
Courtesy Lucas NovaSensor.

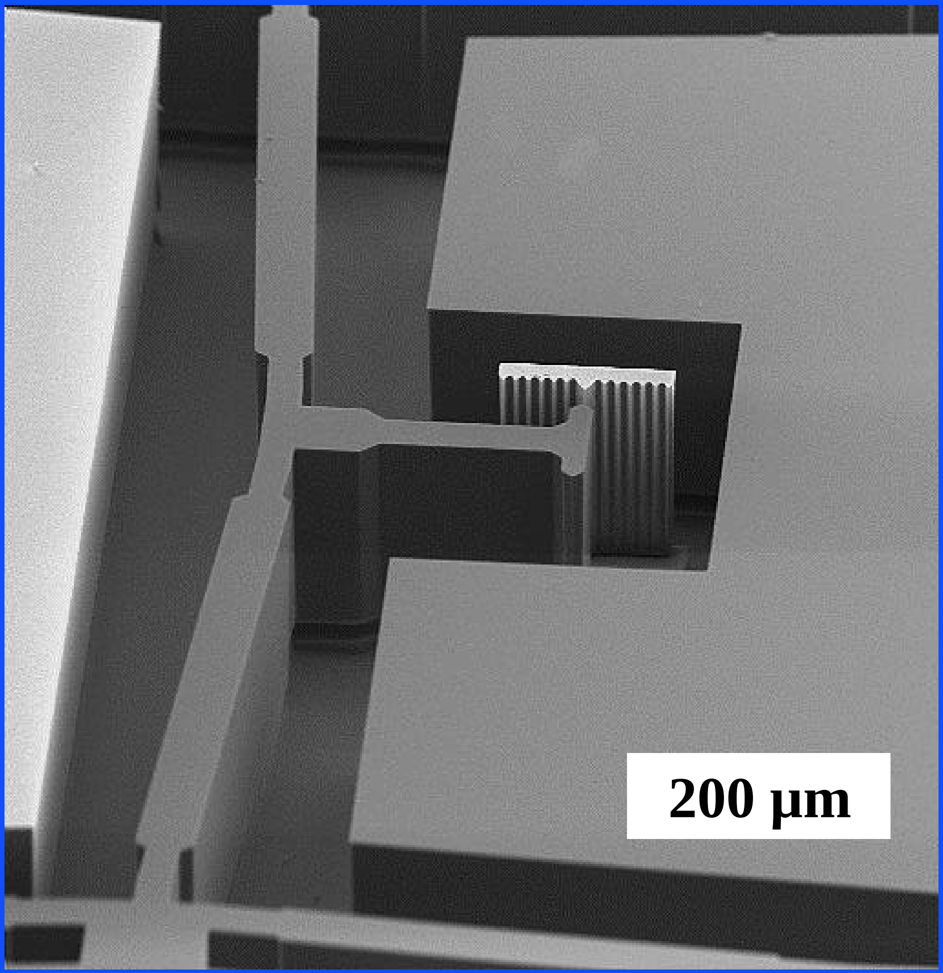
SFB/DRIE THERMAL ACTUATORS



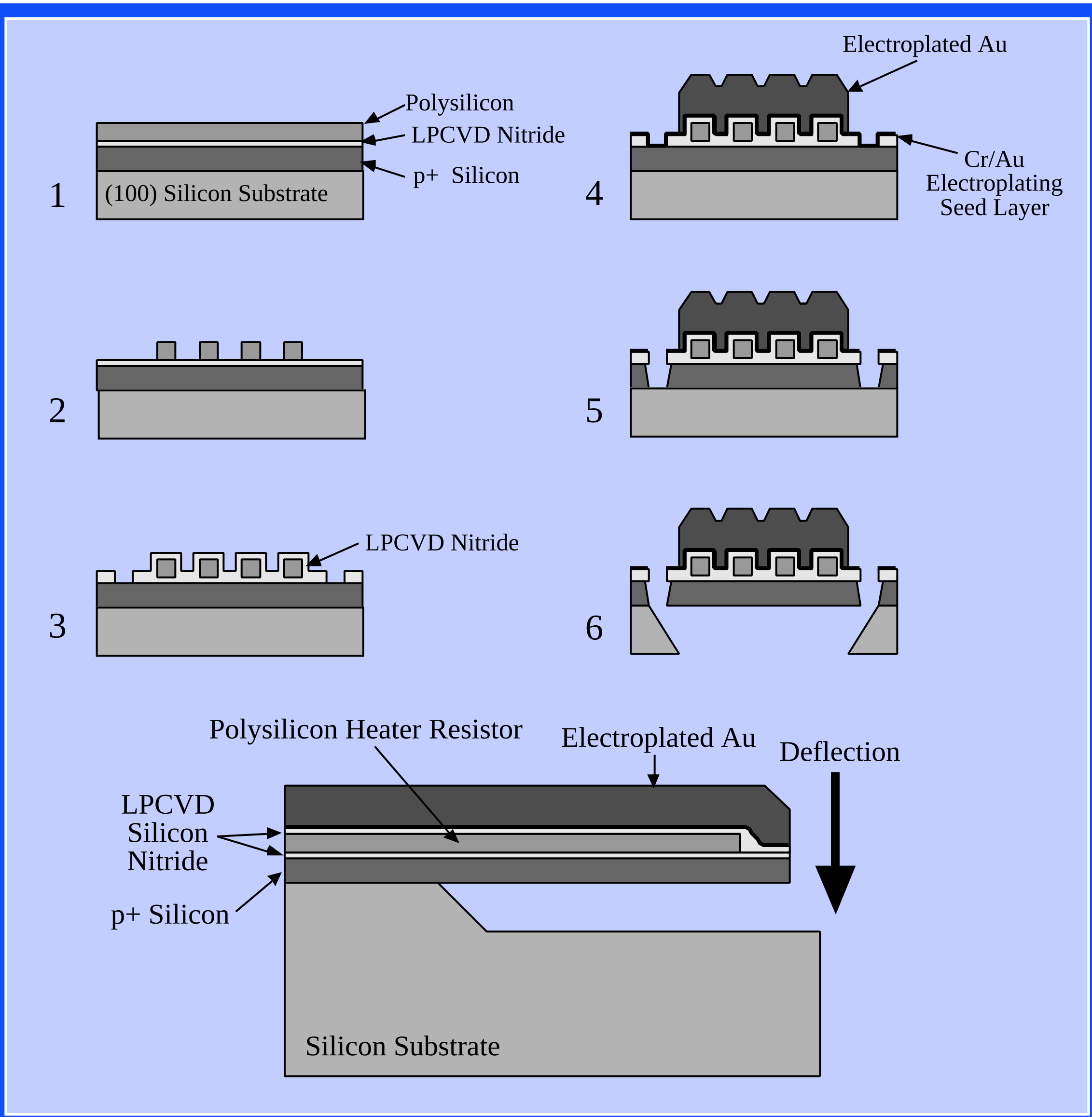
- 100 µm tall
- 10 µm wide tethers
- 100 µm motion

Courtesy Lucas NovaSensor.



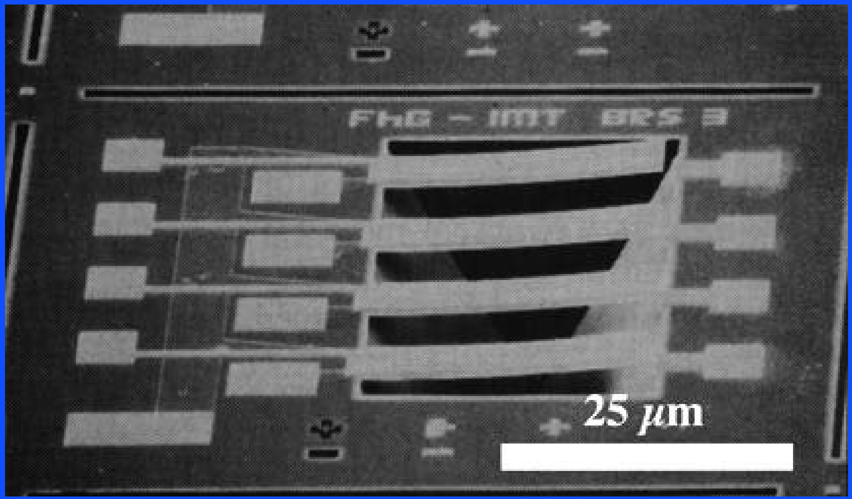


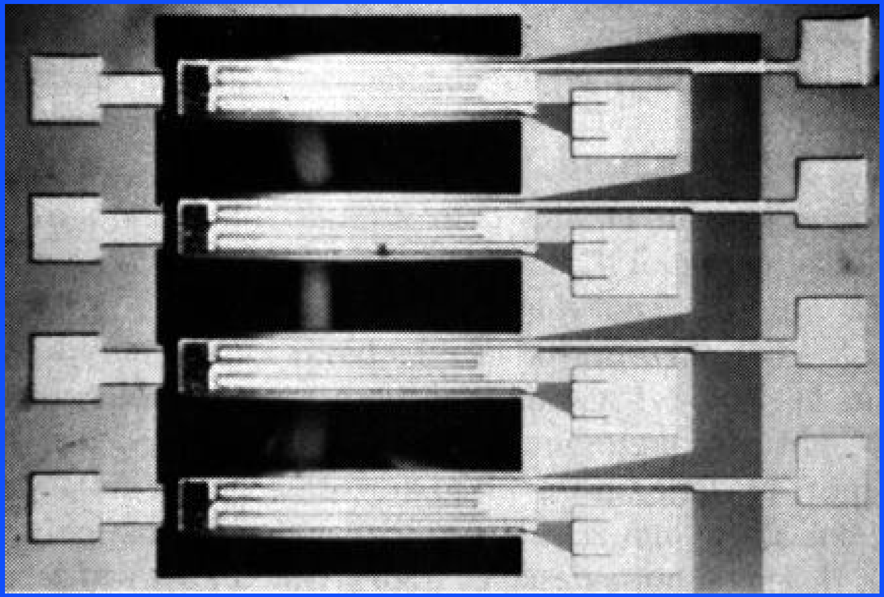
Courtesy Lucas NovaSensor.



Reference: Riethmüller, W. and Benecke, W., "Thermally Excited Silicon Microactuators," IEEE Transactions on Electron Devices, vol. 35, no. 6, June 1988, pp. 758 - 763.

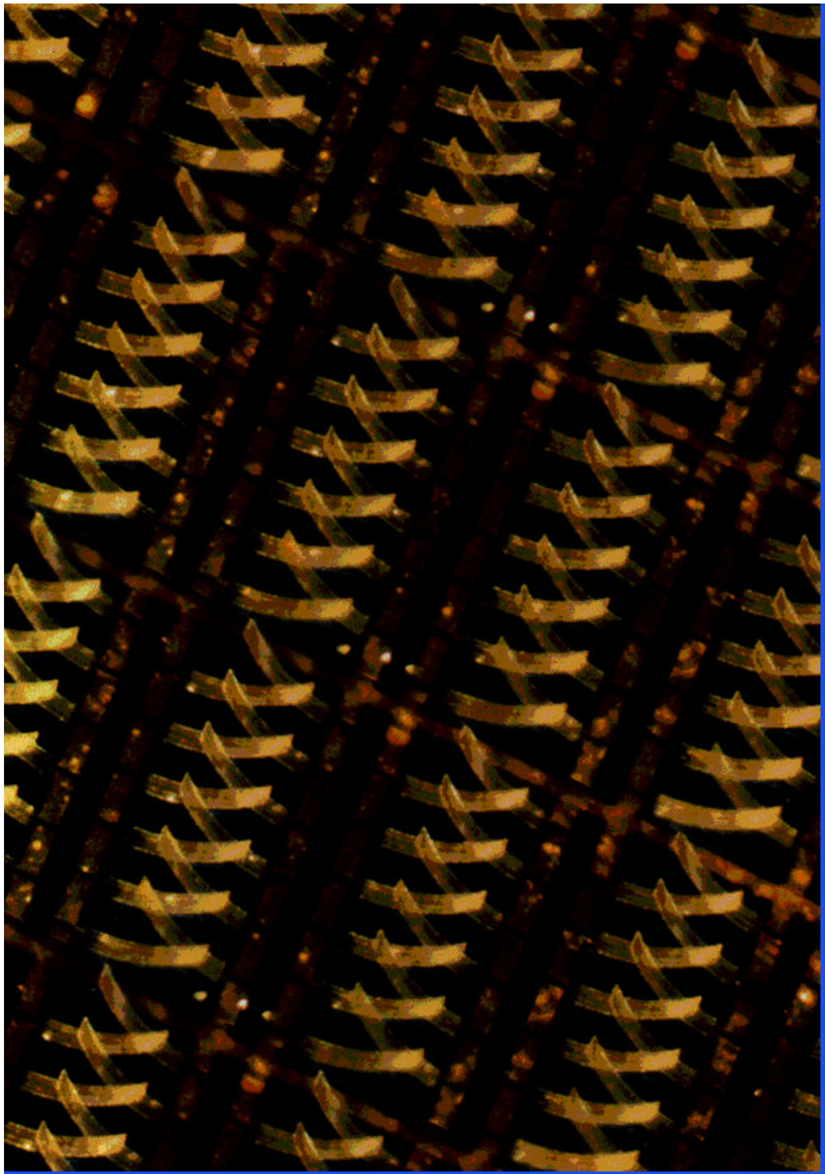
THERMAL BIMORPHS

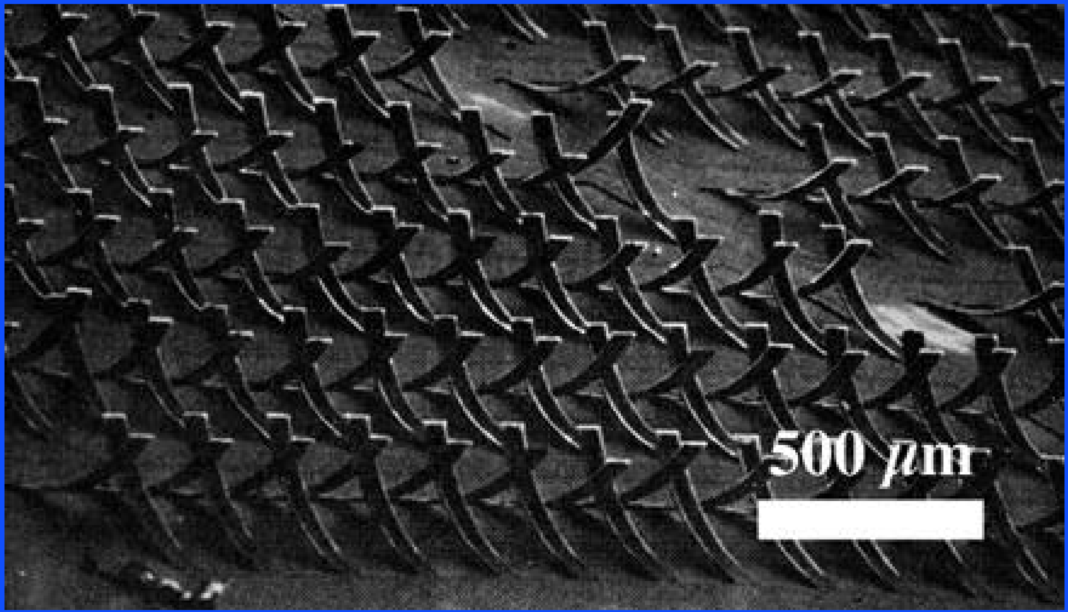




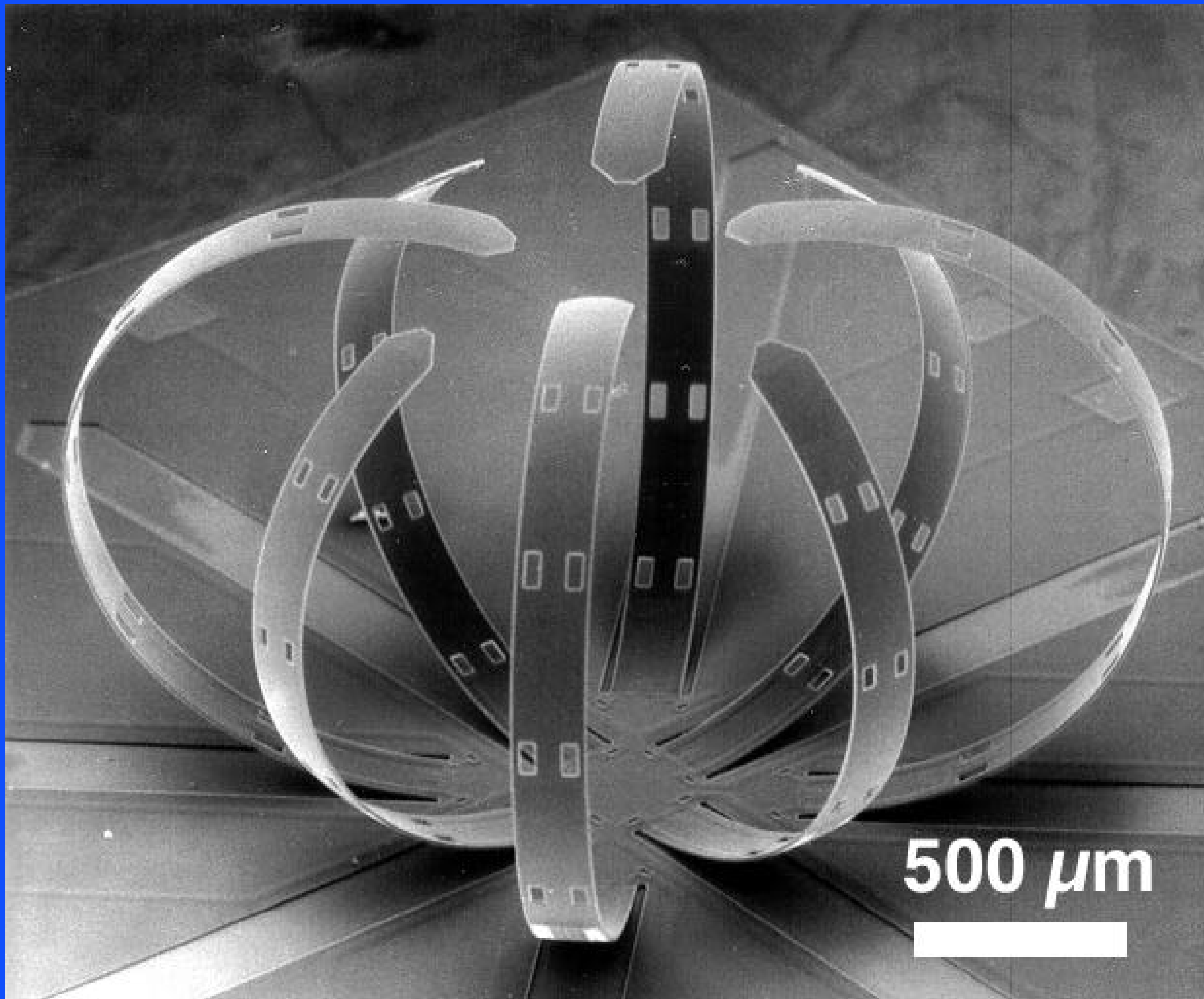
Source: Riethmüller, W. and Benecke, W., “Thermally Excited Silicon Microactuators,” IEEE Transactions on Electron Devices, vol. 35, no. 6, June 1988, pp. 758 - 763.

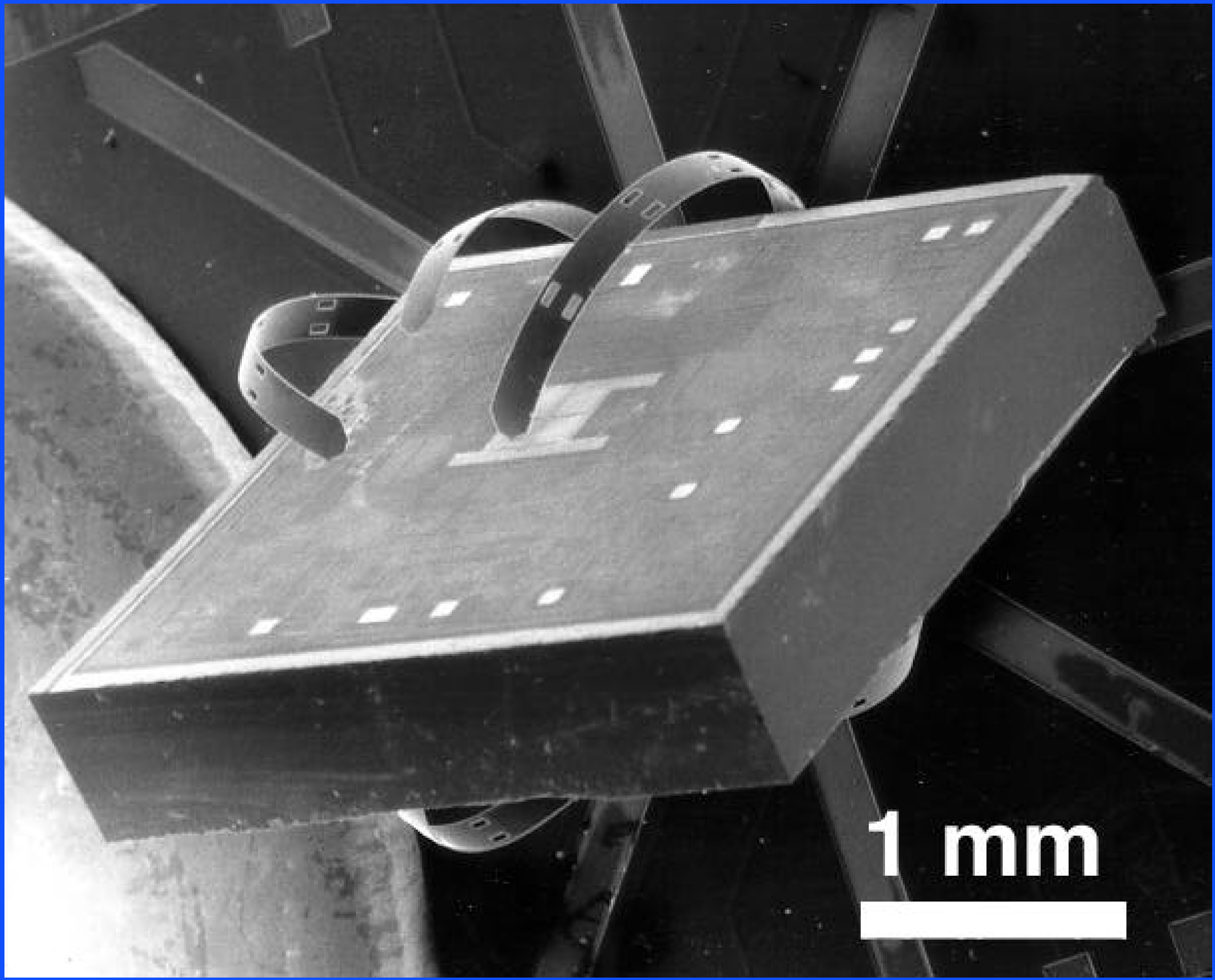
BIMORPH CILIARY ACTUATORS



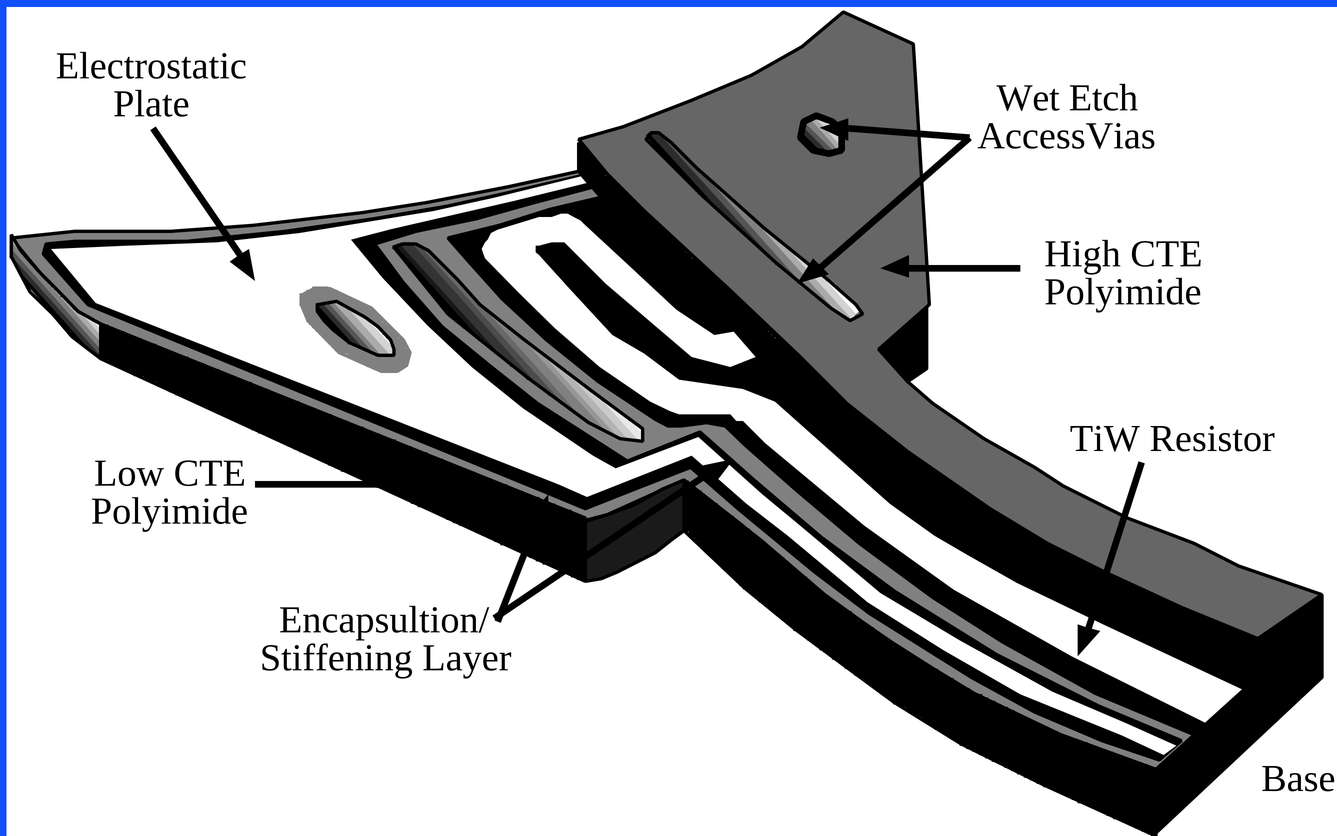


Courtesy Prof. H. Fujita, University of Tokyo.


500 μm

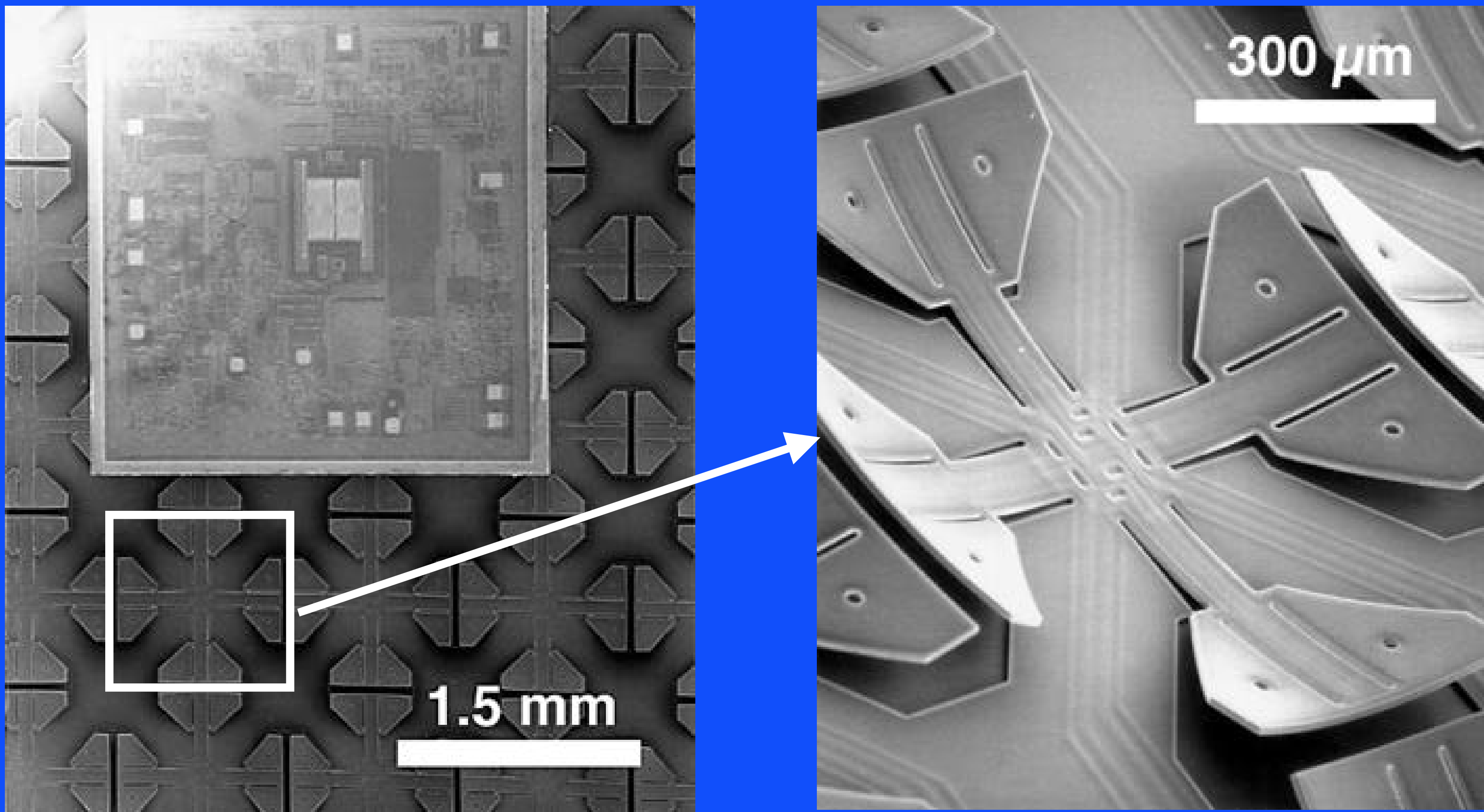

1 mm

CILIARY ACTUATOR ARRAYS

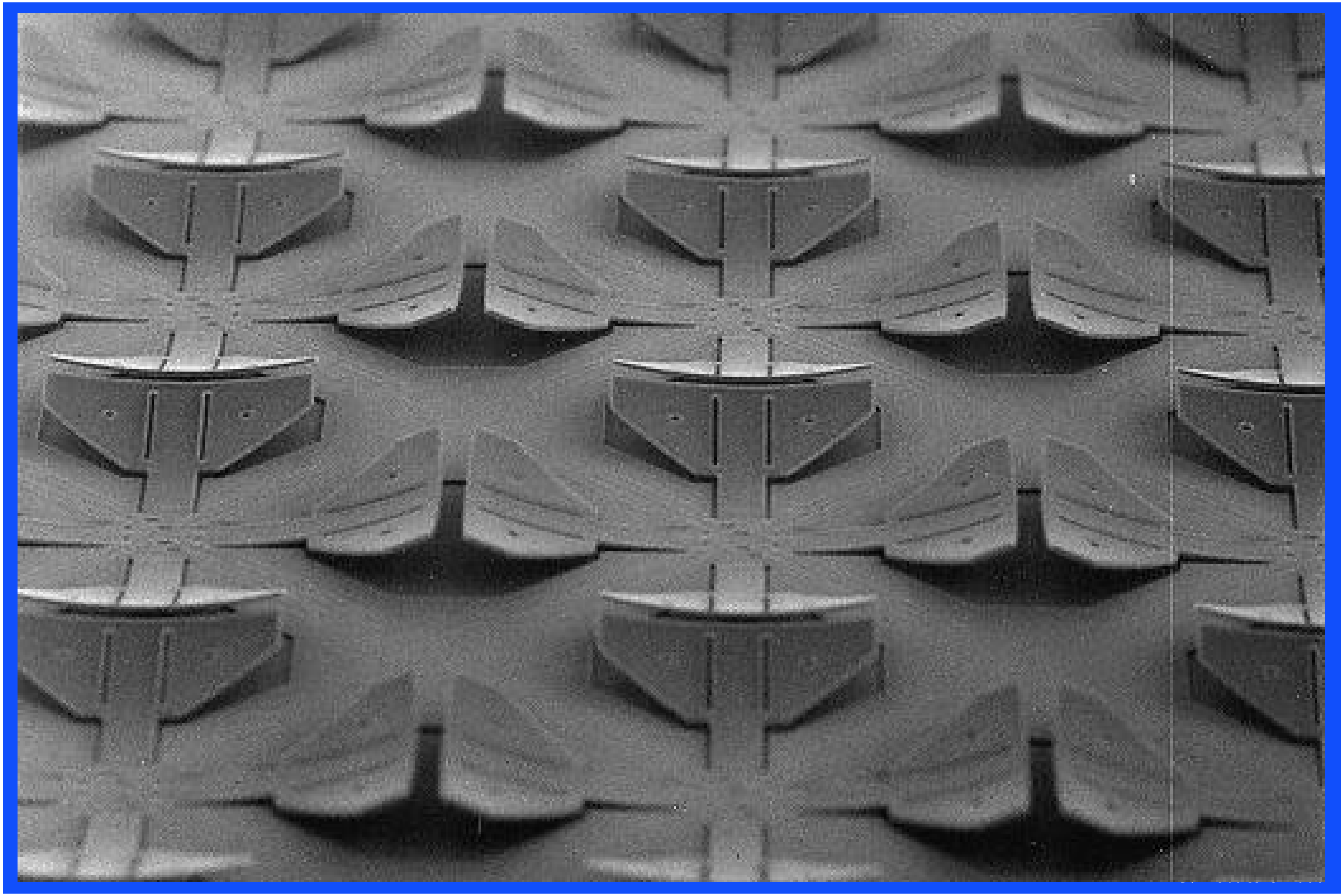


Reference: Suh, J. W., Glander, S. F., Darling, R. B., Storment, C. W., and Kovacs, G. T. A., "Combined Organic Thermal and Electrostatic Omnidirectional Ciliary Microactuator Array for Object Positioning and Inspection," Proceedings of the 1996 Solid-State Sensor and Actuator Workshop, Hilton Head, South Carolina, June 3 - 6, 1996, pp. 168 - 173.

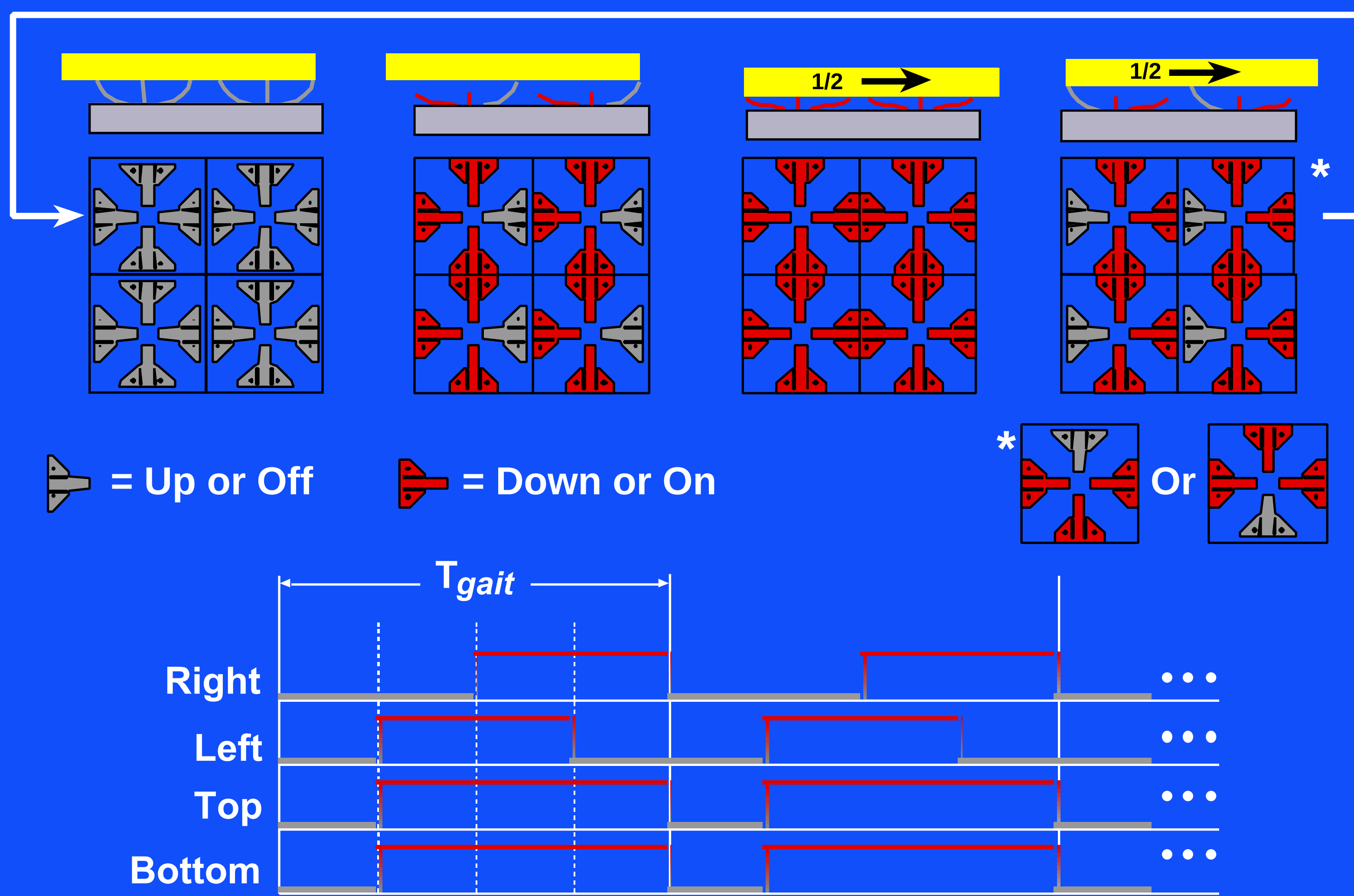
CILIARY MICROACTUATOR ARRAY



Reference: Suh, J. W., Glander, S. F., Darling, R. B., Storment, C. W., and Kovacs, G. T. A., "Combined Organic Thermal and Electrostatic Omnidirectional Ciliary Microactuator Array for Object Positioning and Inspection," Proceedings of the 1996 Solid-State Sensor and Actuator Workshop, Hilton Head, South Carolina, June 3 - 6, 1996, pp. 168 - 173.



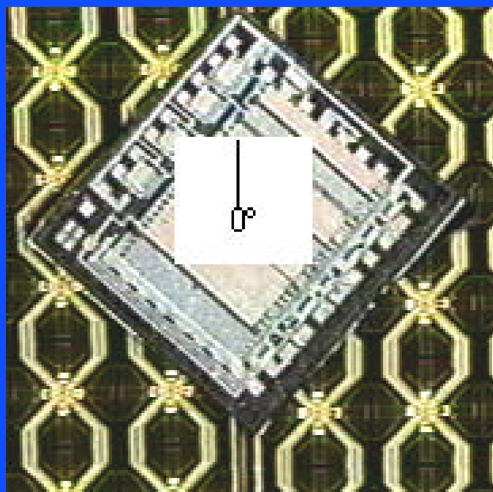
FOUR PHASE GAIT



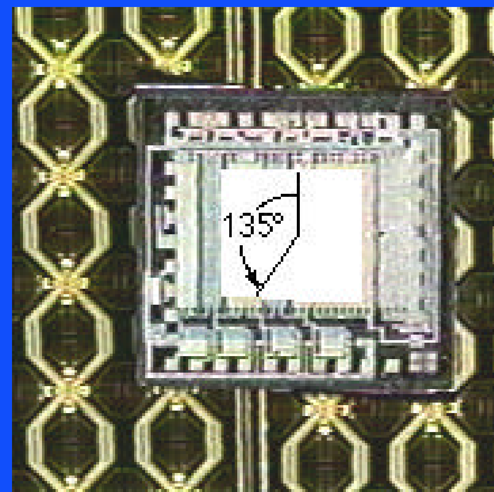
Courtesy J. Suh, Stanford University.

OBJECT ROTATION

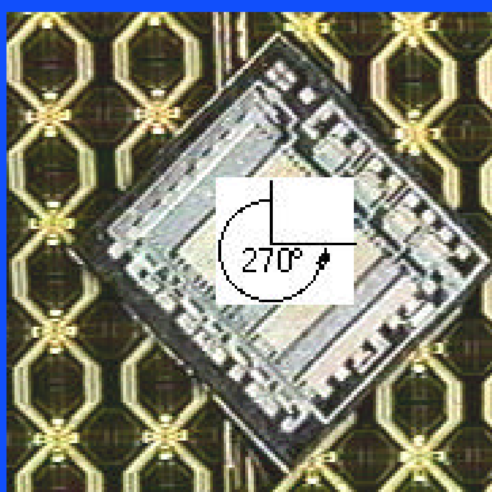
(A)



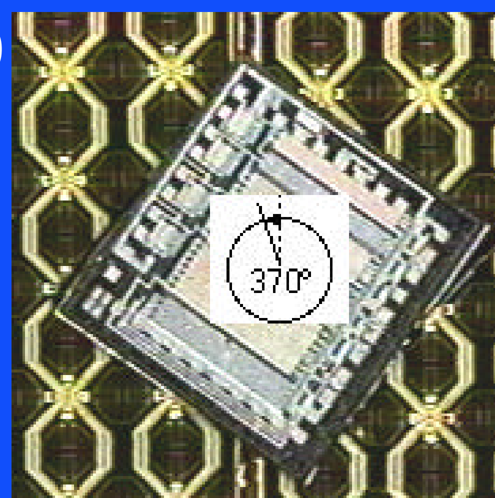
(B)

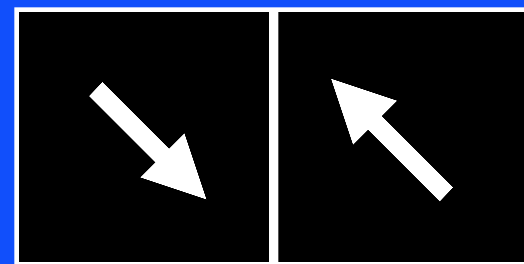


(C)



(D)





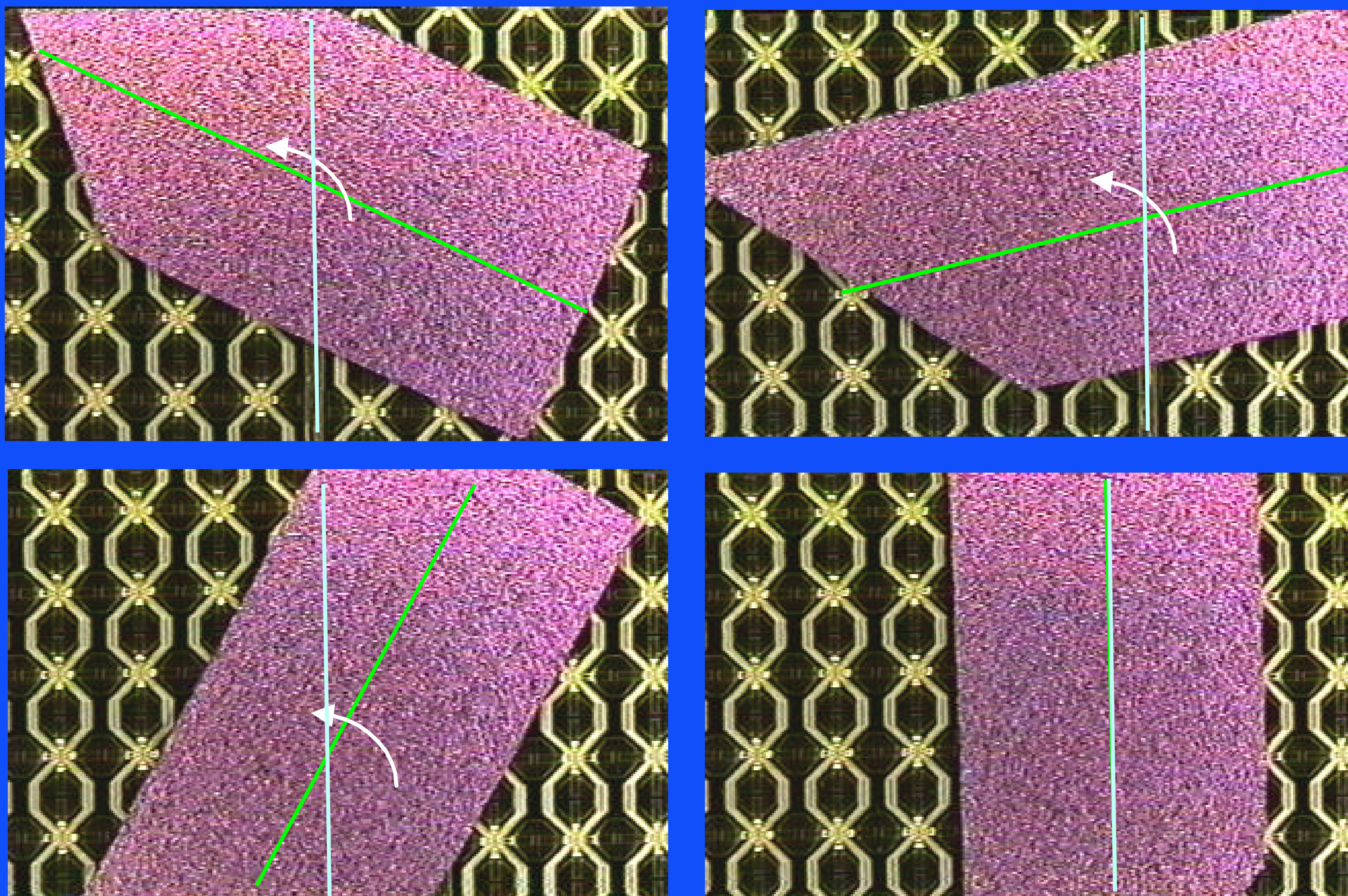
- **Two ciliary arrays producing diagonal gaits, rotate object.**

Courtesy J. Suh, Stanford University.

OBJECT ALIGNMENT

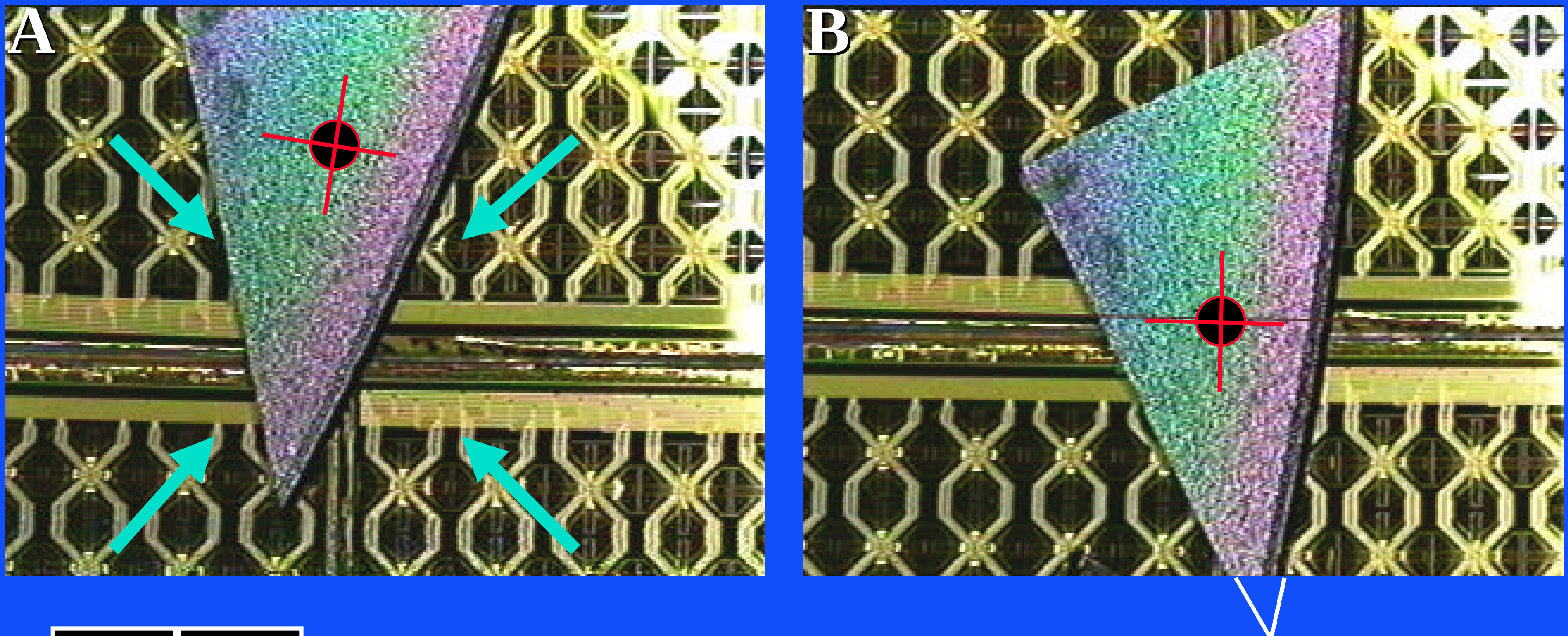
(A) (B)

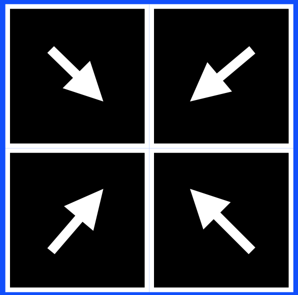
(C) (D)



Courtesy J. Suh, Stanford University.

OBJECT CENTERING

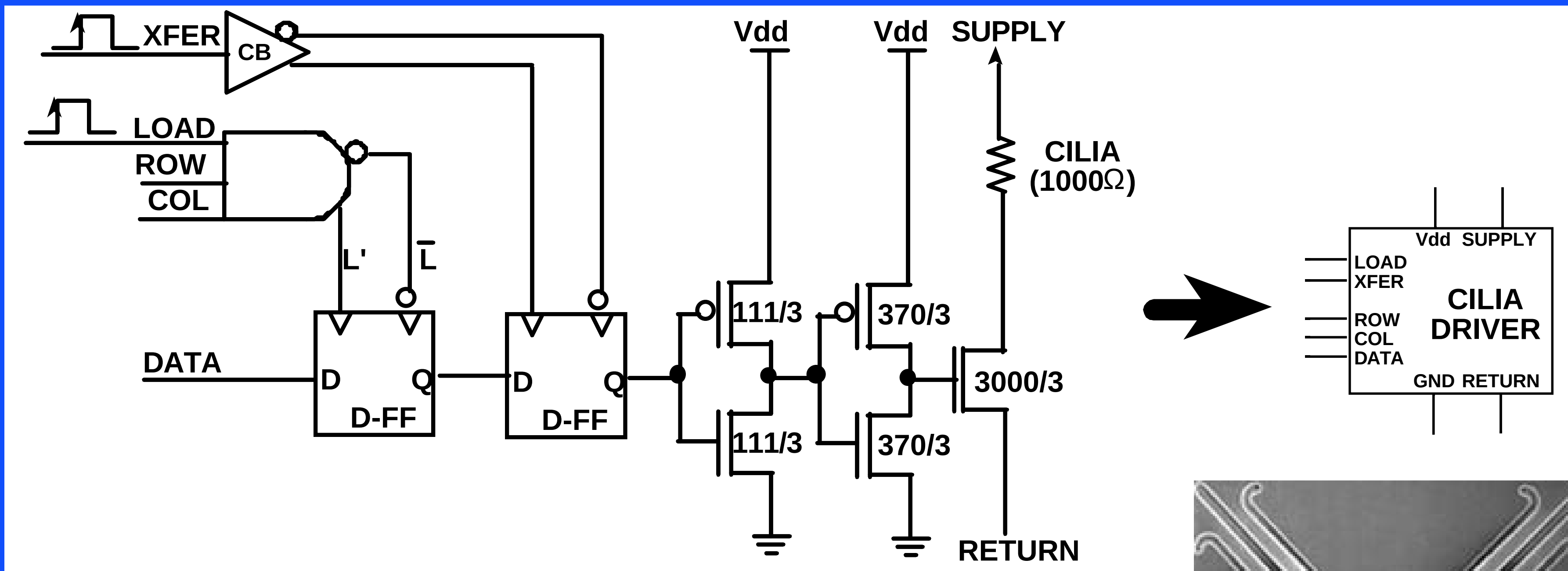


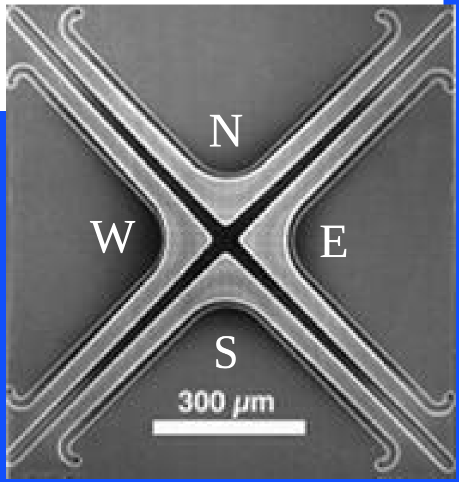


- **Four ciliary arrays each producing diagonal gait, centers object.**

Courtesy J. Suh, Stanford University.

CMOS INTEGRATED CILIA





- To turn on actuator in a given cell, ROW and COL go HIGH.
- The desired orientation is chosen with DATA (N, E, W, or S).
- First FF is clocked by a LOAD pulse.
- Second FF continuously drives the CILIA until there is a change in state of first FF and the 2nd FF is clocked with XFER signal.

Courtesy J. Suh, Stanford University.

TECHNOLOGY INTEGRATION

Quick CMOS
- 9 Masks

Active
P-Well
Poly Si
N-Plus
Poly Vias
Metal1
Metal Vias
Metal2
Scratch LTO

CMOS Integrated MEMS
- 17 Masks: 9 CMOS + 8 MEMS

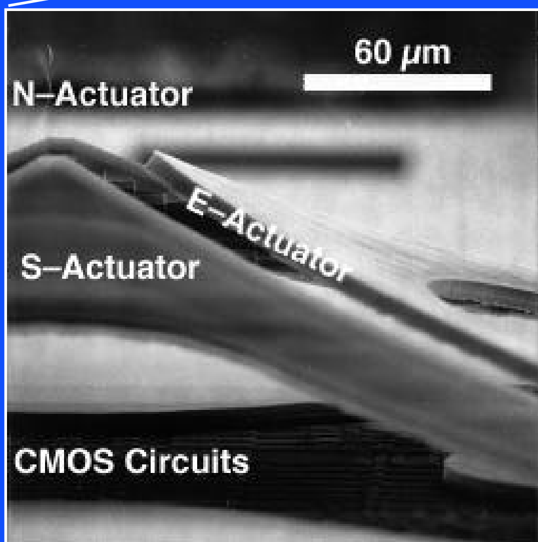
Active
P-Well
Poly Si
N-Plus
Poly Vias
Metal1
Metal Vias
Metal2
Scratch LTO
Nitride
Metal3
Polyimide1
Nitride2
Metal4
Metal5
Nitride3
Polyimide2
Nitride4

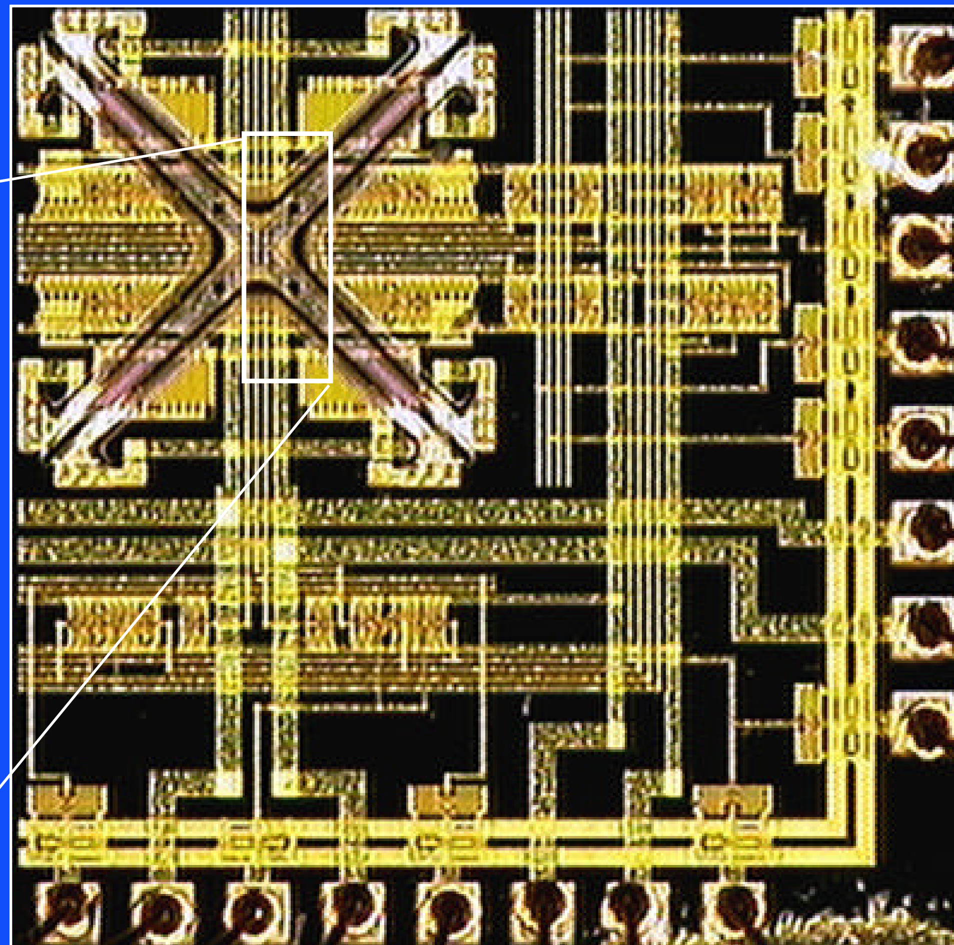
Bimorph MEMS
- 9 Masks

Metal1
LTO
Metal2
Nitride1
Polyimide1
Nitride2
Metal2
Metal3
Nitride3
Polyimide2
Nitride4

Courtesy J. Suh, Stanford University.

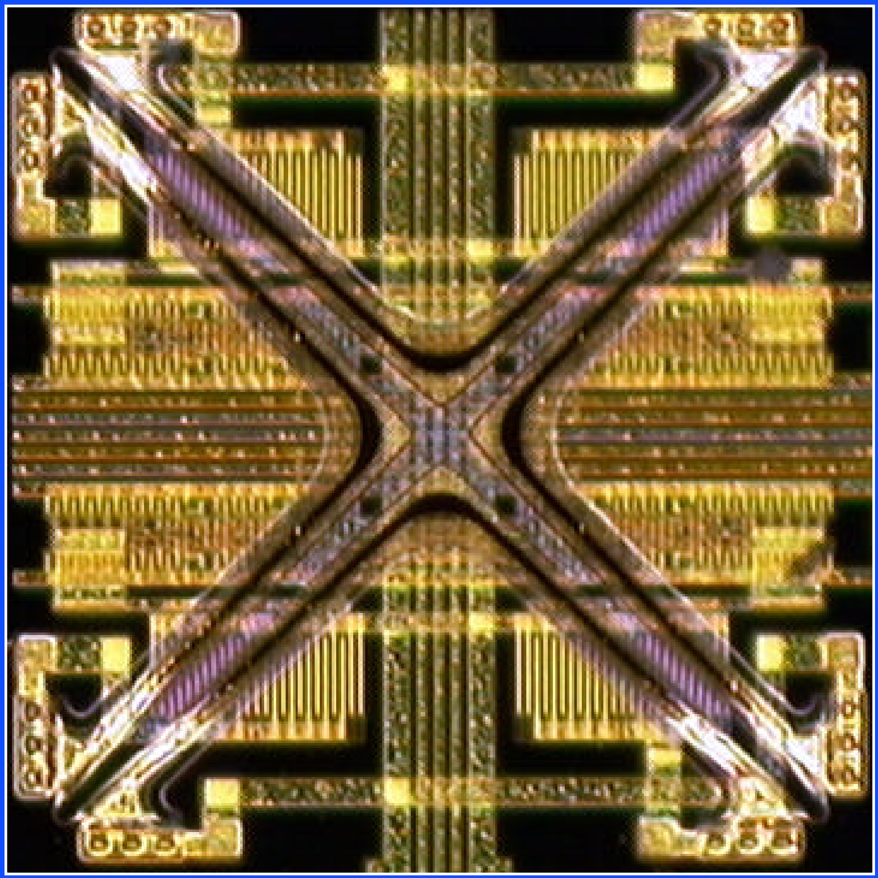
INTEGRATED CILIUM

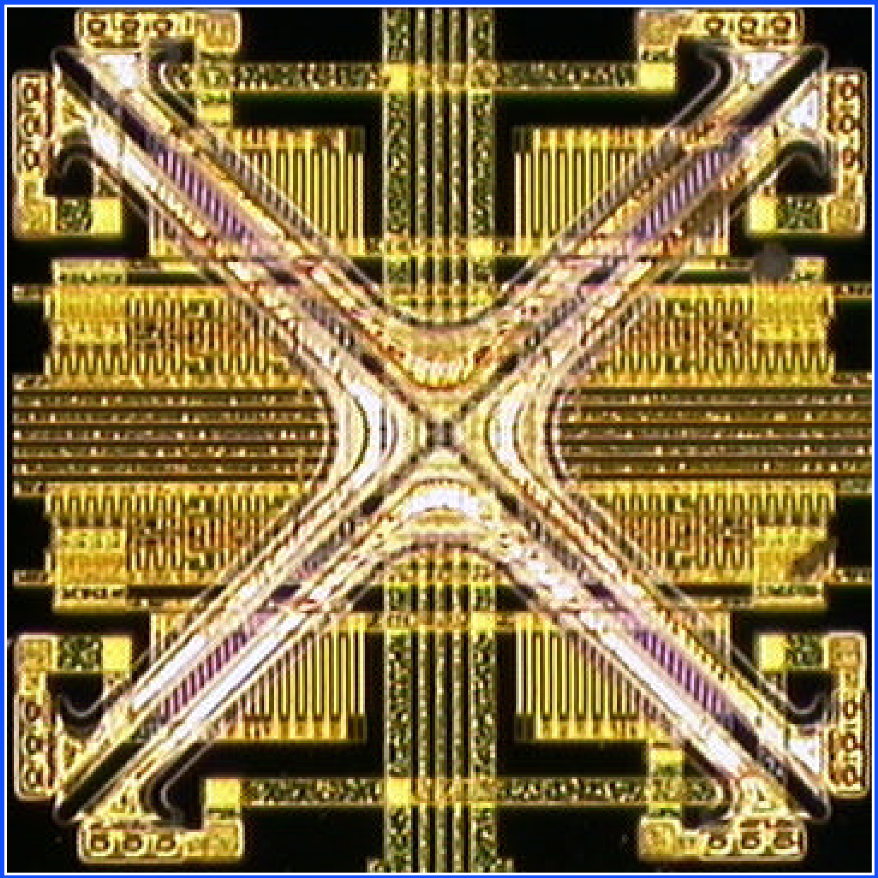




Reference: Suh, J. W., Darling, R. B., Böhringer, K.-F., Donald, B. R., Baltes, H., and Kovacs, G. T. A., "CMOS Integrated Ciliary Actuator Array as a General-Purpose Micromanipulation Tool for Small Objects," IEEE/ASME Journal of Microelectromechanical Systems, Dec. 1999, vol. 8, no. 4, pp. 483 - 496.

Courtesy J. Suh, Stanford University.





Off **On**

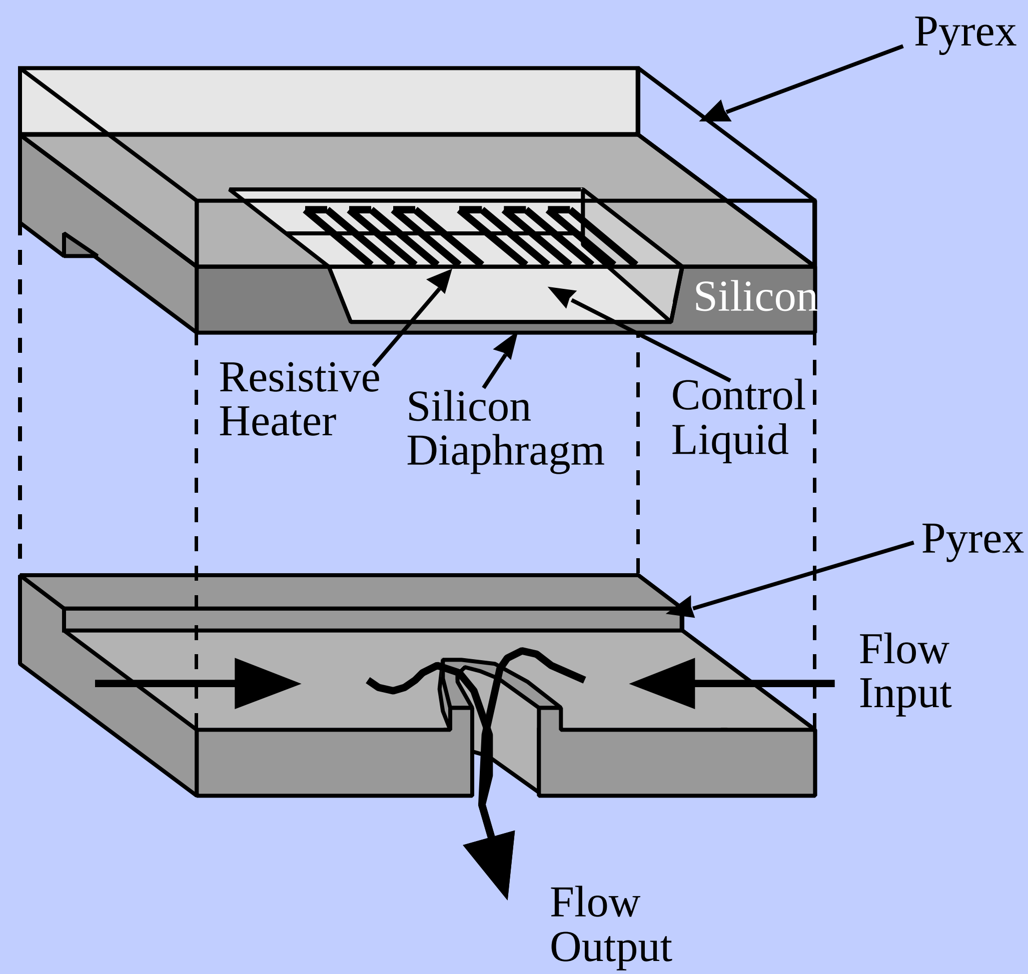
Test conditions per device to make "flat":

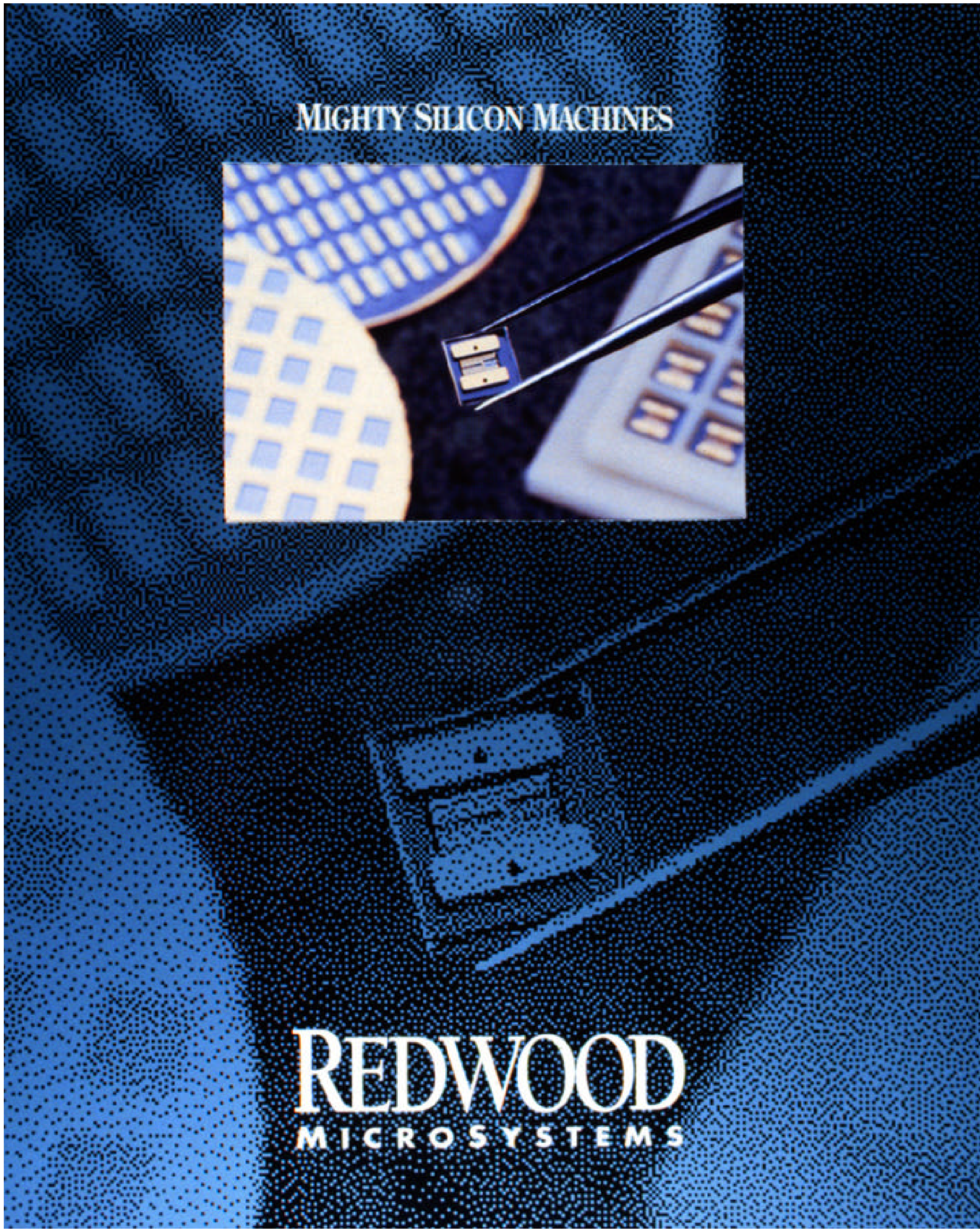
• Supply voltage = 6.25 V • Actuator current ≈ 6 mA

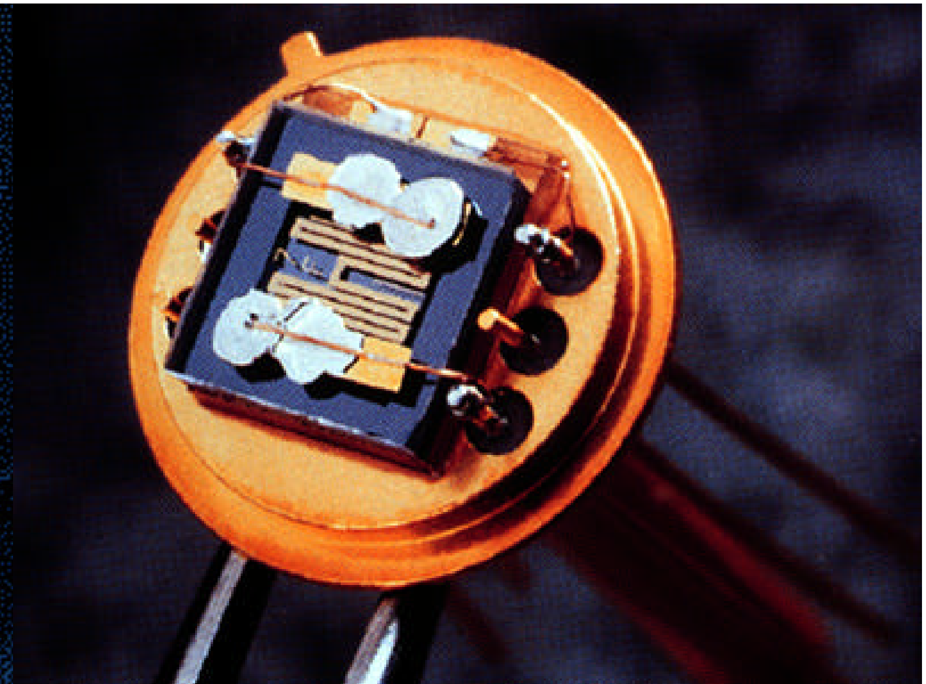
Courtesy J. Suh, Stanford University.

THERMAL EXPANSION ACTUATORS

- **Electrically-controlled heaters are used to expand liquid or gas to generate pressure/force.**
- **The pressure in turn deforms a membrane, doing mechanical work.**
- **Valves (Redwood Microsystems) have been fabricated using the is approach, require power on the order of 1 W and have responses in the millisecond range.**



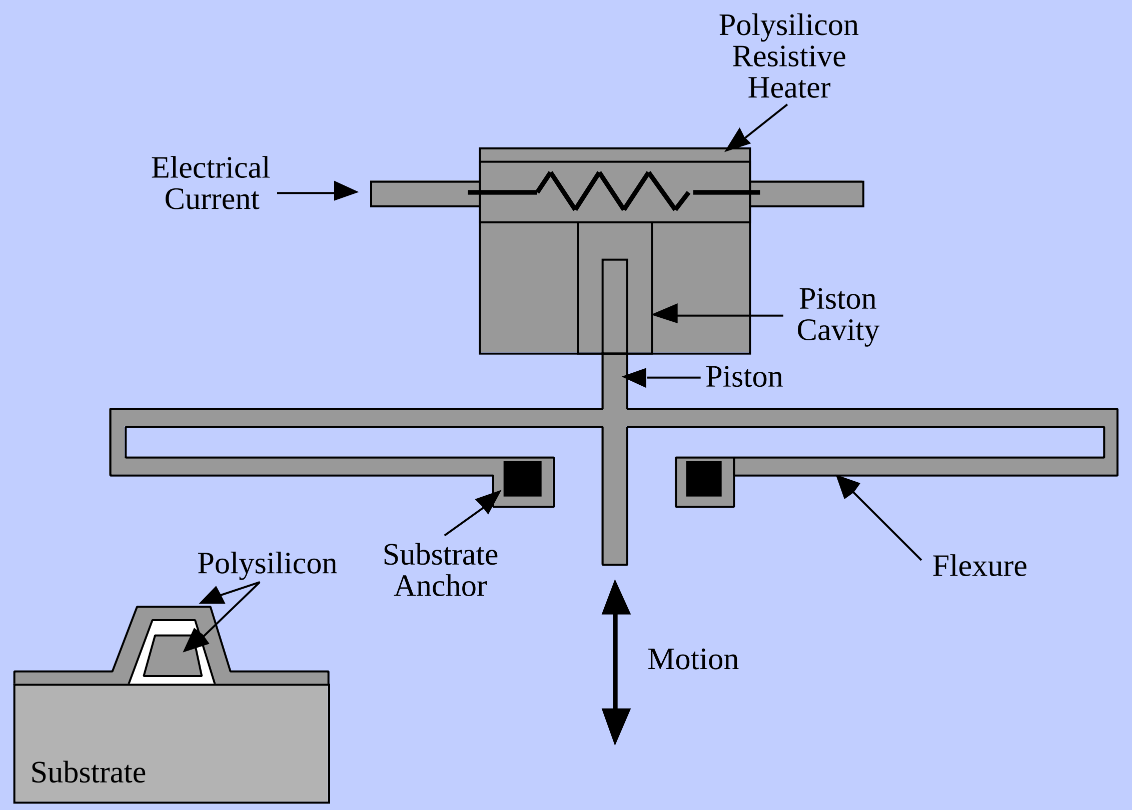




Courtesy Dr. M. Zdeblick, Redwood Microsystems.

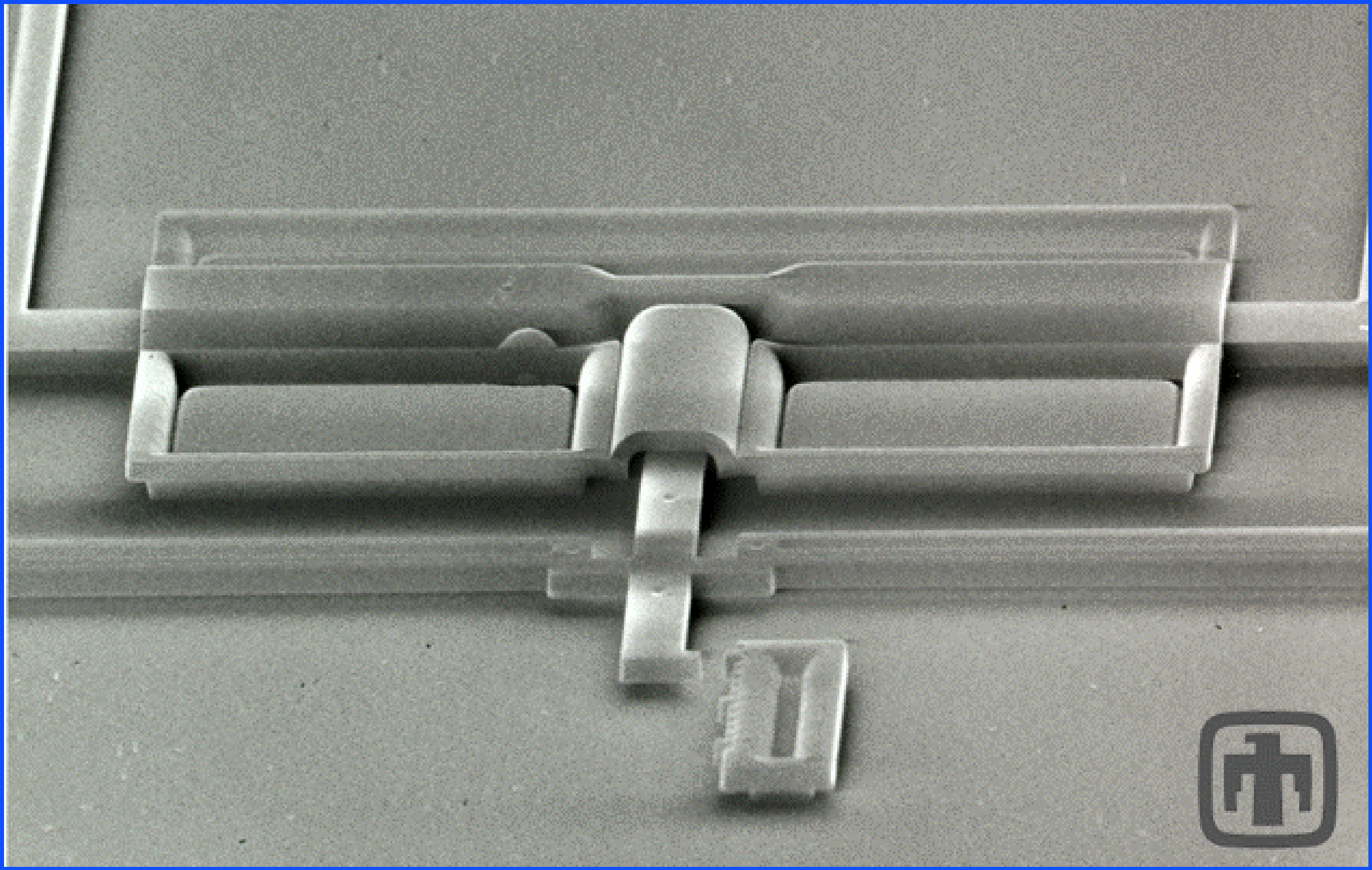
PHASE-CHANGE ACTUATORS

- **Using a heater to form vapor bubbles in a liquid can be used to actuate mechanisms.**
- **Liquid media must be used, and their thermal conductivity may limit efficiency.**



Cross-Section at Piston

Reference: Sniegowski, J. J., "A Microactuation Mechanism Based on Liquid-Vapor Surface Tension," Abstracts of Late News Papers from Transducers '93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, Institute of Electrical Engineers, Japan, pp. 12 - 13.



http://www.mdl.sandia.gov/Micromachine/images.html

SHAPE MEMORY ALLOY ACTUATORS

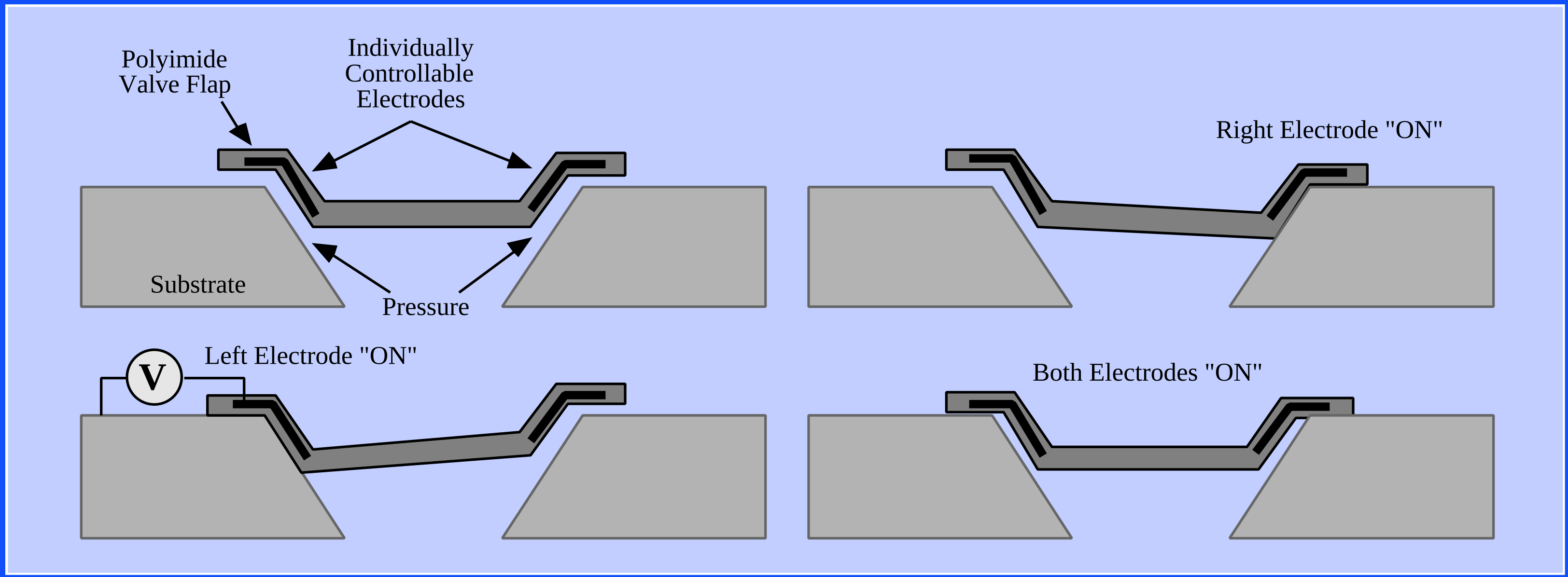
- Since the 1950's, it has been known that certain alloys, such as AuCu, InTi and TiNi, could be deformed but would return to their original shape once heated.

- TiNi exhibits the SMA effect due to a temperature-dependent phase transition between the *martensite* and *austensite* forms. Heating causes contraction via transition to the austensite phase.

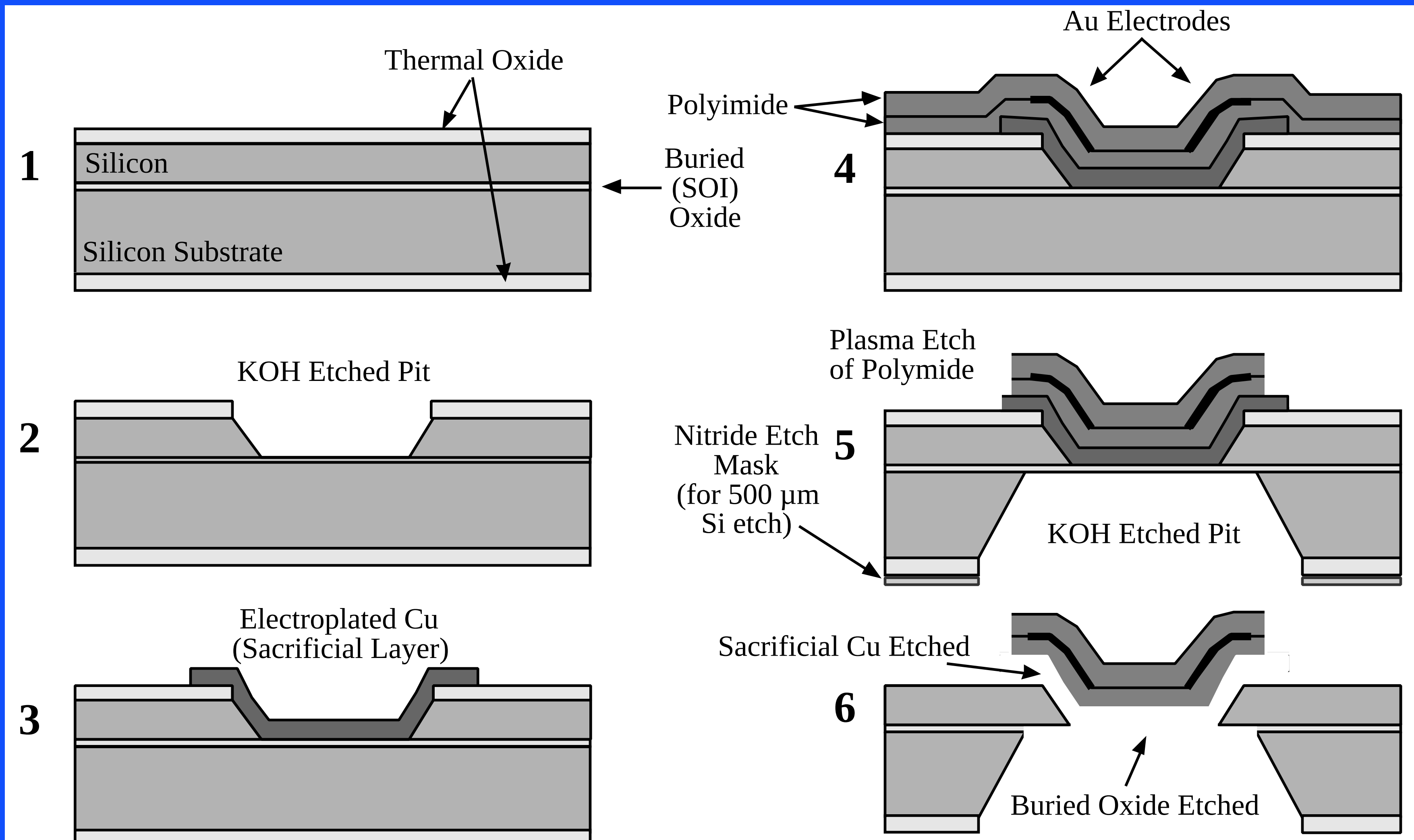
- TiNi thin films have been used in microactuators, and can generate stresses greater than 200 MPa with strains > 5% and with rather low efficiencies (≈ 3%).

PNEUMATIC ACTUATION

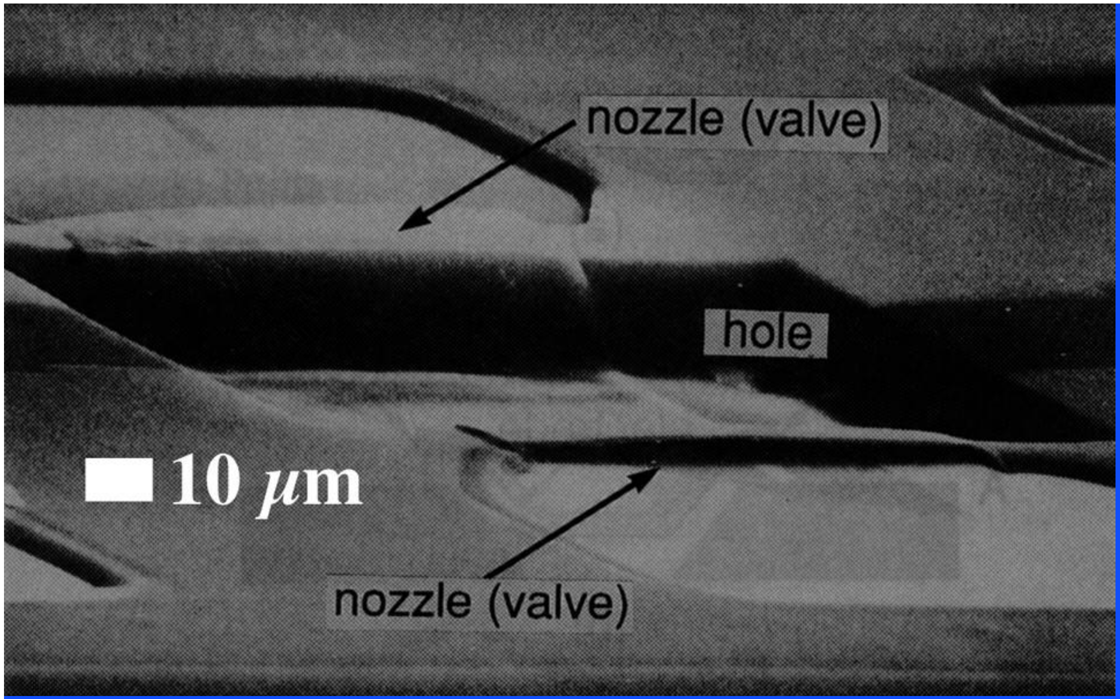
- **Such actuators generally rely on a low power mechanism to gate gas pressure on and off (liquid gating would be referred to as hydraulic).**
- **The added complications of fluidics are brought into play with these actuators, but large forces are possible.**

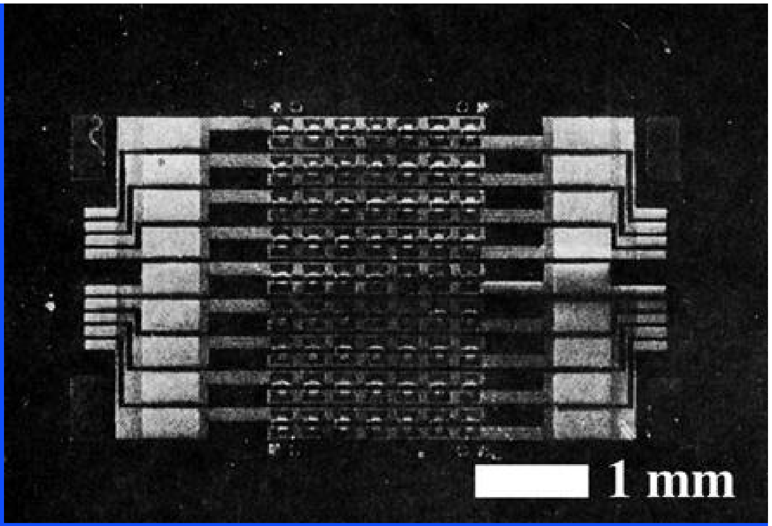


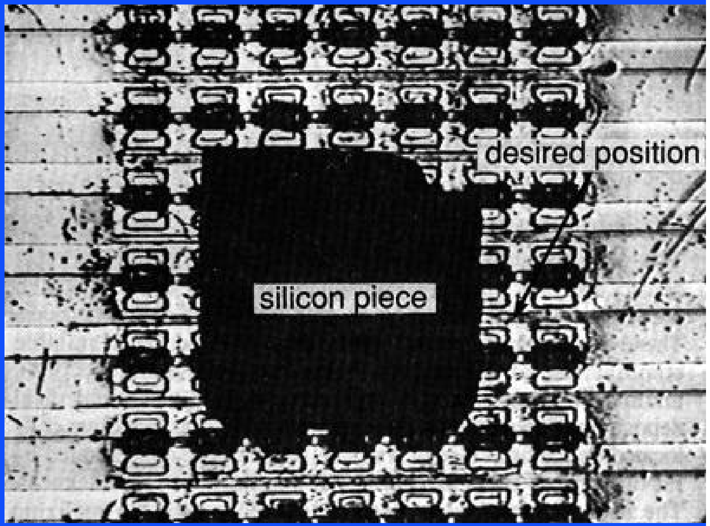
Reference: Konishi, S., and Fujita, H., "A Conveyance System Using Air Flow Based on the Concept of Distributed Micro Motion Systems," Proceedings of Transducers '93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, Institute of Electrical Engineers, Japan, pp. 28 - 31.



Reference: Konishi, S., and Fujita, H., "A Conveyance System Using Air Flow Based on the Concept of Distributed Micro Motion Systems," Proceedings of Transducers '93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, Institute of Electrical Engineers, Japan, pp. 28 - 31.



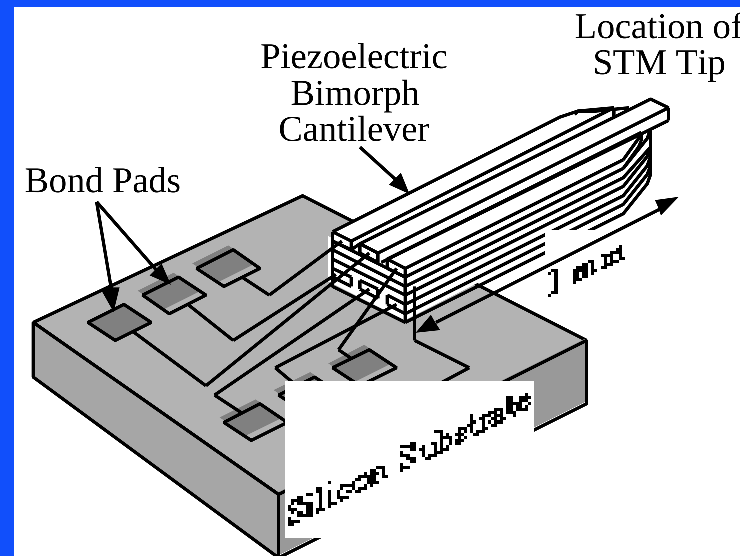


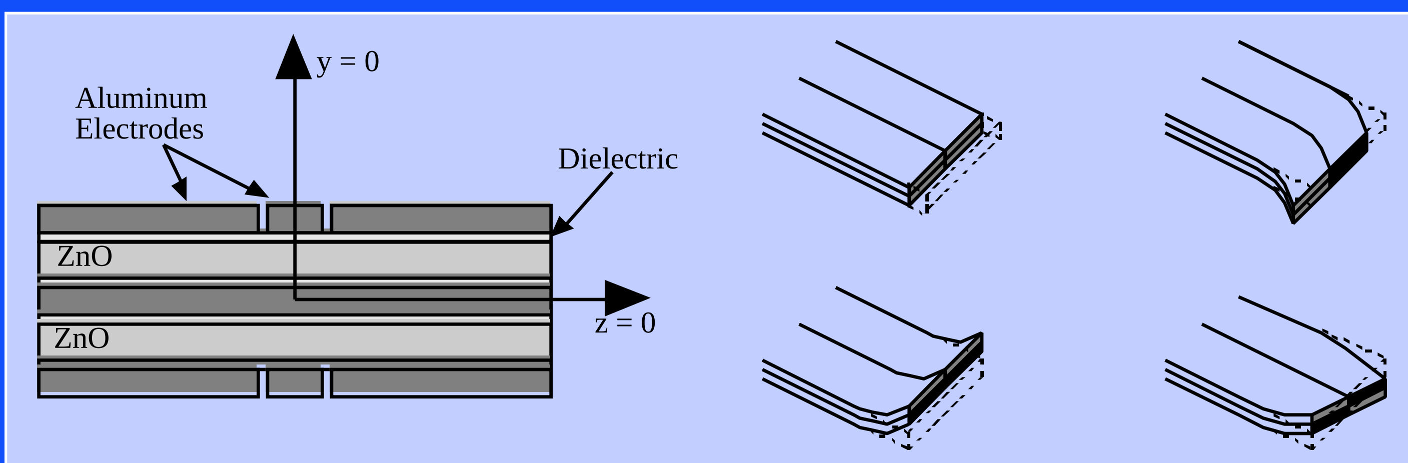


Source: Konishi, S., and Fujita, H., "A Conveyance System Using Air Flow Based on the Concept of Distributed Micro Motion Systems," Proceedings of Transducers '93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, Institute of Electrical Engineers, Japan, pp. 28 - 31.

PIEZOELECTRIC ACTUATION

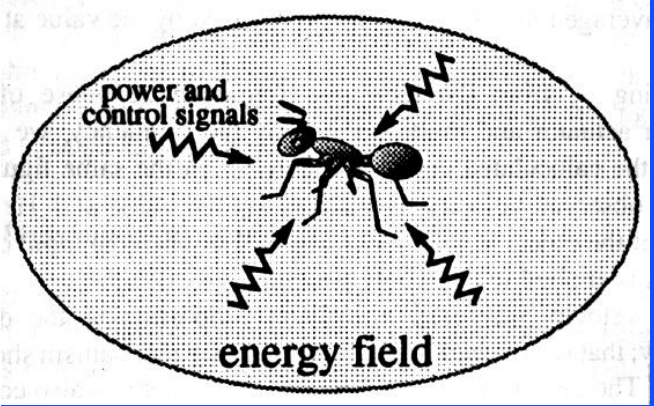
- **Small strains (< 0.1%) but high forces (≈ 40 MPa) and speeds are characteristic of piezoelectric actuators.**



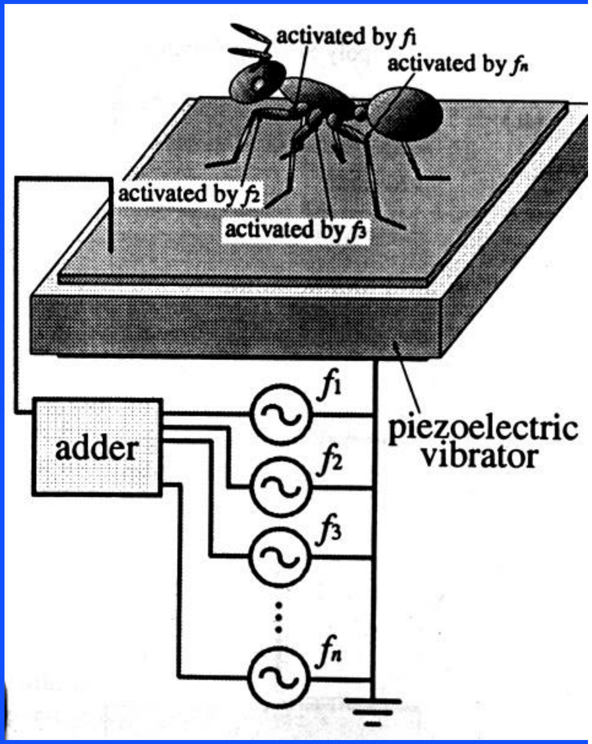


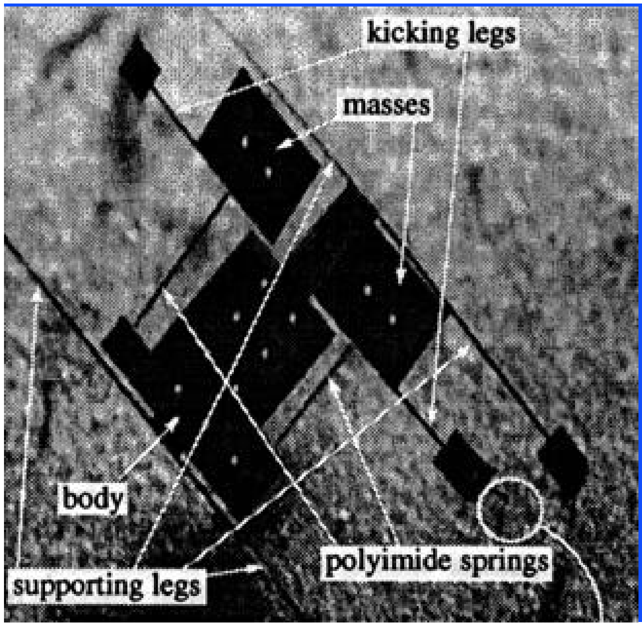
Reference: Akamine, S., Albrecht, T. R., Zdeblick, M. J., and Quate, C. F., "A Planar Process for Microfabrication of a Scanning Tunneling Microscope," Sensors and Actuators, A21-A23, 1990, pp. 964 - 970.

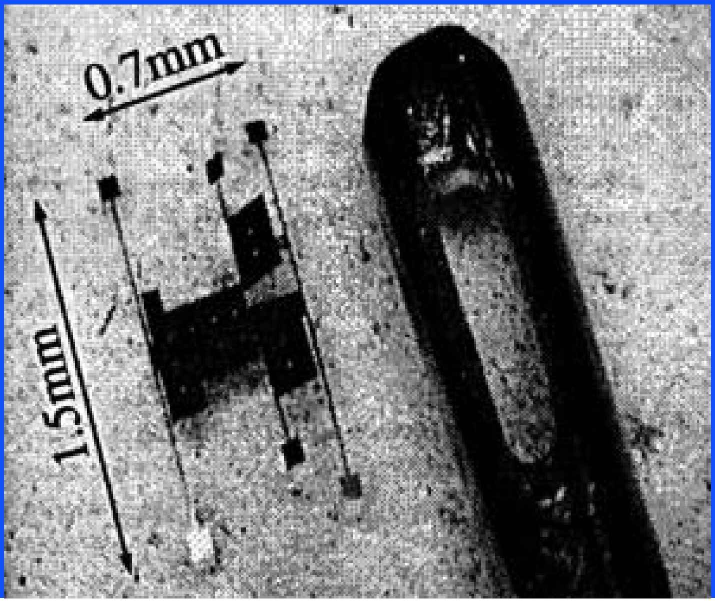
VIBRATORY ACTUATION



Source: Yasuda, T., Shimoyama, I., and Miura, H., "Microrobot Actuated by a Vibration Energy Field," Proceedings of Transducers '93, the 7th International Conference on Solid-State Sensors and Actuators, Yokohama, Japan, June 7 - 10, 1993, pp. 42 - 45.







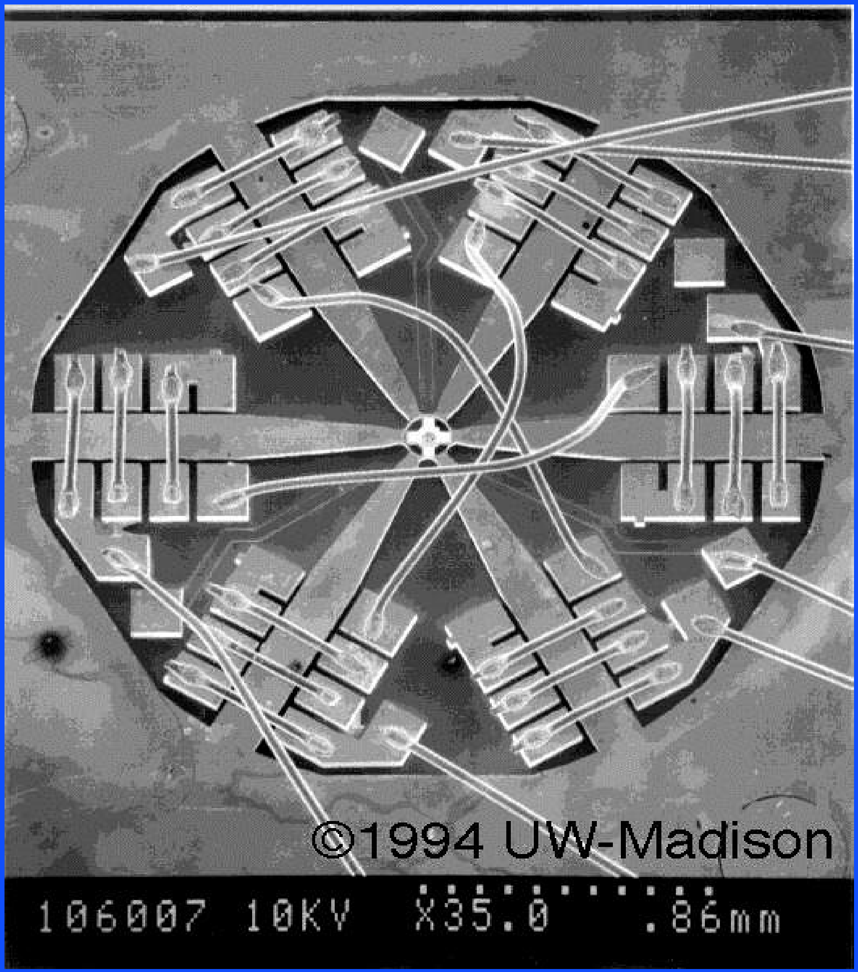
MAGNETIC ACTUATION

- Forces between current carrying wires and/or permanent magnets (e.g. electroplated Permalloy) can be used to generate considerable forces with fast response times.
- Magnetic forces can be used to drive rotary motors, galvanometers, etc.
- Resistive losses must be carefully taken into account.
- This material is covered in the Magnetic Transducers section.

Courtesy of Prof. H. Guckel, University of Wisconsin.

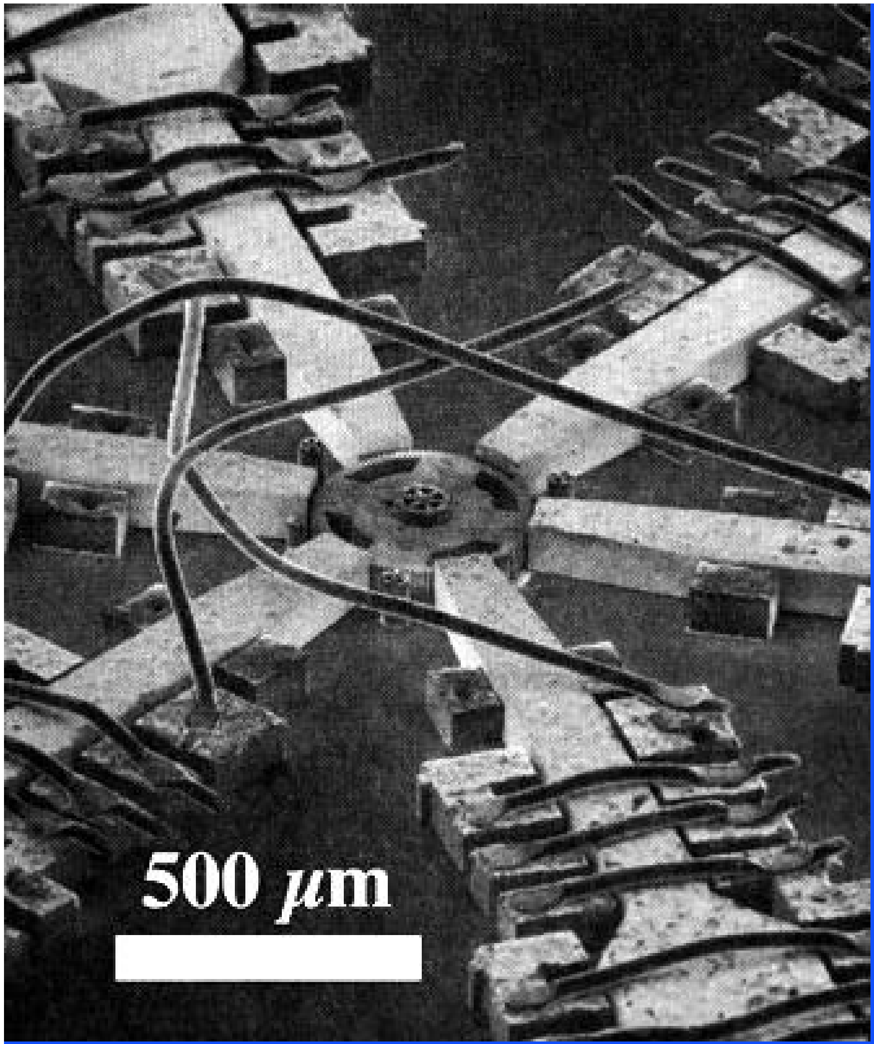
http://mems.engr.wisc.edu/images/

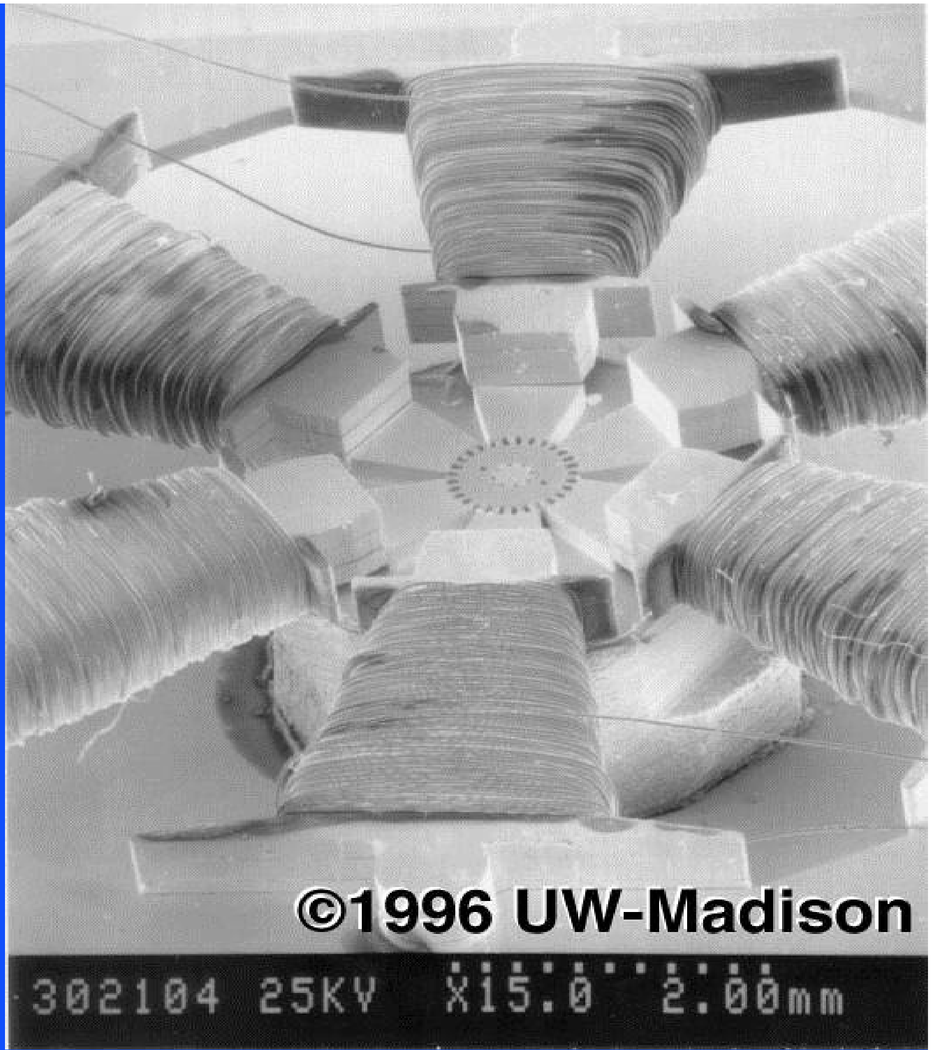
COILS



Courtesy of Prof. Henry Guckel

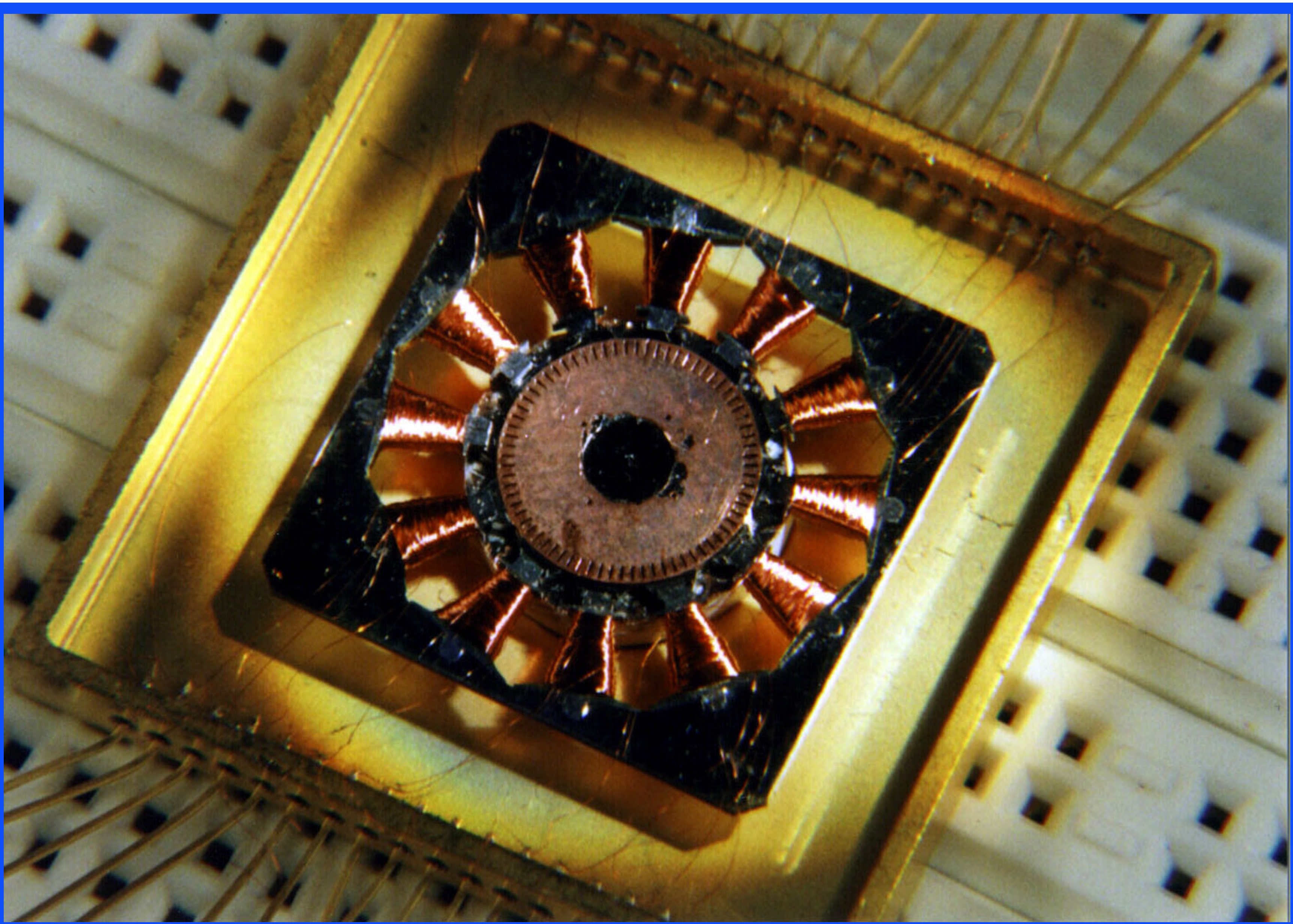
http://mems.engr.wisc.edu/images/





Courtesy of Prof. H. Guckel, University of Wisconsin.

http://mems.engr.wisc.edu/images/

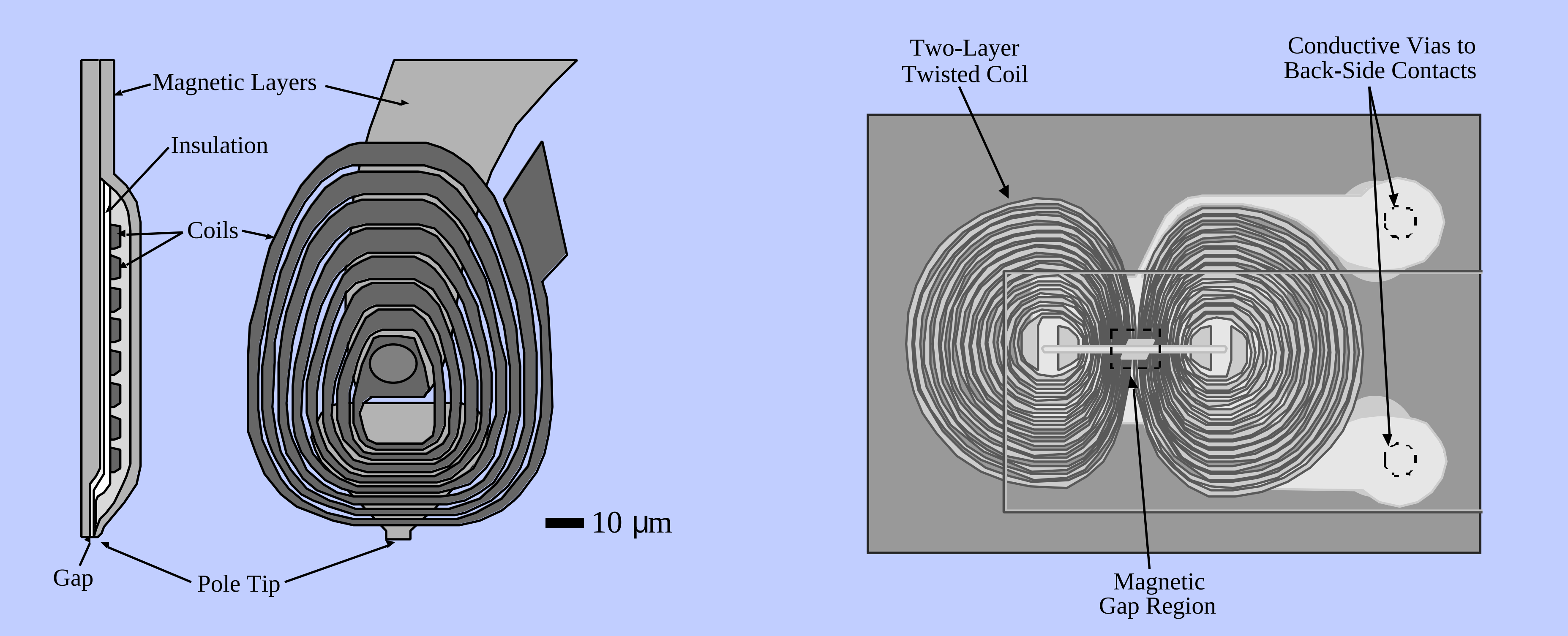


Courtesy of Prof. H. Guckel, University of Wisconsin.

Courtesy of J. Klein, University of Wisconsin.

Reference: Klein J, Preliminary Results of a micro induction motor, Ph.D Thesis, University of Wisconsin at Madison, 1998.

MAGNETIC READ/WRITE HEADS



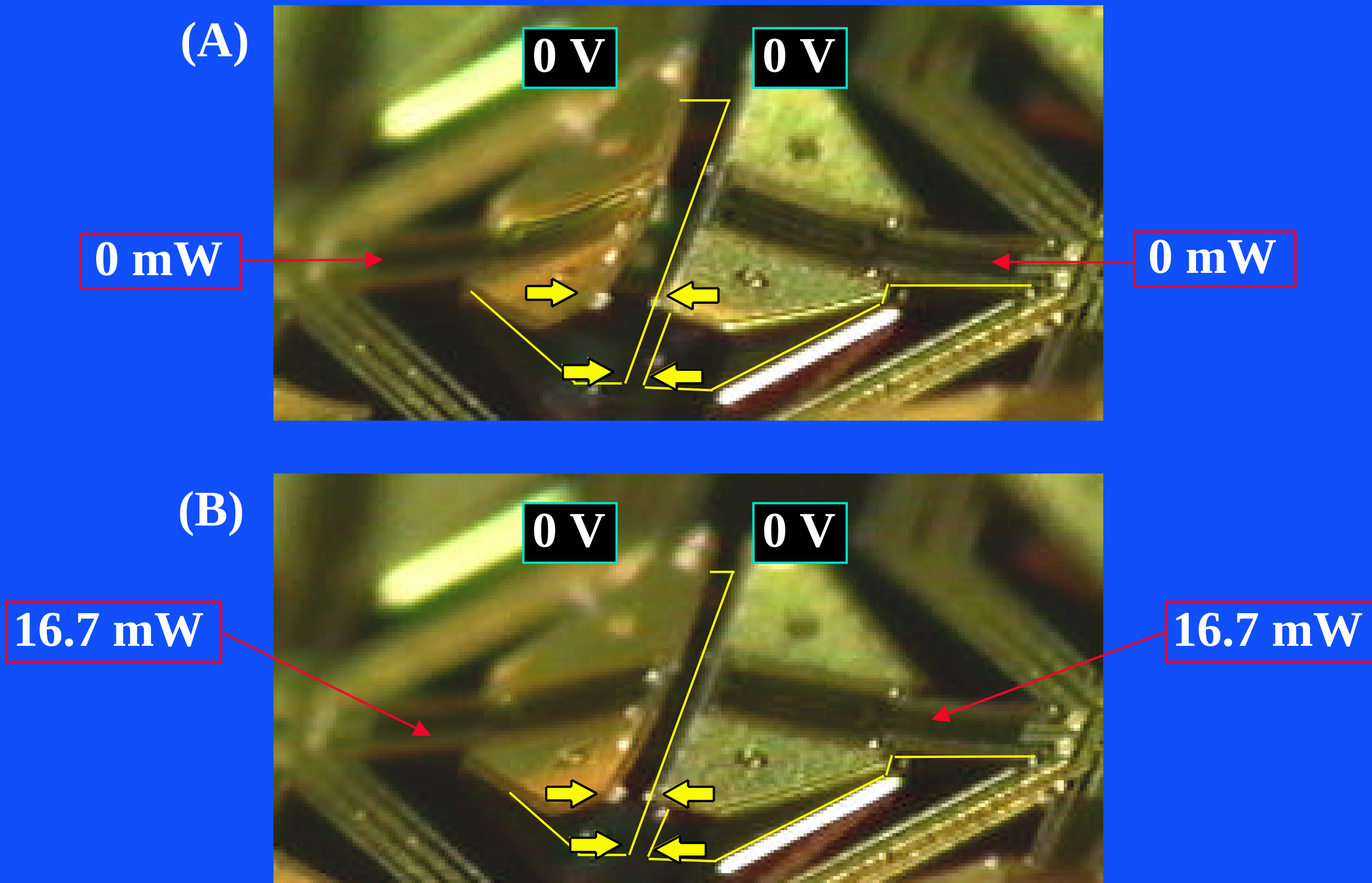
Reference: Romankiw, L. T., "Evolution of the Plating Through Lithographic Mask Technology," Proceedings of the Fourth International Symposium on Magnetic Materials, Processes and Devices - Applications to Storage and Microelectromechanical Systems (MEMS), Chicago, IL, Oct. 9 - 12, 1995 (published in 1996), pp. 253 - 272.

Reference: Lazzari, J. P., "Planar Silicon Heads for Disc Drive Industry," Proceedings of Transducers '97, the 1997 International Conference on Solid-State Sensors and Actuators, Chicago, IL, June 16 - 19, 1997, vol. 2, pp. 1077 - 1080.

HYBRID ACTUATORS

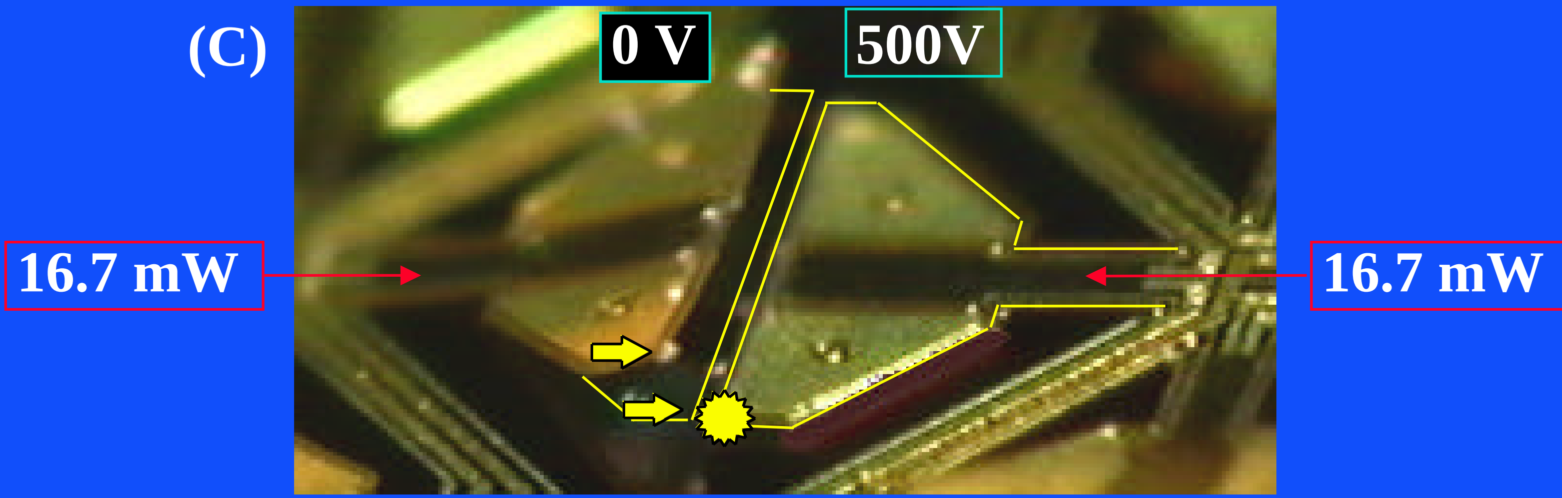
- It is sometimes possible to combine more than one actuation scheme to help mitigate the drawbacks of each one individually.

- Combinations that have been demonstrated in micromachined devices include thermal/electrostatic and magnetic/electrostatic.



Reference: Suh, J. W., Glander, S. F., Darling, R. B., Storment, C. W., and Kovacs, G. T. A., "Combined Organic Thermal and Electrostatic Omnidirectional Ciliary Microactuator Array for Object Positioning and Inspection," Proceedings of the 1996 Solid-State Sensor and Actuator Workshop, Hilton Head, South Carolina, June 3 - 6, 1996, pp. 168 - 173.

(C)



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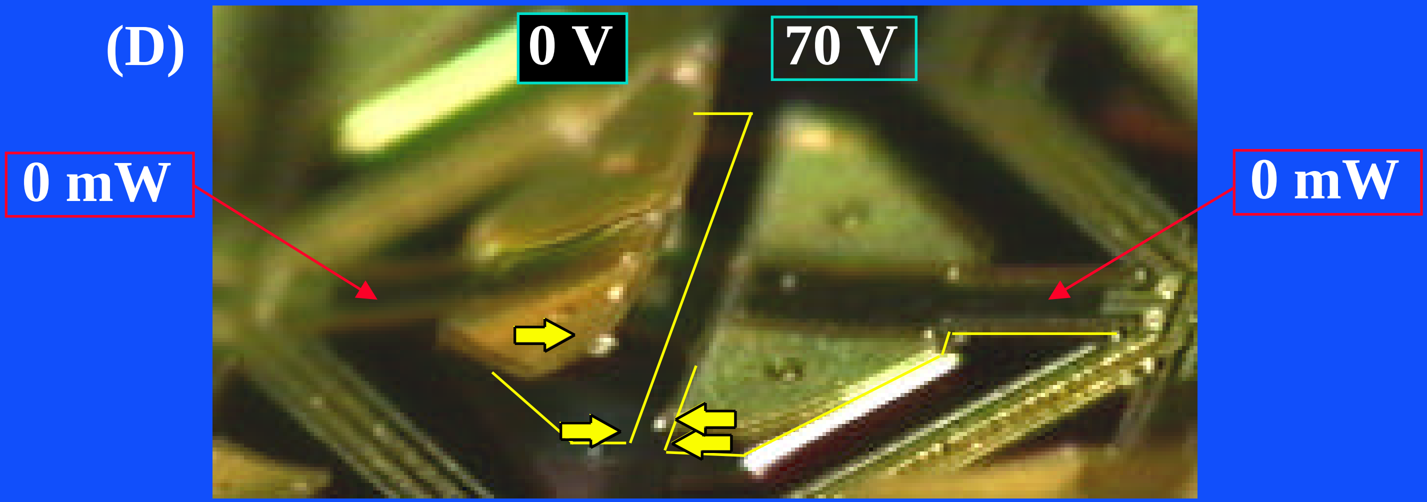


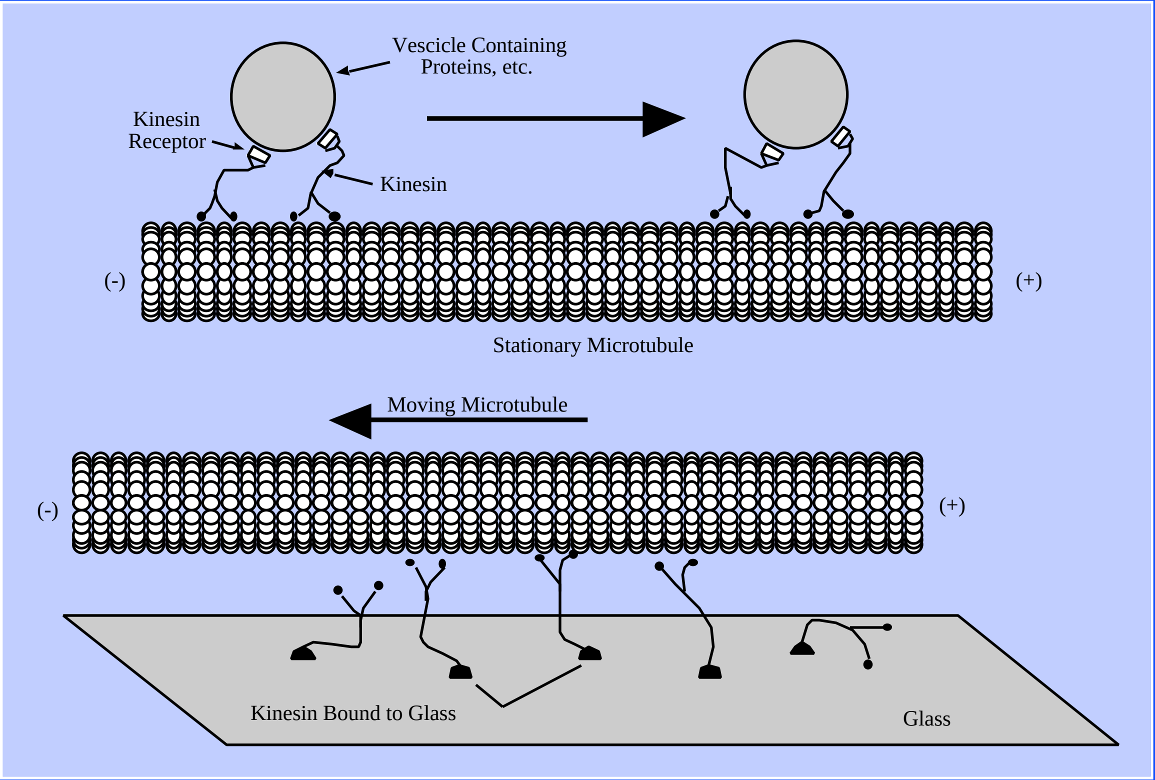
Reference: Suh, J. W., Glander, S. F., Darling, R. B., Storment, C. W., and Kovacs, G. T. A., "Combined Organic Thermal and Electrostatic Omnidirectional Ciliary Microactuator Array for Object Positioning and Inspection," Proceedings of the 1996 Solid-State Sensor and Actuator Workshop, Hilton Head, South Carolina, June 3 - 6, 1996, pp. 168 - 173.

BIOLOGICAL ACTUATORS

- Clearly, a wide variety of efficient actuation mechanisms have evolved in order to allow organisms to move.
- These are chemical to mechanical transducers.
- Microtubules are cellular scaffholding, along which kinesin molecules can move (powered by ATP) themselves and bound vesicles containing cellular products.

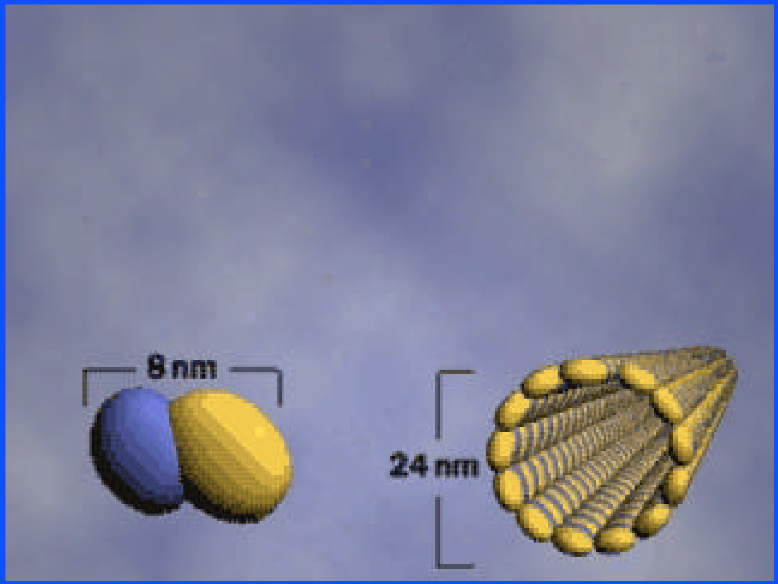
Microtubule dimensions: 24 nm diameter, length varies.

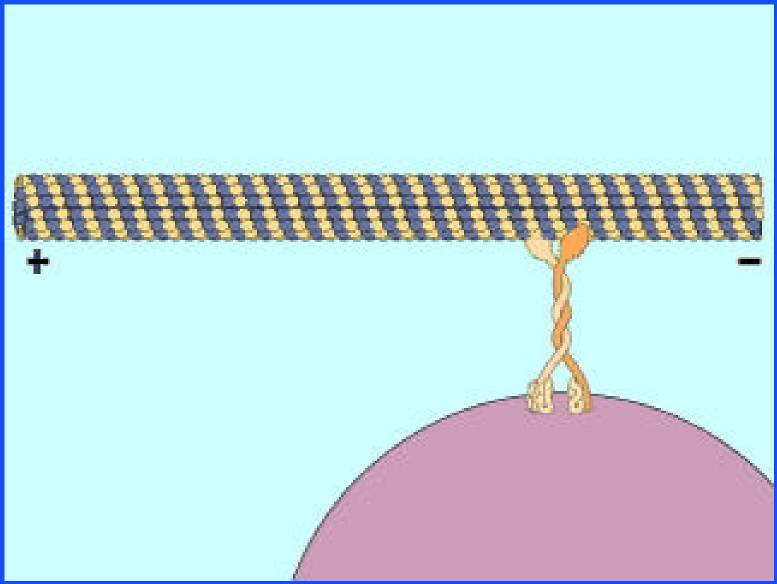
Kinesin dimensions: ≈70 nm length.



Reference: Darnell, J., Lodish, H., and Baltimore, D., “Molecular Cell Biology,” Second Edition, Scientific American Books, W. H. Freeman and Co., New York, NY, 1991.

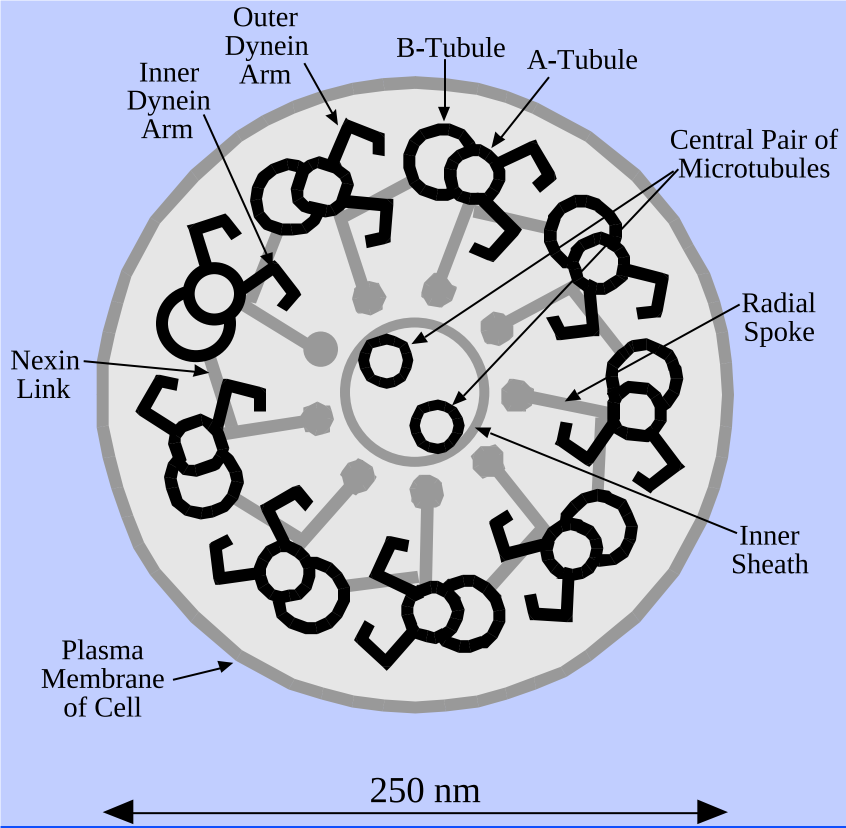
MICROTUBULES & KINESIN

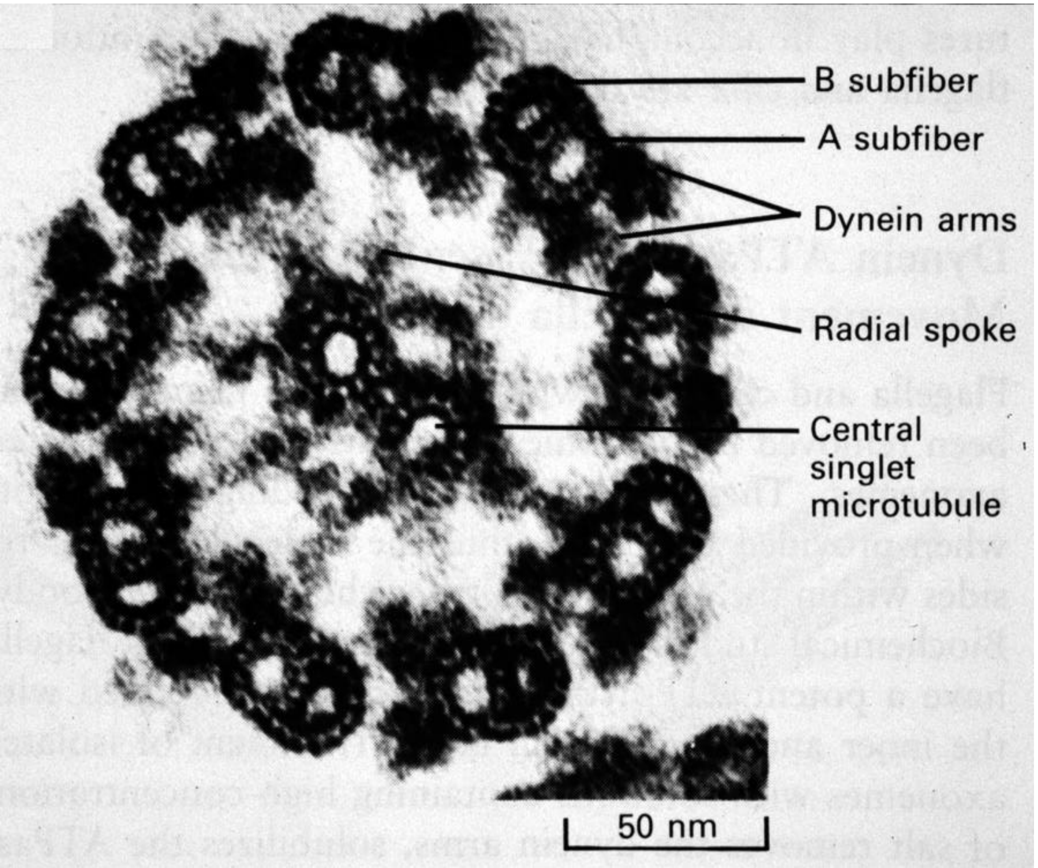




Movies courtesy Prof. H. C. Heller, Stanford University.

Source: Purves, Orians, Heller, and Sadava, "Life: The Science of Biology," Sinauer Associates/W.H. Freeman & Co., New York, 1999.





Source: Darnell, J., Lodish, H., and Baltimore, D., “Molecular Cell Biology,” Second Edition, Scientific American Books, W. H. Freeman and Co., New York, NY, 1991.

Movie courtesy Prof. H. C. Heller, Stanford University.

Source: Purves, Orians, Heller, and Sadava, "Life: The Science of Biology," Sinauer Associates/W.H. Freeman & Co., New York, 1999.

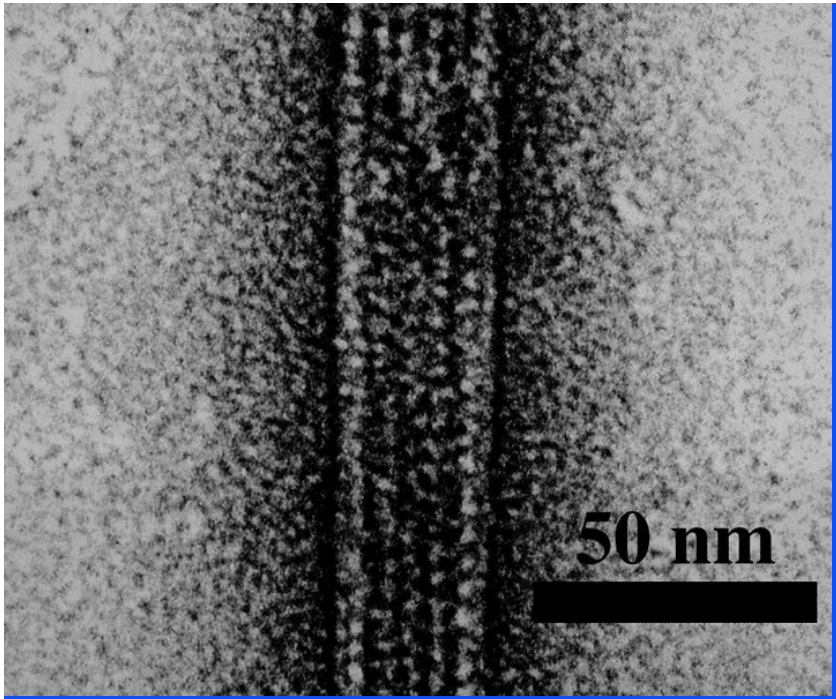
Video Enhanced DIC Microscopy
of Mitosis in Newt Lung Cells
(Taricha granulosa)

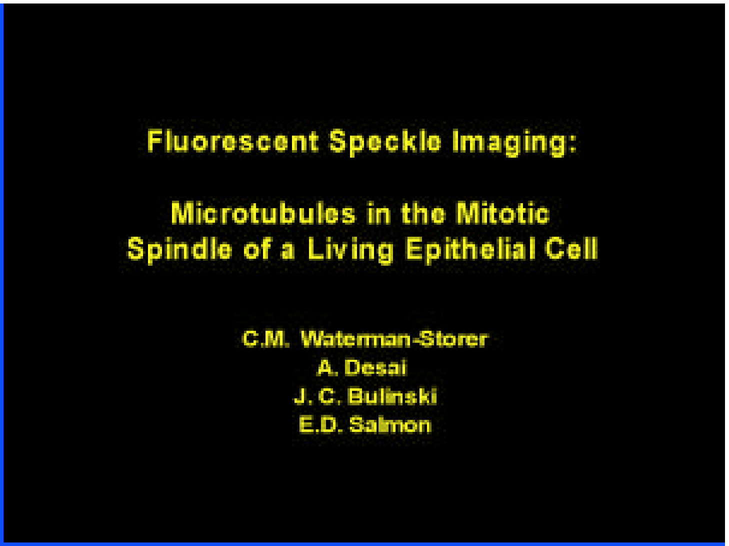
Victoria Skeen,
Robert Skibbens, and
E. D. Salmon

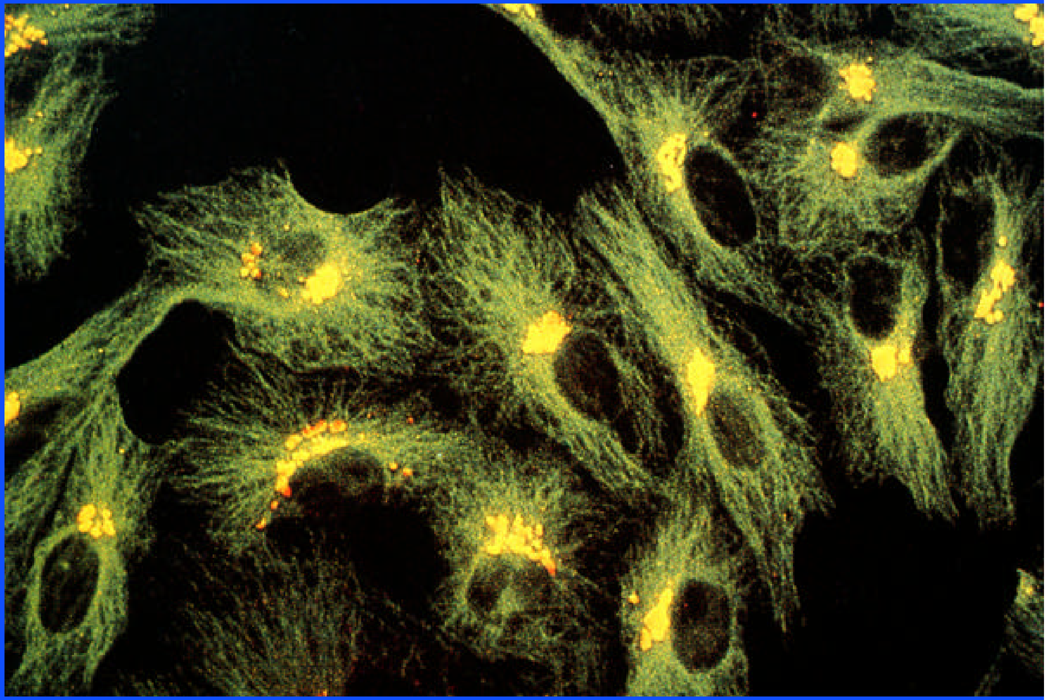
University of North Carolina at Chapel Hill
(see Skibbens et al., 1993, J. Cell biol. 122:859-875)
Frame Time = HR:MIN:SEC

Mitosis and
cell plate formation in a
flattened endosperm cell
of the African blood lily,
Haemanthus katherinae,
observed with
phase contrast microscopy

Mitosis in tissue-cultured
lung cell of a newt,
Traicha granulosa, recorded
with the new Pol-Scope.

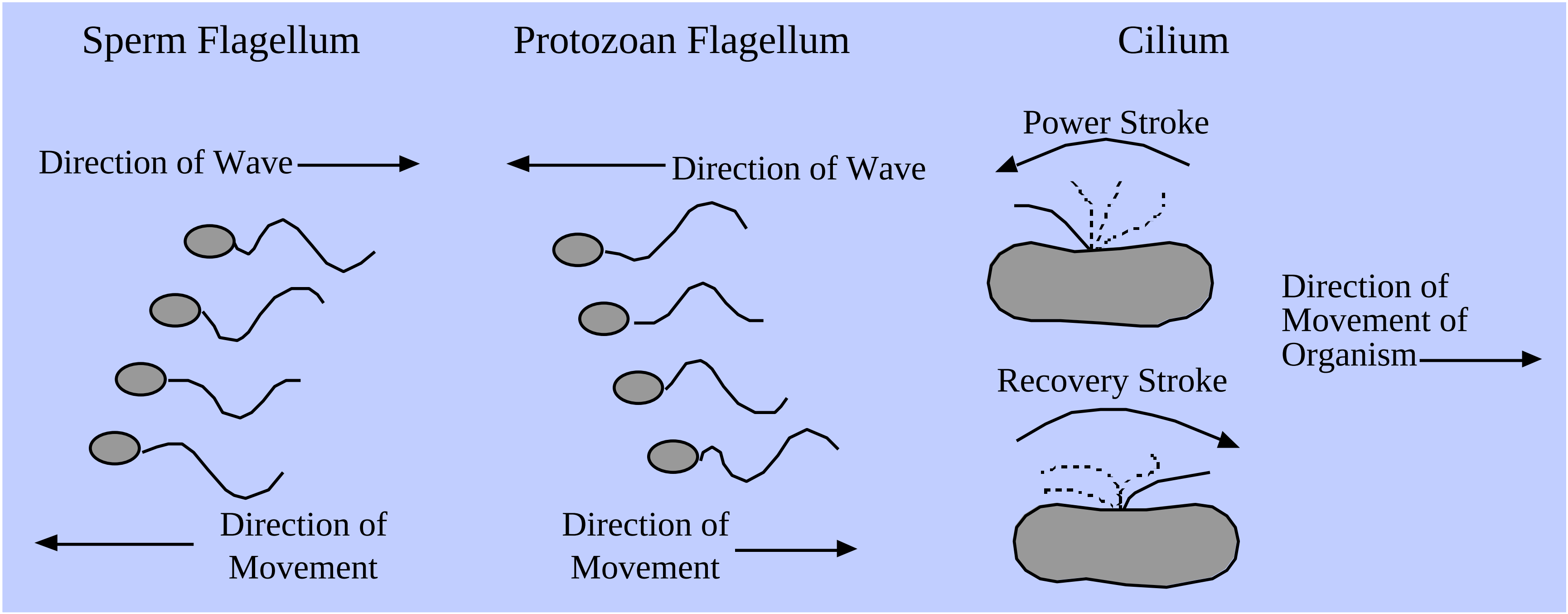

50 nm


Fluorescent Speckle Imaging:
Microtubules in the Mitotic Spindle of a Living Epithelial Cell
C.M. Waterman-Storer
A. Desai
J. C. Bulinski
E.D. Salmon

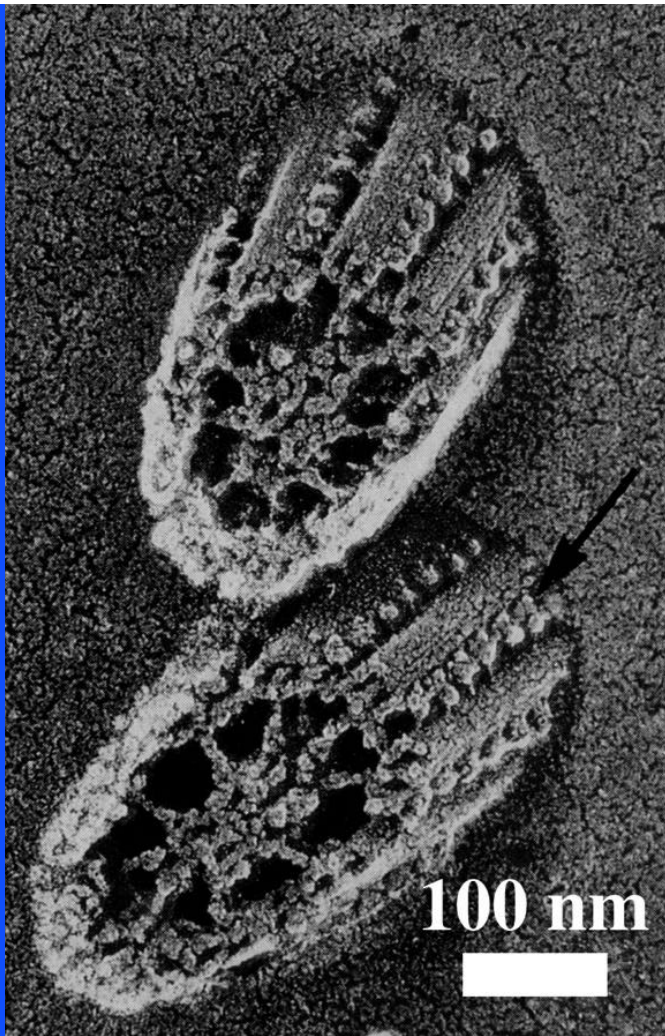


CILIA AND FLAGELLA

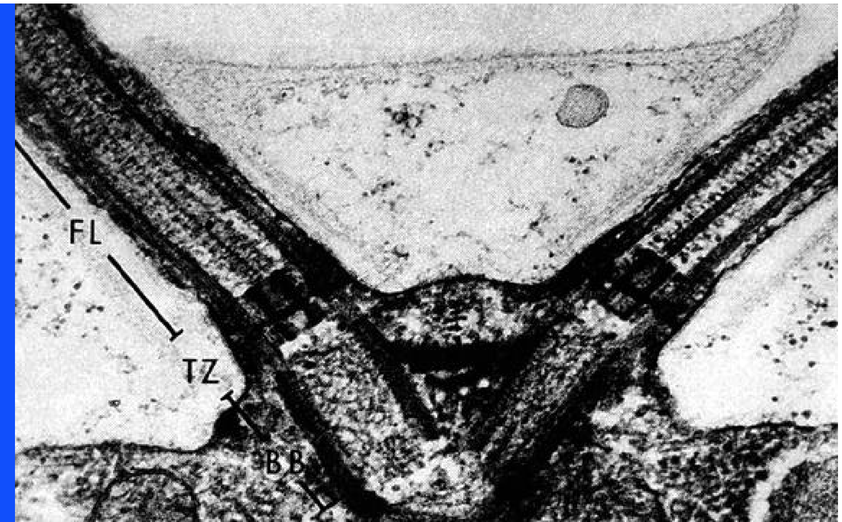
- A bundle of microtubules surrounded by an extension of the cell's membrane forms these actuators.
- Nine pairs of A and B subunits surround a pair of single microtubules.
- Dynein "arms" on A subunits push B subunits and radial "spokes" convert the pushing into bending motion.



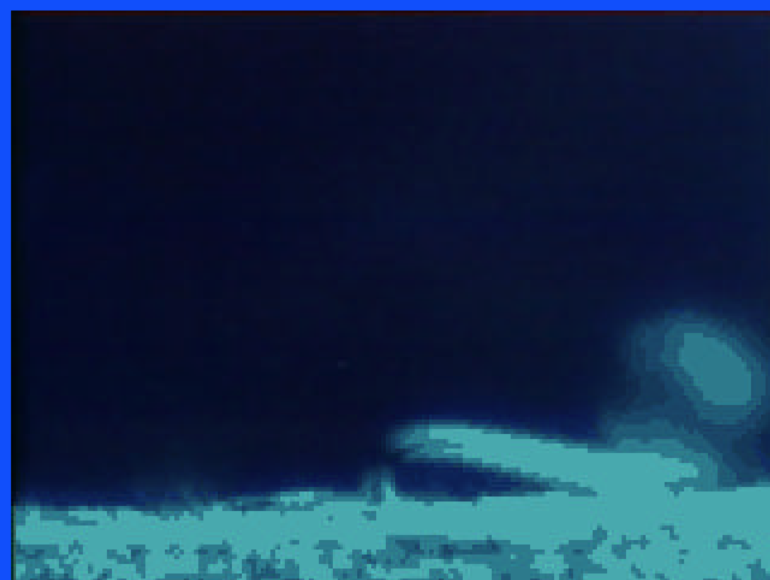
Reference: Darnell, J., Lodish, H., and Baltimore, D., "Molecular Cell Biology," Second Edition, Scientific American Books, W. H. Freeman and Co., New York, NY, 1991.



Source (images): Darnell, J., Lodish, H., and Baltimore, D., “Molecular Cell Biology,” Second Edition, Scientific American Books, W. H. Freeman and Co., New York, NY, 1991.



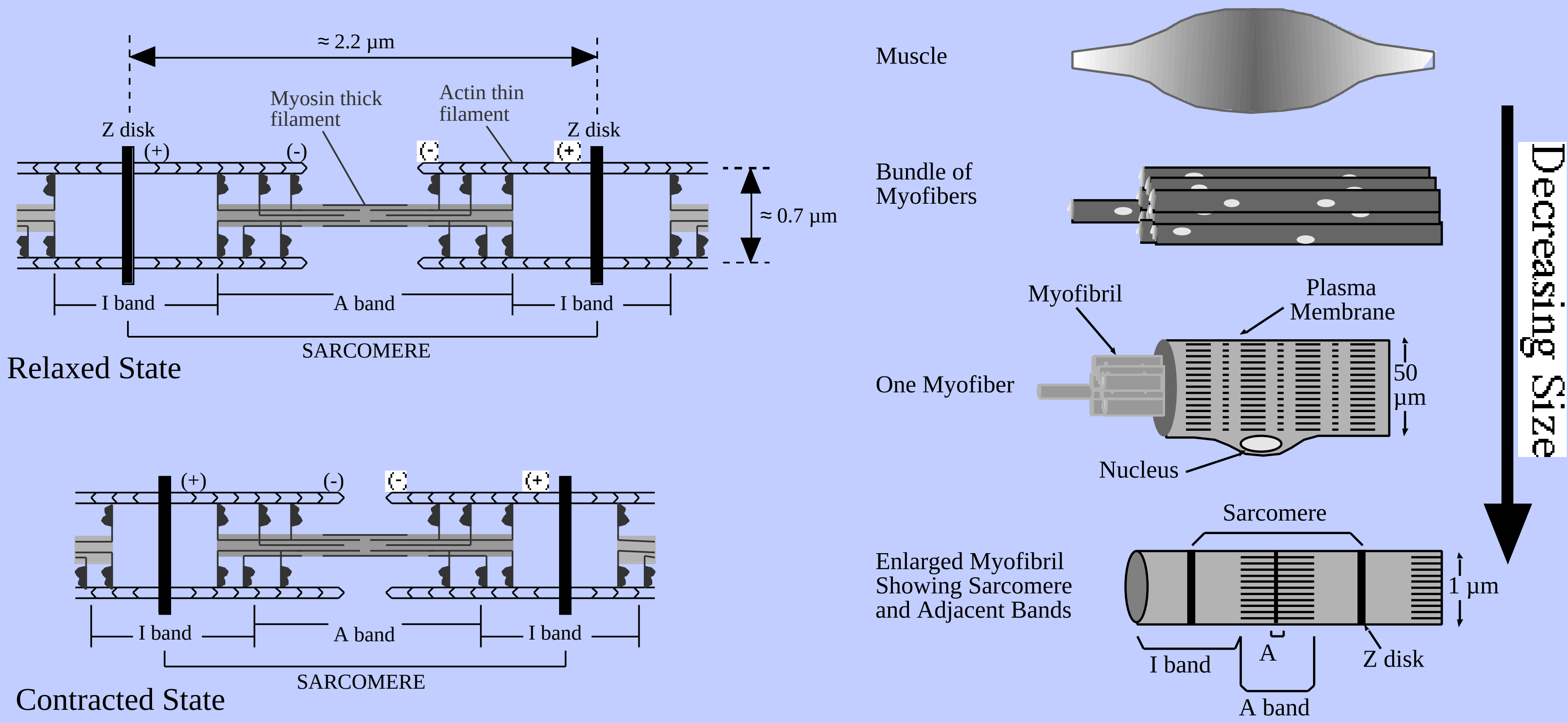
Flagellar basal region.



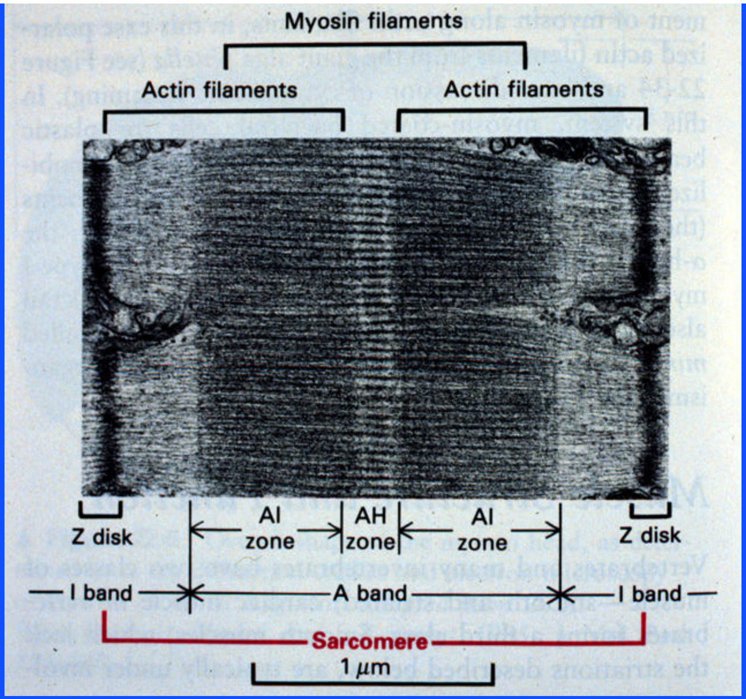
Movie courtesy Prof. H. C. Heller, Stanford University.

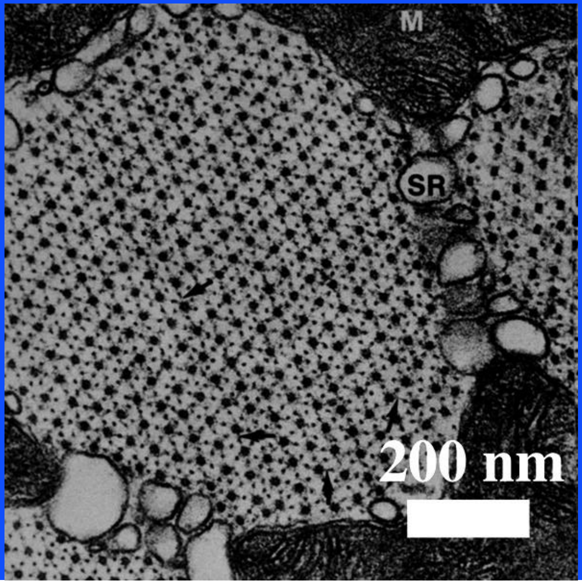
Source: Purves, Orians, Heller, and Sadava, “Life: The Science of Biology,” Sinauer Associates/W.H. Freeman & Co., New York, 1999.

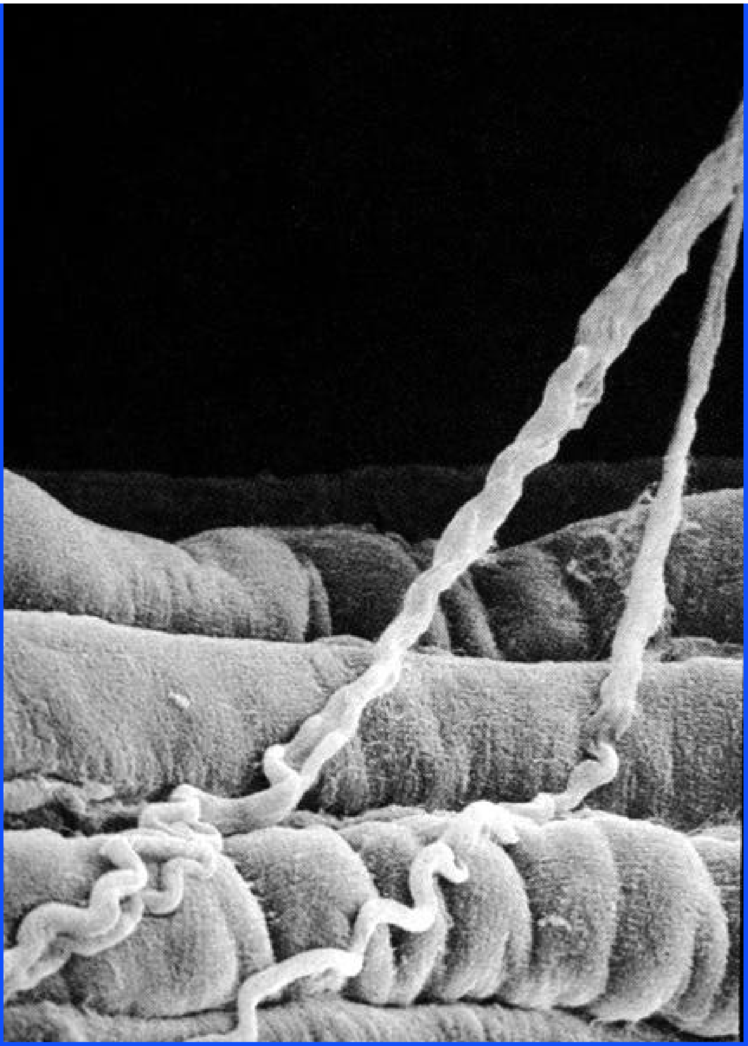
MUSCLES



Reference: Darnell, J., Lodish, H., and Baltimore, D., "Molecular Cell Biology," Second Edition, Scientific American Books, W. H. Freeman and Co., New York, NY, 1991.







Source: Darnell, J., Lodish, H., and Baltimore, D., "Molecular Cell Biology," Second Edition, Scientific American Books, W. H. Freeman and Co., New York, NY, 1991.