# Microelectromechanical Systems (MEMS)

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CS114 Guest Lecture May 11, 2020

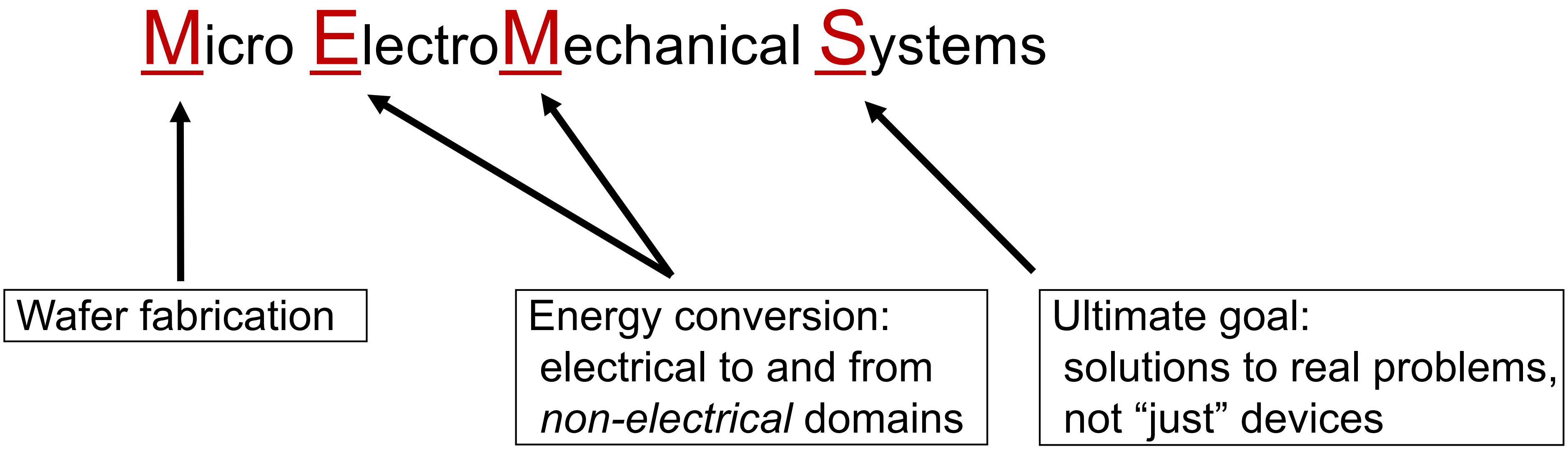
Stanford | ENGINEERING
Electrical Engineering

# Outline

- Background and Stanford History
- Core Technologies
    - *Structures*: fabrication and design of diaphragms, beams, …
    - *Transduction*: moving energy between domains
    - *Electronics*: dealing with tiny signals
    - *Encapsulation*: taming surface phenomena
- Whither MEMS?
    - The MEMS Industry in 2022
    - New challenges: MEMS inside CMOS, intelligent structures for soft robotics

# MEMS:

Devices with microscale dimensions (30 nm – 300 μm), typically made using “wafer fabrication” – the tools and processes developed by the semiconductor industry



Micro ElectroMechanical Systems

Wafer fabrication

Energy conversion:
electrical to and from
*non-electrical* domains

Ultimate goal:
solutions to real problems,
not “just” devices

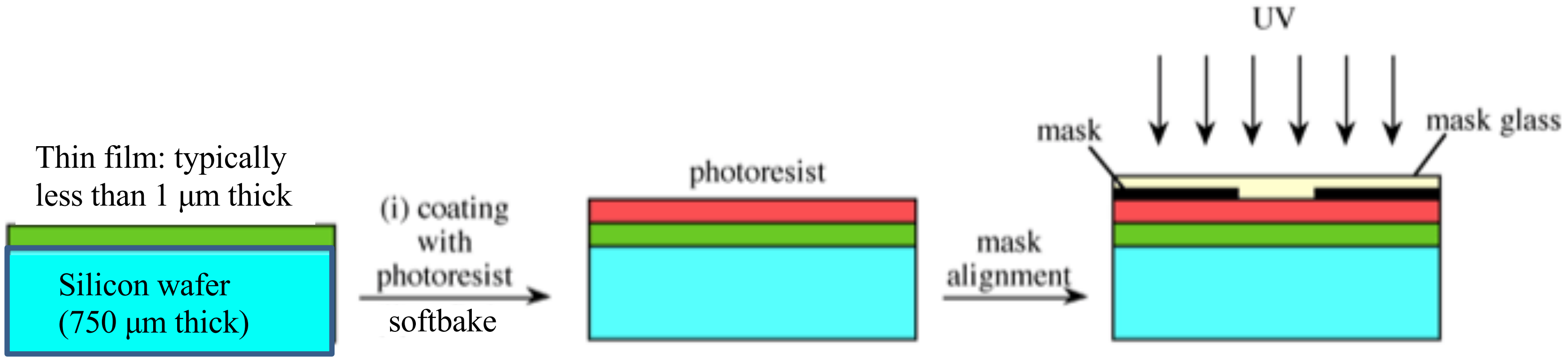
# *Not* MEMS

The **DENSO Micro-Car** is a miniature version of Toyota's first passenger car, the 1936 Model AA sedan. Its size is astounding: 1/1000th the size of the actual car or about the size of a grain of rice. Dimensions are: 4.785 mm X 1.73 mm wide X 1.736 mm tall.

The Micro-Car has a total of 24 parts which come in 13 different types including body, tires, spare tire, wheels, axle, bearings, headlights, rear lights, front bumper, rear bumper, step, number plate and emblem. A 0.67 mm-sized magnetic motor consisting of five different parts including a magnet and core powers the tiny car. When supplied with 3V, 20 mA of AC current through an 18-micron-diameter copper wire, the motor reach 600 rpm.

"microtechnology demonstrator" circa 1994
http://japanesenostalgiccar.com/the-worlds-smallest-car-is-a-toyota-aa/

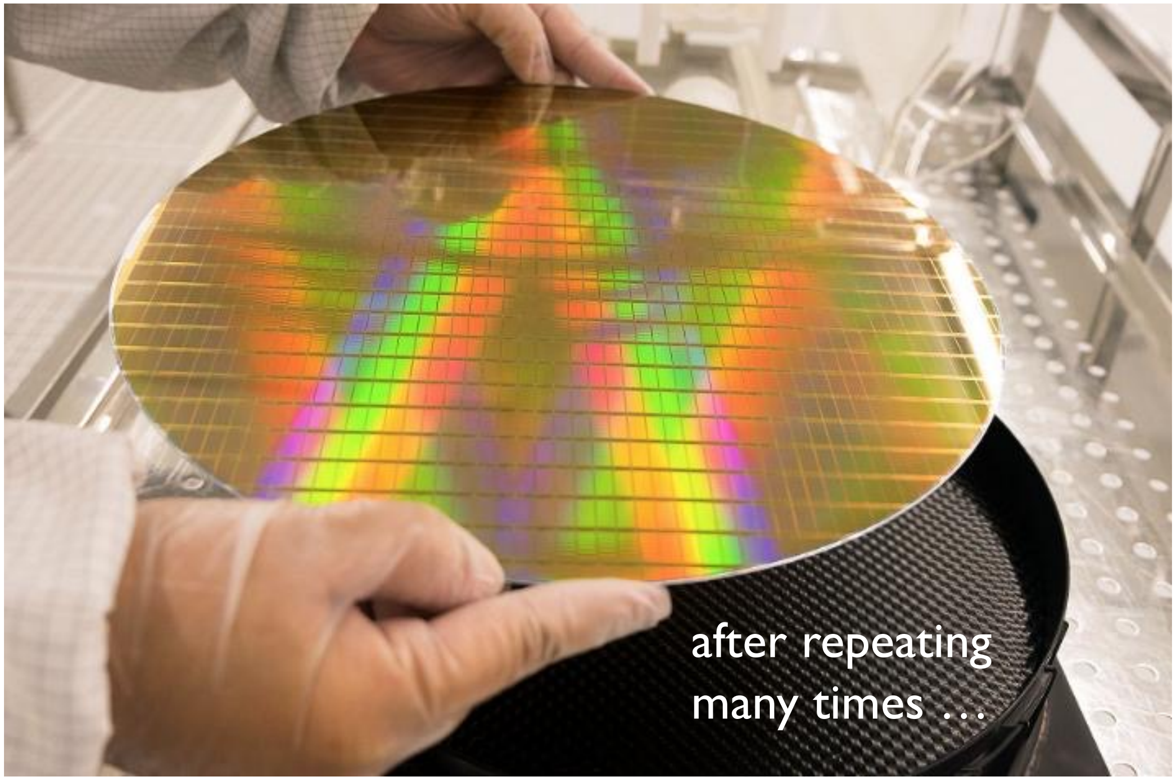
# Wafer Fabrication



Thin film: typically less than 1 μm thick

Silicon wafer (750 μm thick)

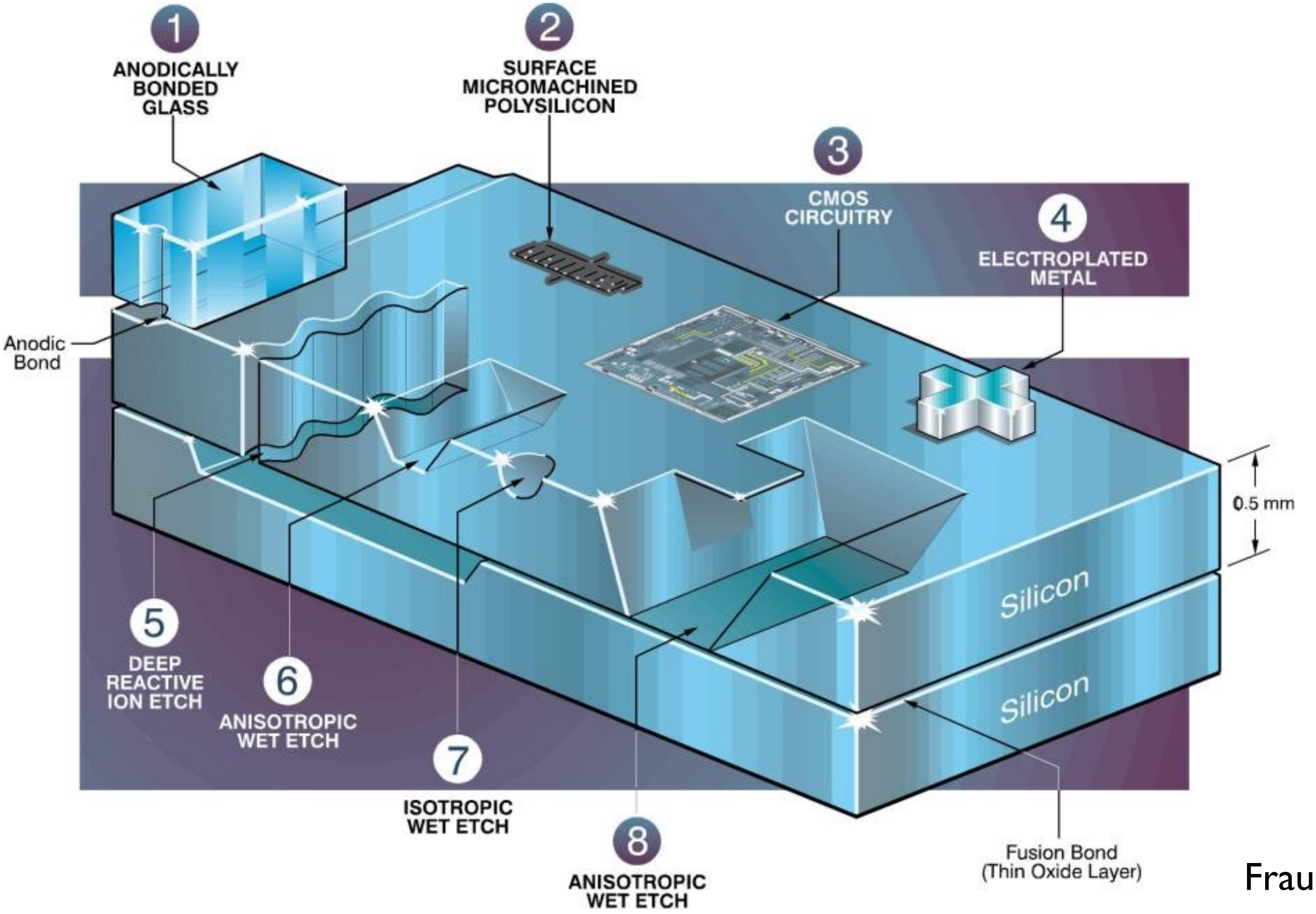
softbake



after repeating many times …

# Making More than Circuits

To make 3D structures, several techniques have been developed as extensions of wafer processing

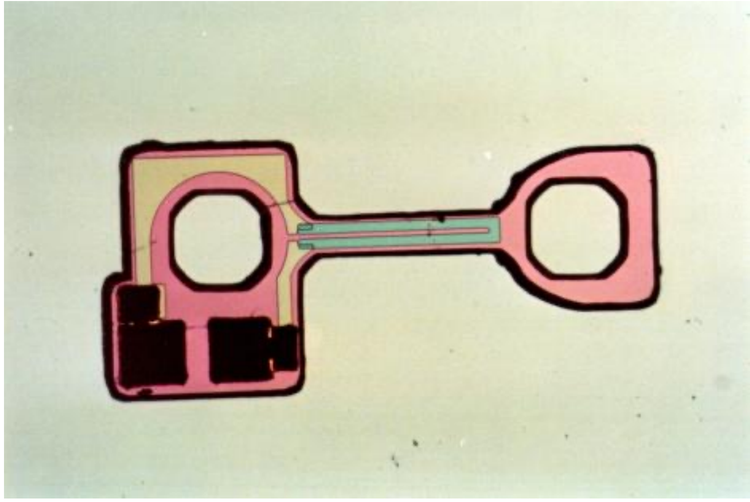


Fraunhofer Institute

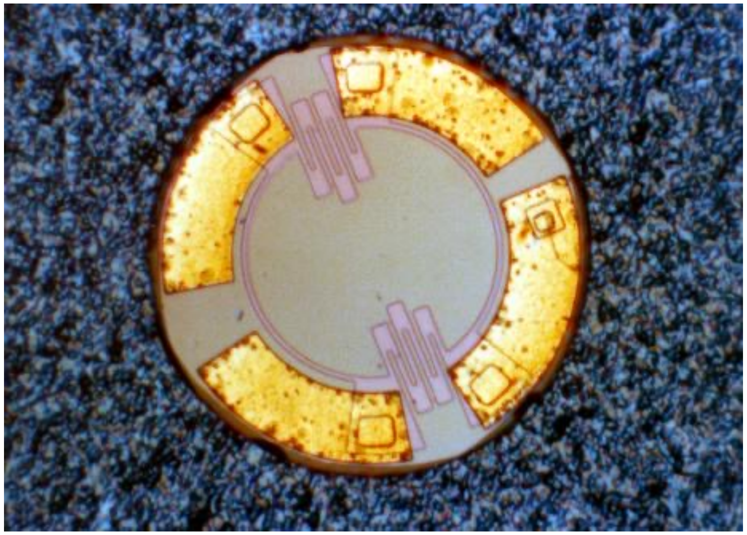
# How did this field get started?

- At a welcome breakfast for Medical School faculty in 1960, who had just moved from San Francisco to Stanford
- Thomas Nelsen (Surgery) asked Jim Angell (EE) about an article he'd read about "miniature electronics" – he wondered if the technology could be used to make biomedical implantable devices.
- The question at breakfast led to a decade-long collaboration that led to the first silicon smart sutures and implantable pressure sensors.

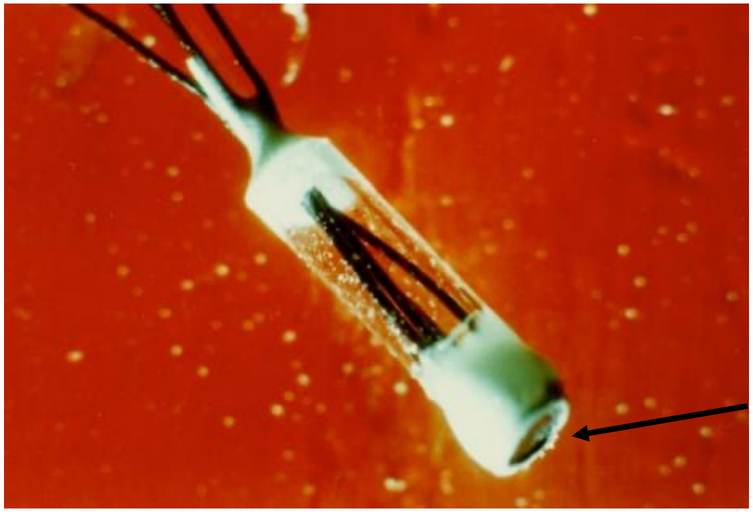
# Silicon Implantable Devices



Silicon “smart suture” with built-in force-sensing resistor



Silicon diaphragm pressure sensor



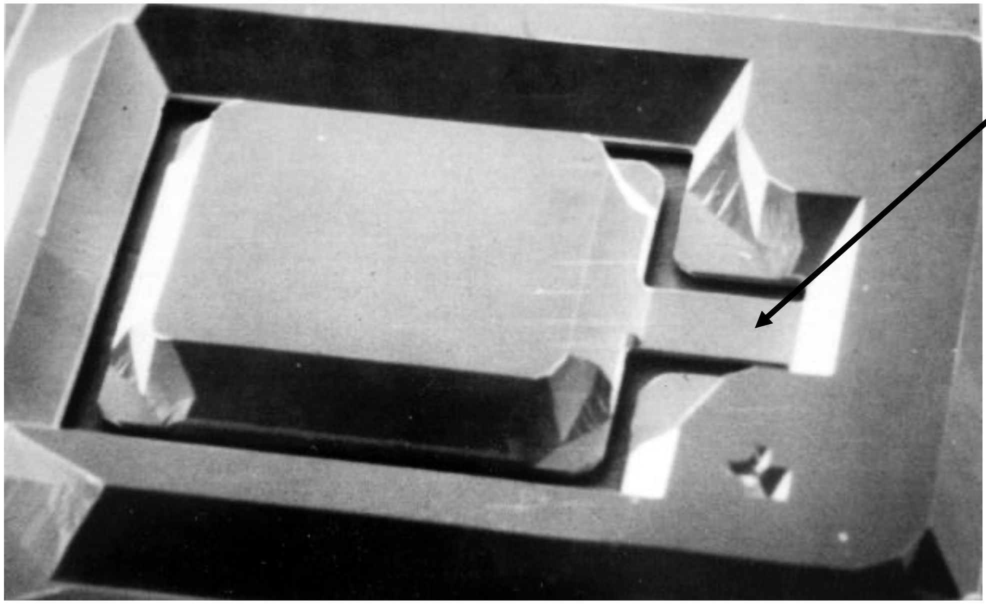
Pressure sensor on catheter tip

T. S. Nelsen and J. B. Angell, 1960s

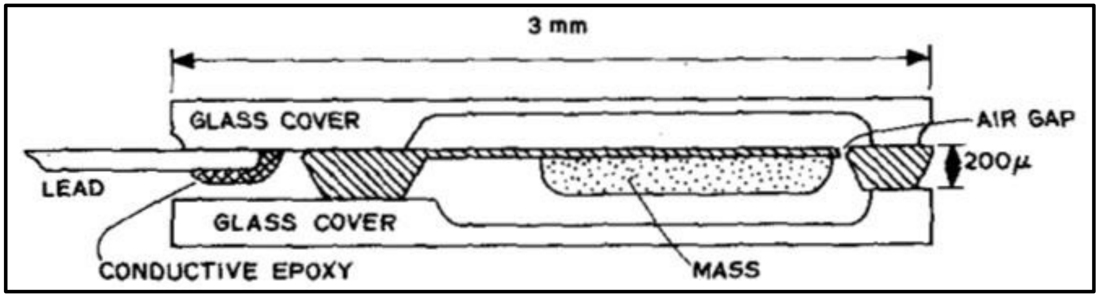
# What Next?

- Heart pacemakers had been invented and first used in patients in 1958 by researchers in Sweden
- A major drawback was that the pacemaker had a single pace, whatever the patient was doing – sleeping or running up stairs
- In the early 1970s, Jim Angell and his graduate student, Lynn Roylance, developed the concept of incorporating an activity monitor into the pacemaker … how to do that?

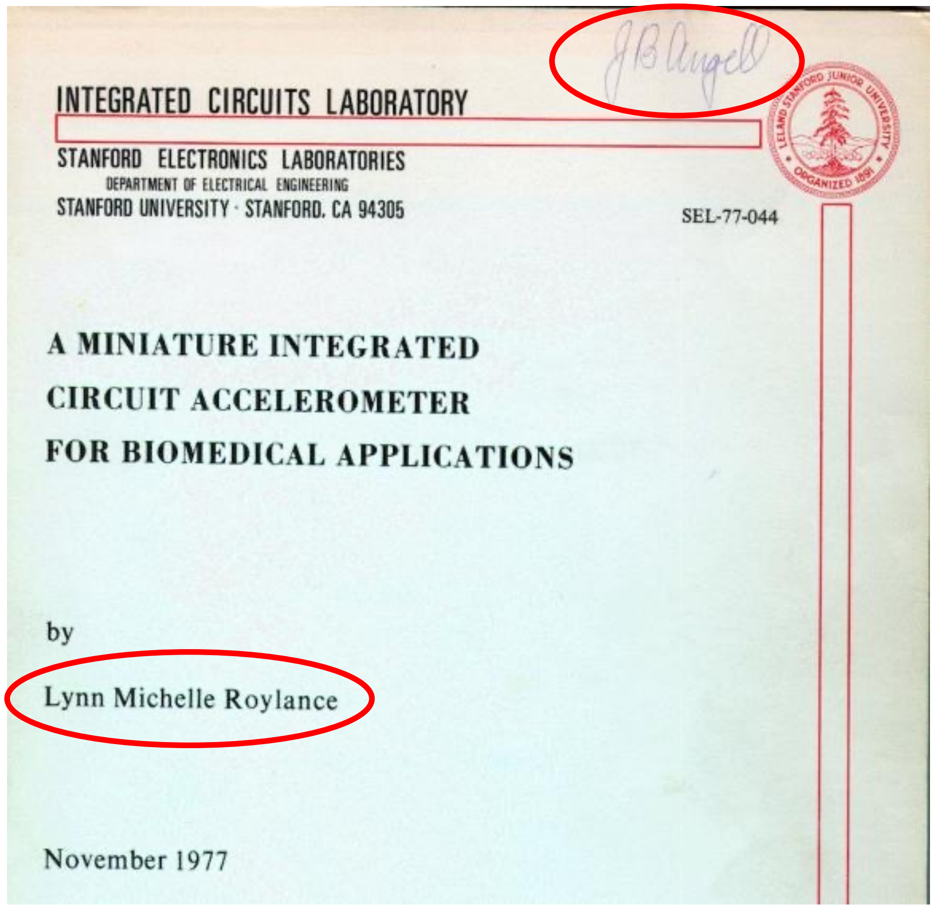
# Miniature Silicon Accelerometers



Strain-sensing resistors are built into the suspension beam



Cross section of the accelerometer



J B Angell

INTEGRATED CIRCUITS LABORATORY

STANFORD ELECTRONICS LABORATORIES
DEPARTMENT OF ELECTRICAL ENGINEERING
STANFORD UNIVERSITY · STANFORD, CA 94305

SEL-77-044

**A MINIATURE INTEGRATED**
**CIRCUIT ACCELEROMETER**
**FOR BIOMEDICAL APPLICATIONS**

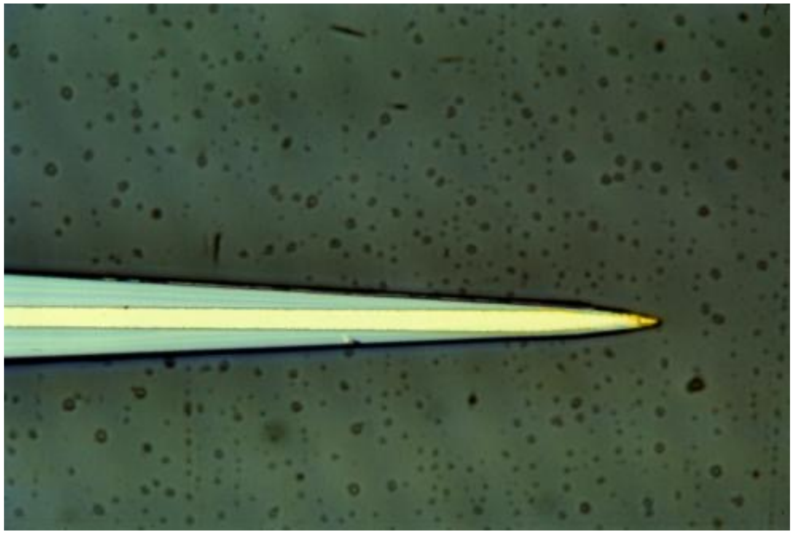
by

Lynn Michelle Roylance

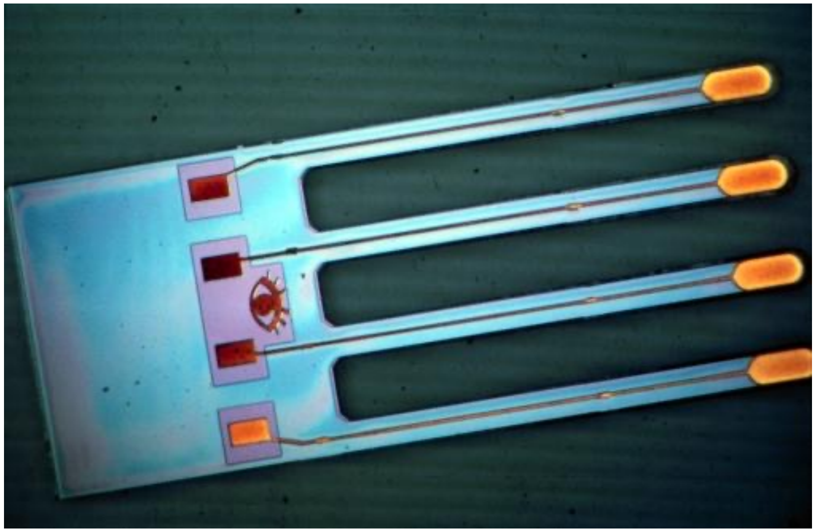
November 1977

Pacemakers with silicon accelerometers were finally introduced in the 1990s

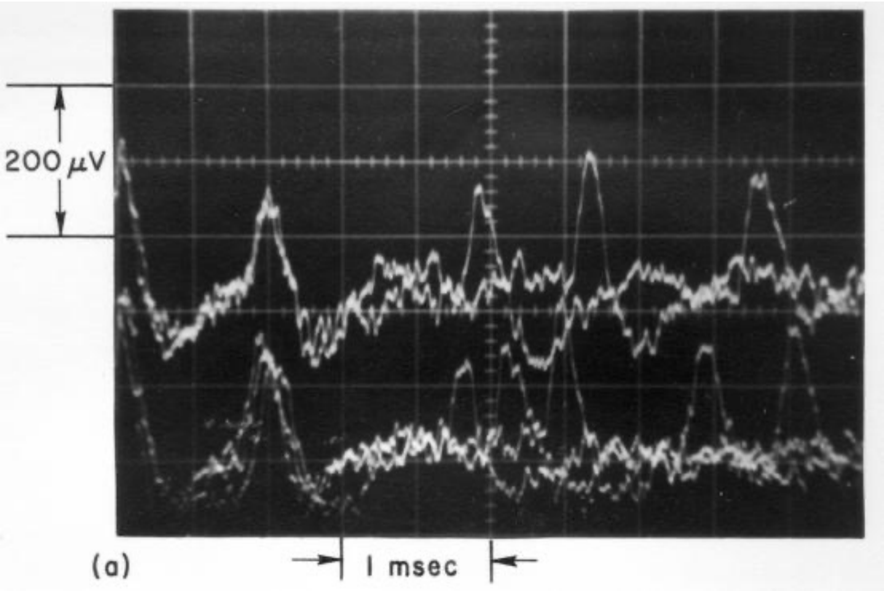
# Neural Probes



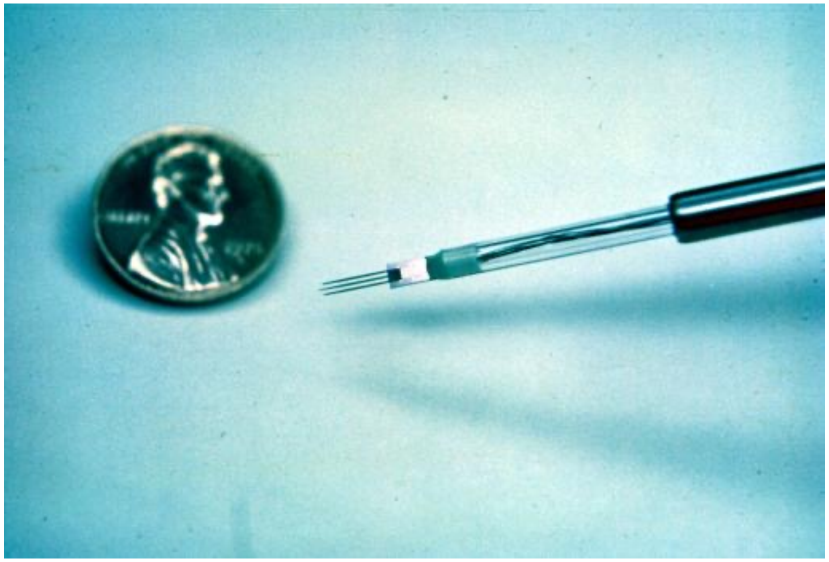
First silicon recording probe, 1968



Four channel stimulating probe, 1971



Neural voltage recording



Ken Wise and Jim Angell, Stanford EE

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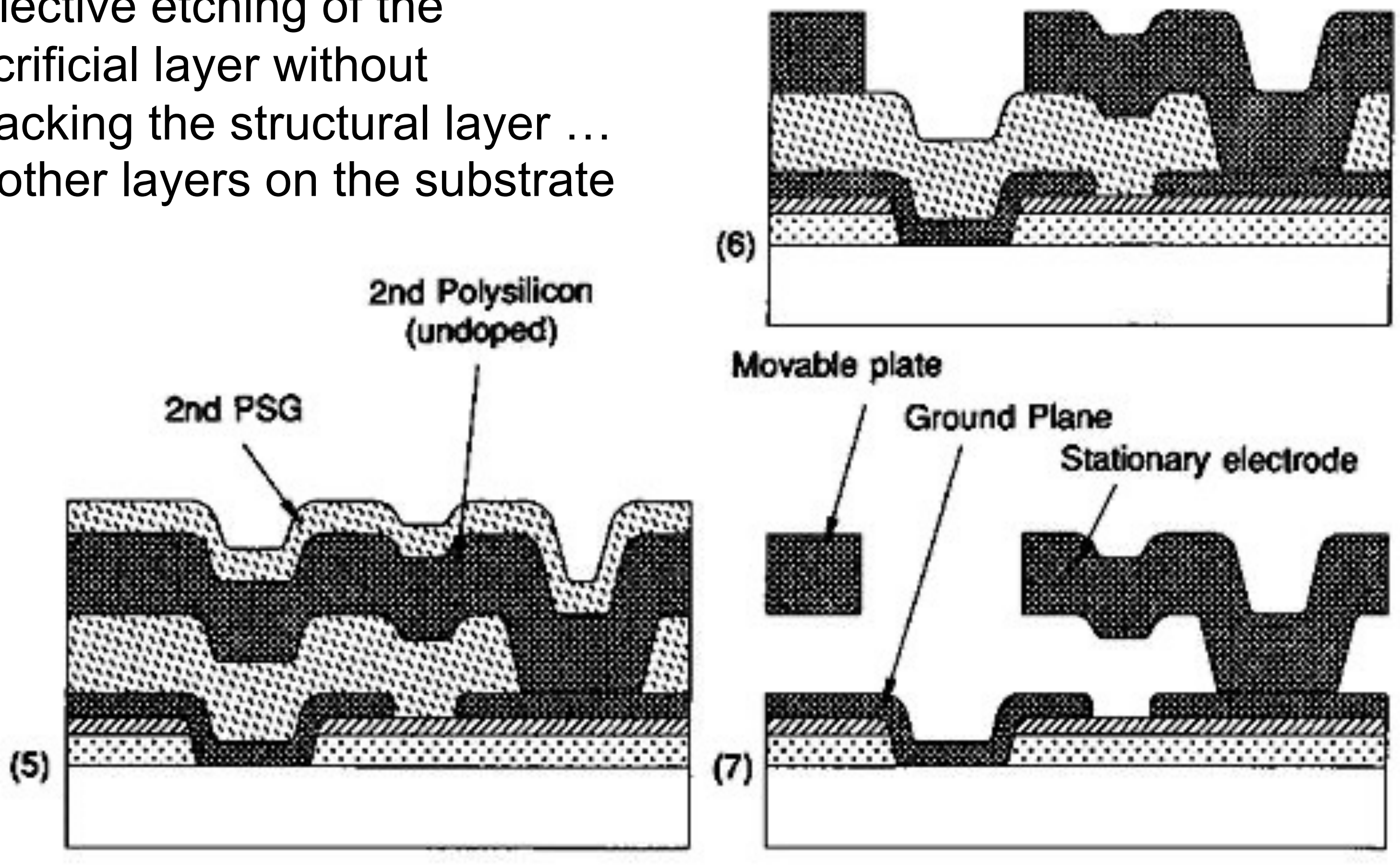
# Surface Micromachining

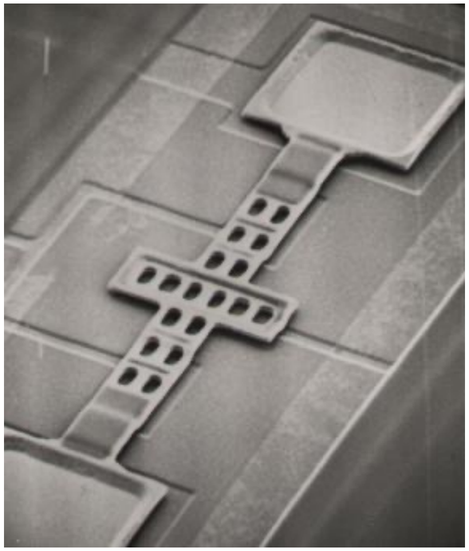
Basic Requirement:

Selective etching of the sacrificial layer without attacking the structural layer … or other layers on the substrate

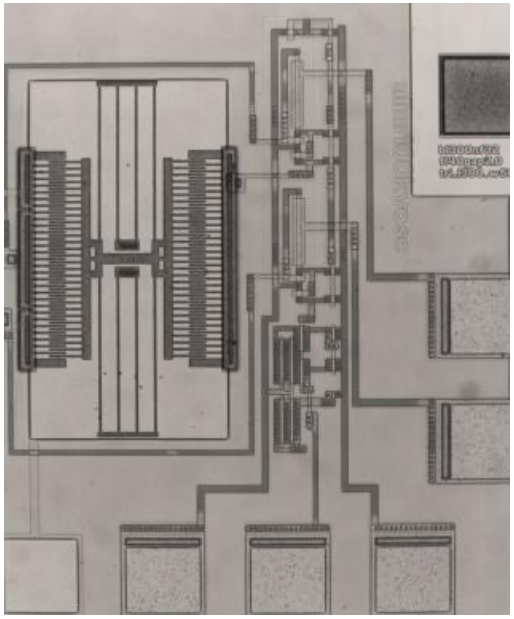


W. C. Tang, Ph.D. Thesis,
Dept. of EECS, UC Berkeley, 1990

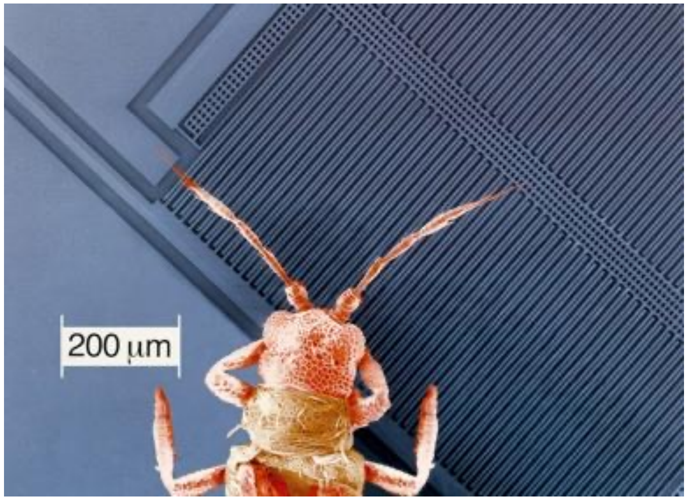
# Polysilicon Microstructures



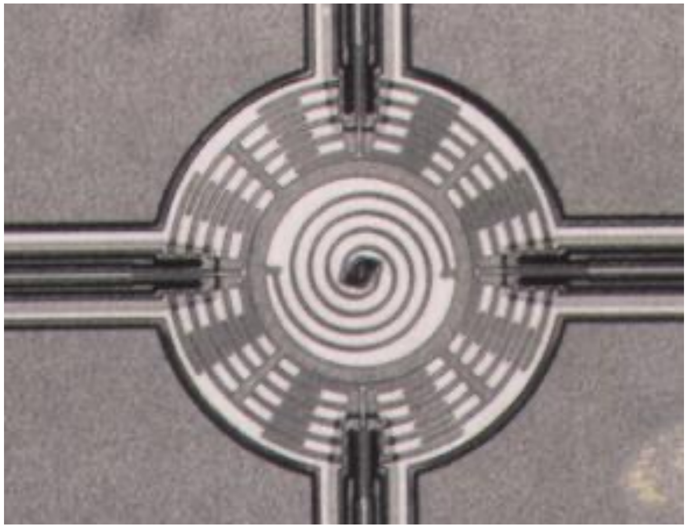
R. T. Howe and R. S. Muller 1983



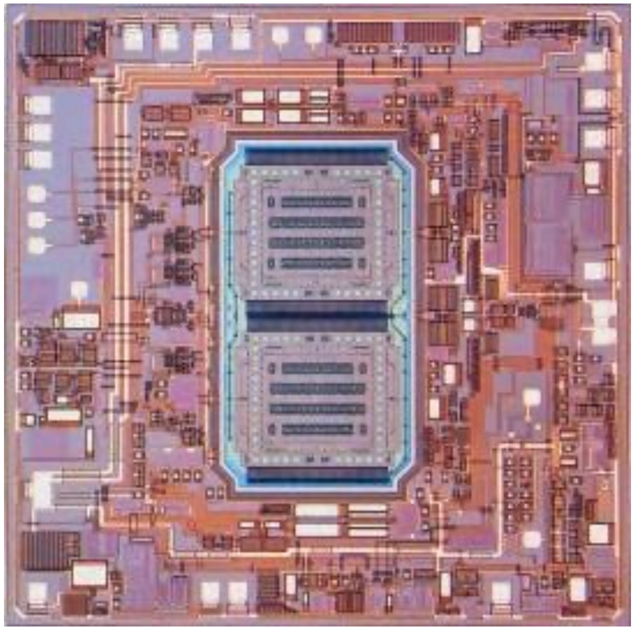
C. T. Nguyen and R. T. Howe 1993



Bosch Sensortech accelerometer

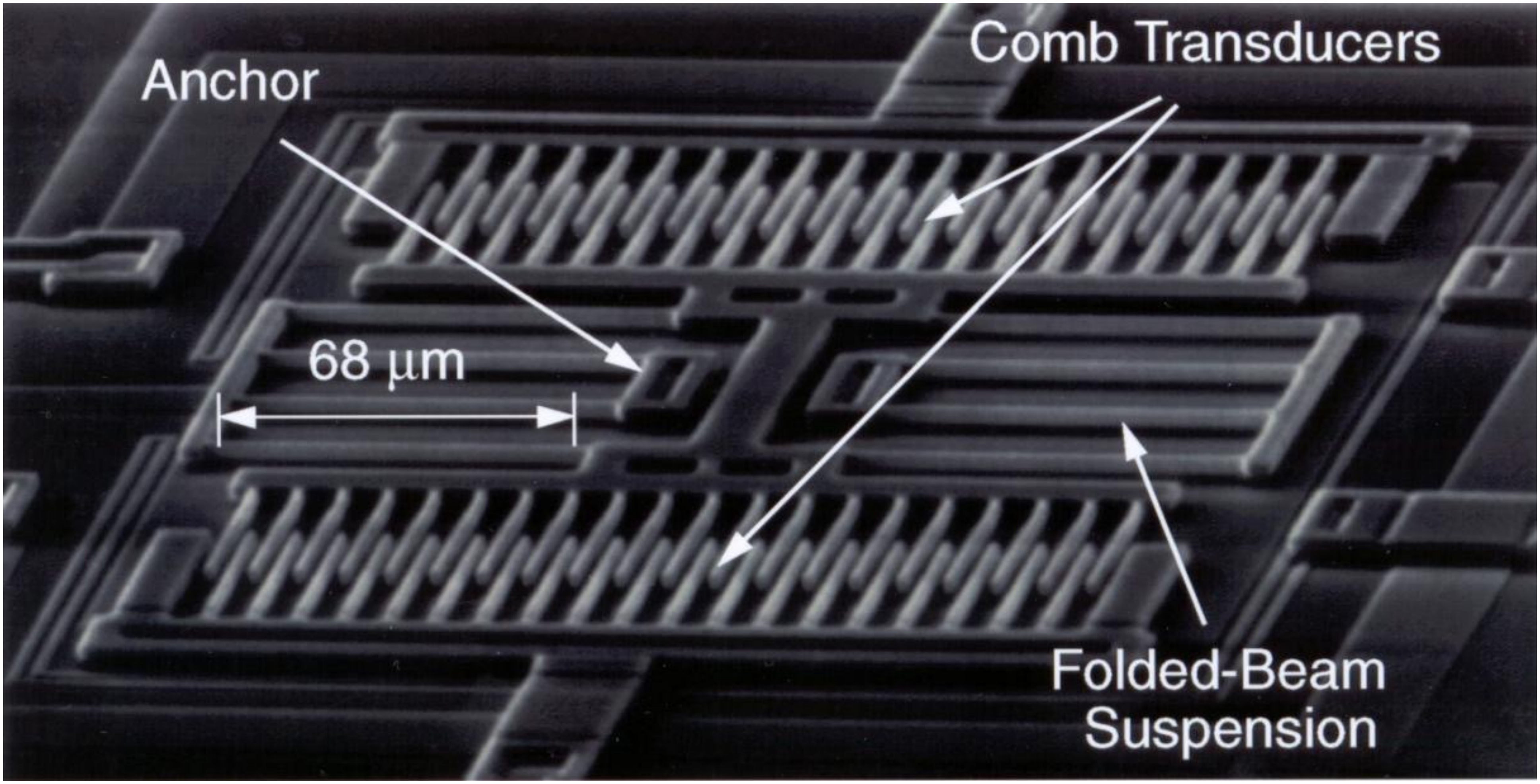


W. C. Tang and R. T. Howe 1988



Analog Devices rate gyroscope

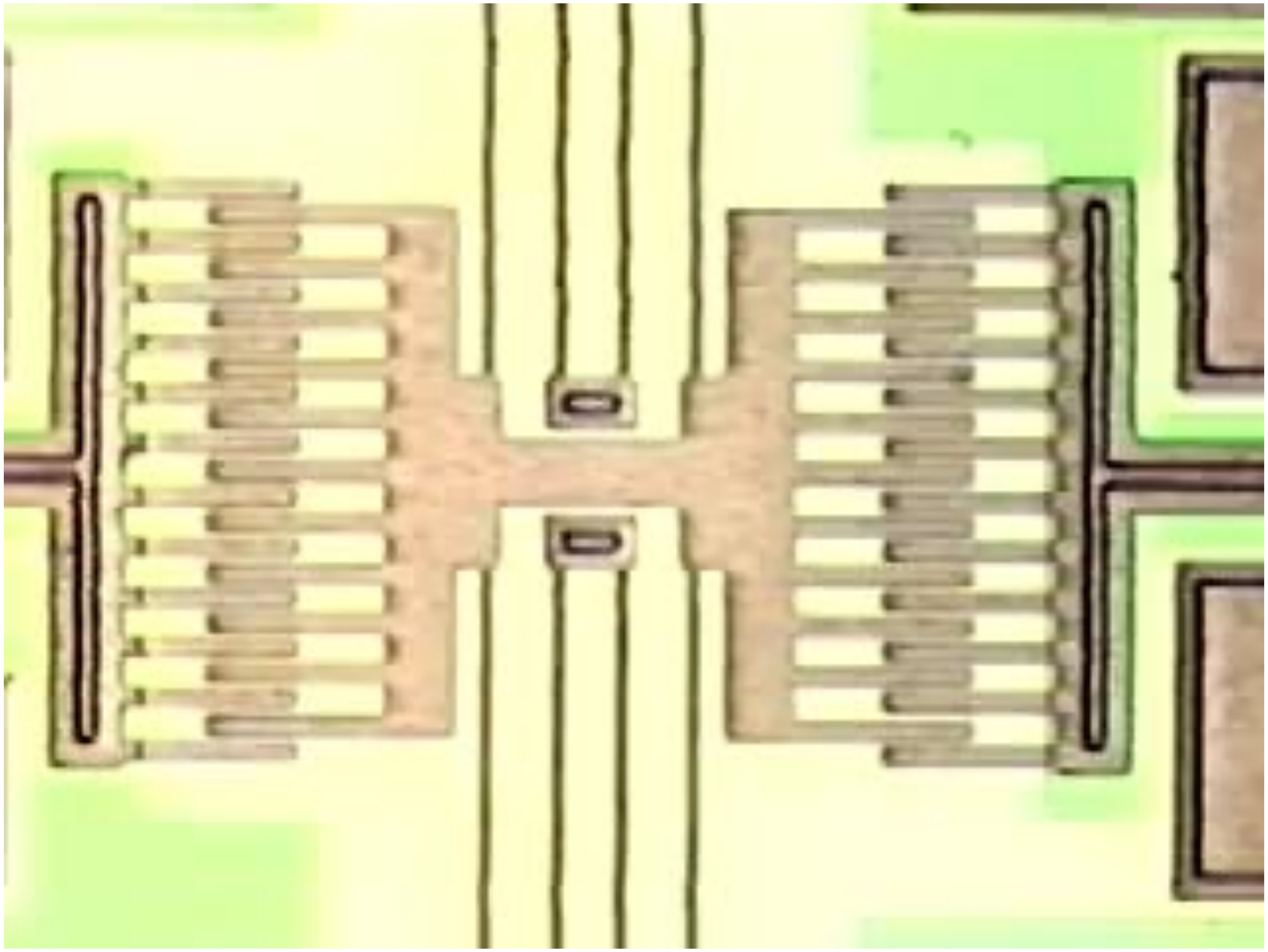
# Polysilicon Lateral Resonator



Clark T.-C. Nguyen and R. T. Howe, IEEE IEDM 1993.

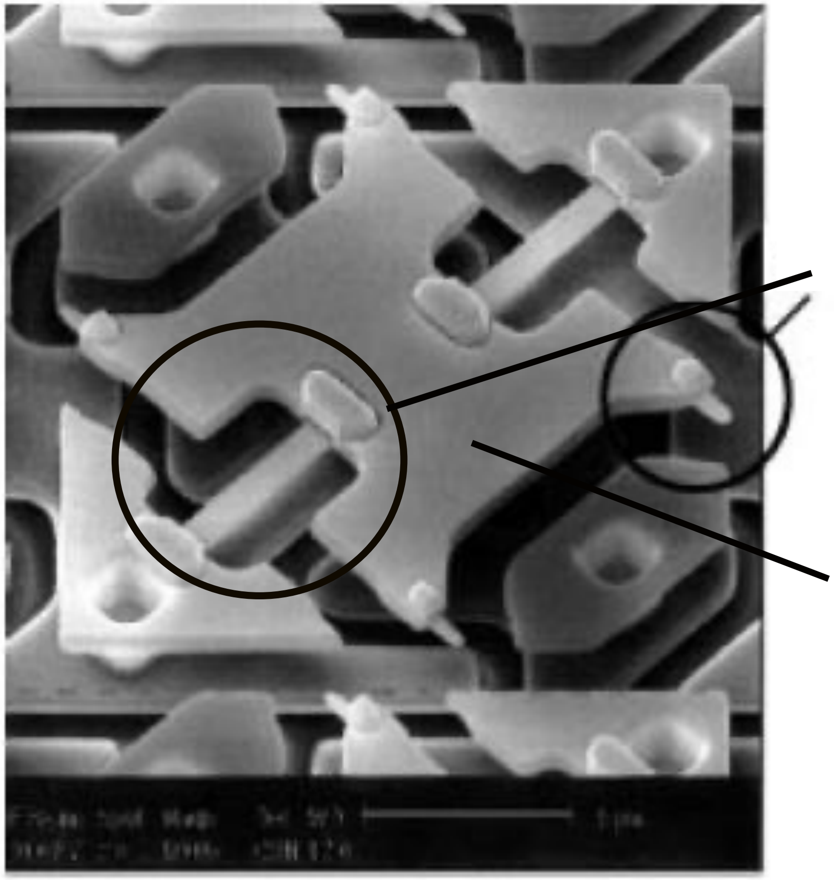
# Polysilicon Resonator in Action

DC + AC voltage on interdigitated comb causes electrostatic force on shuttle.



William C. Tang and R. T. Howe, Dept. of EECS, UC Berkeley

# Texas Instruments Digital Mirror Device



Spring tip and hinge ≈ 50-60 nm amorphous $TiAl_3$-O(4%)

Yoke $TiAl_3$-N(2-4%): low strain gradient

*Not shown*: the mirror on top of the yoke

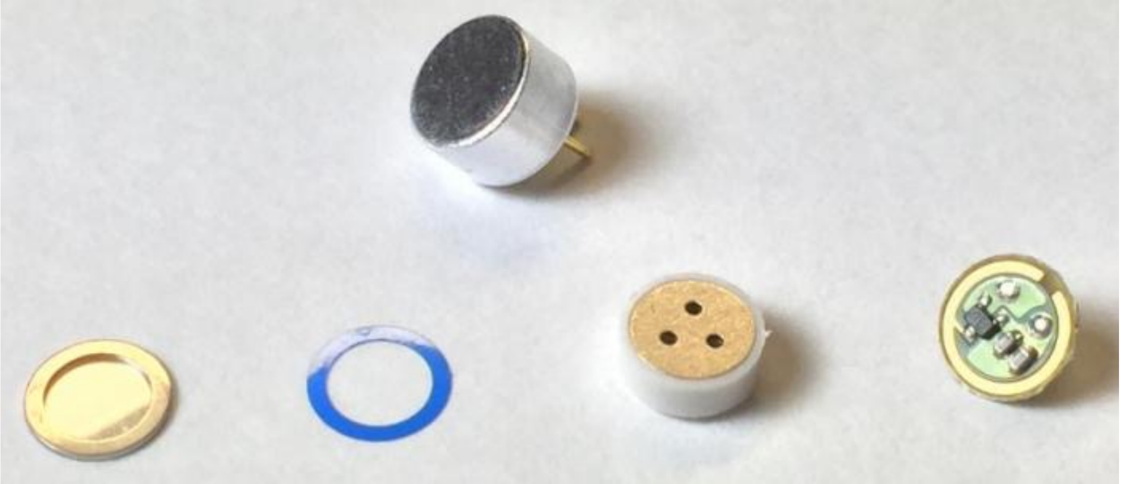
> 1,000,000 mirrors per chip

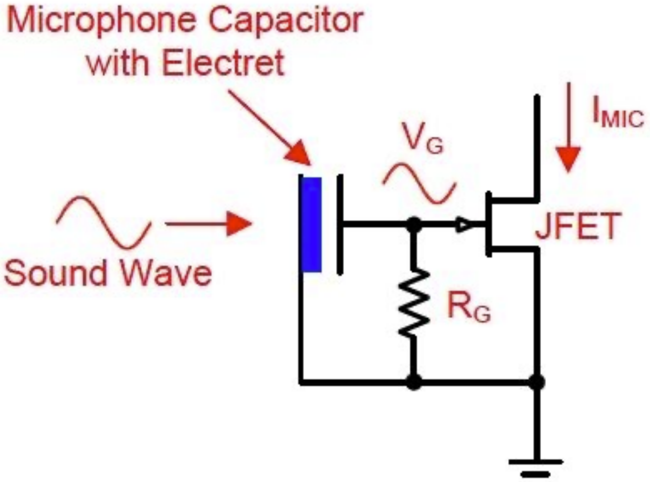
John Tregilgas, "How we developed an amorphous hinge material," *Advanced Materials and Processes*, Jan. 2005, 46.

# The Electret Microphone

The electret microphone was invented at Bell Labs in 1962 by James West and Gerhard Sessler, who discovered that a thin metallized teflon foil could be polarized to create a long-lasting electric dipole moment … dominates market by 1970s.

J. West and G. Sessler, 1960s





$Q_{electret}$ = constant, $C_{\text{mic}} = f(\text{sound pressure}) \rightarrow \quad V_{mic} = V_G(t)$.

J. Caldwell, “Single-Supply, Electret Microphone Pre-Amplifier Reference Design,”Texas Instruments, TIDU765, Jan. 2015

# Why Replace the Electret Microphone?

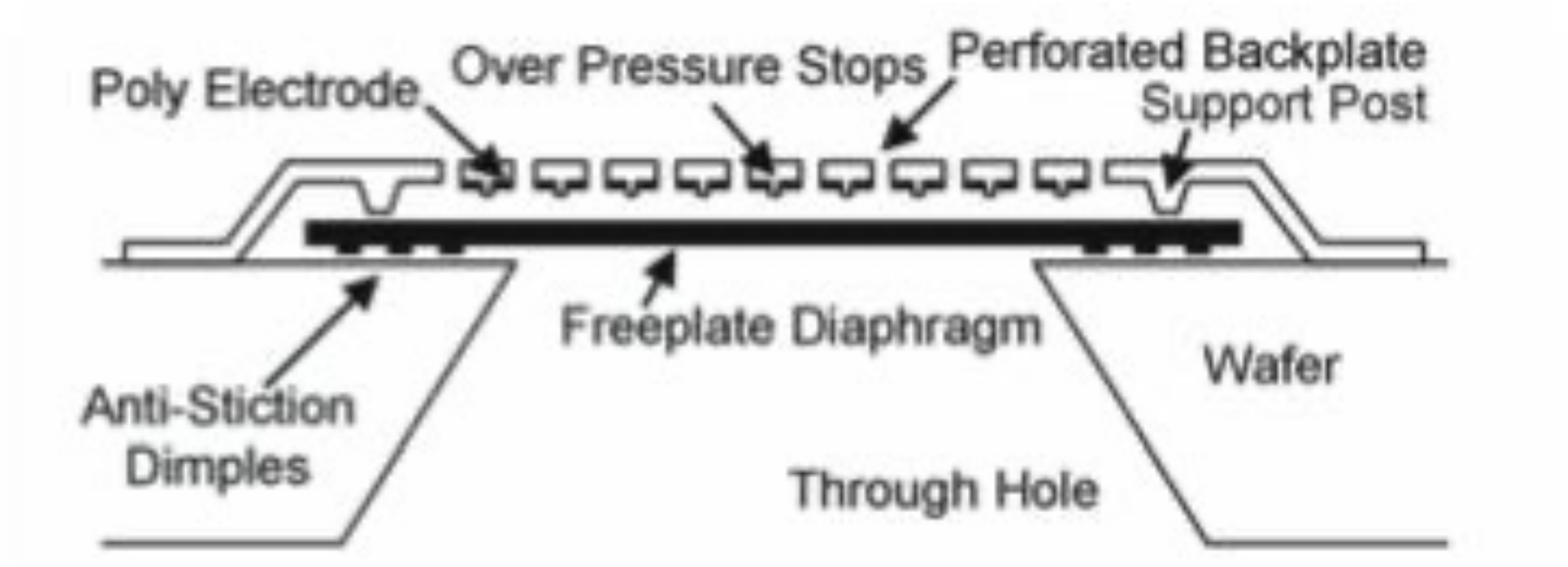
- Electrets depolarize at the temperatures required by RoHS[*]-compliant (lead-free) solder
- Package is incompatible with electronic automated assembly equipment, so it must be hand-soldered → expensive to re-work. Multiple microphones per mobile device (*e.g.*, for background noise cancellation) make this problem worse
- CMOS audio signal processing chip can't be integrated into an electret microphone package

Result: rapid adoption of MEMS microphones, *once they were technically feasible*

[*] RoHS = Restriction on Hazardous Substances Directive, EU– 2002/95/EC

# Free-Floating Polysilicon Diaphragms

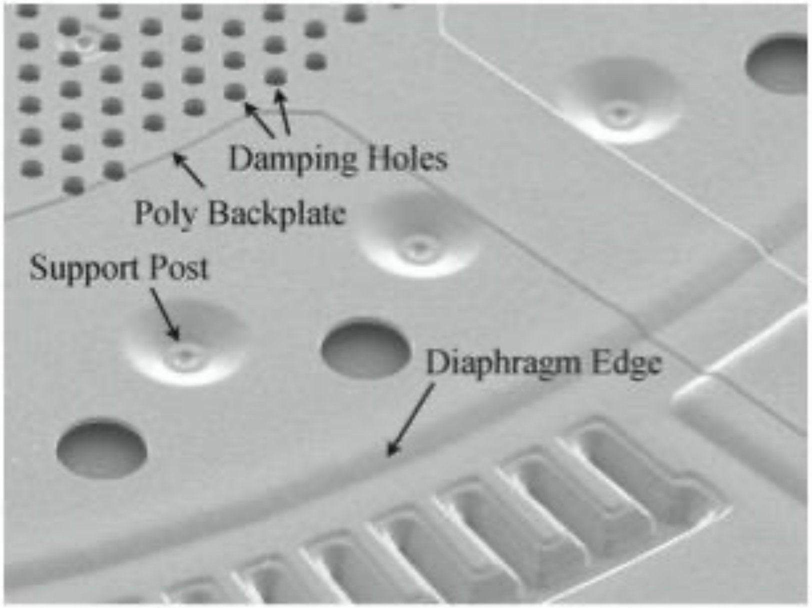
Microphones require *stress-free* diaphragms:

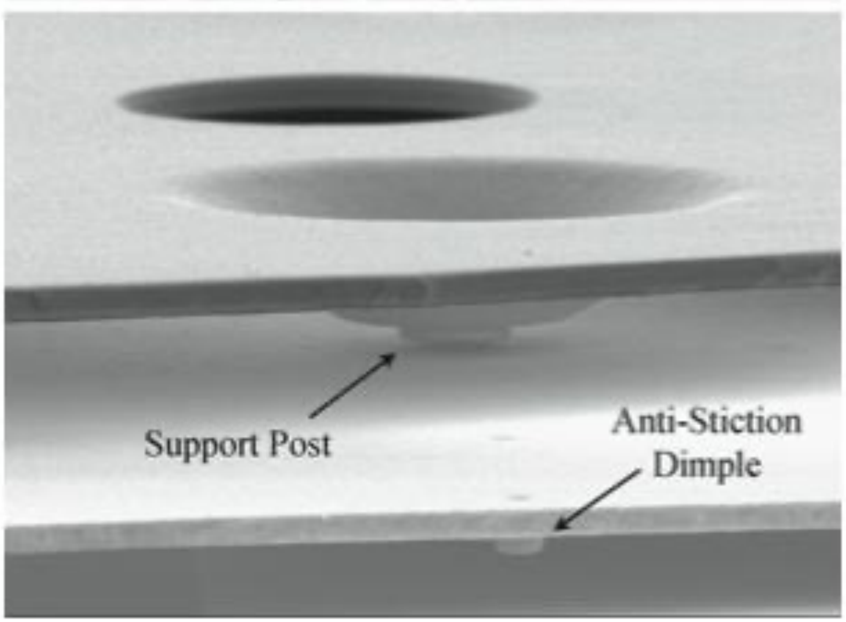


*Solution*: complete release of diaphragm: support posts and dimples keep it from floating away from the substrate

P. V. Loeppert and S. B. Lee, (Knowles Electronics), *Hilton Head Workshop*, June 2006.

# Polysilicon Capacitive Microphone





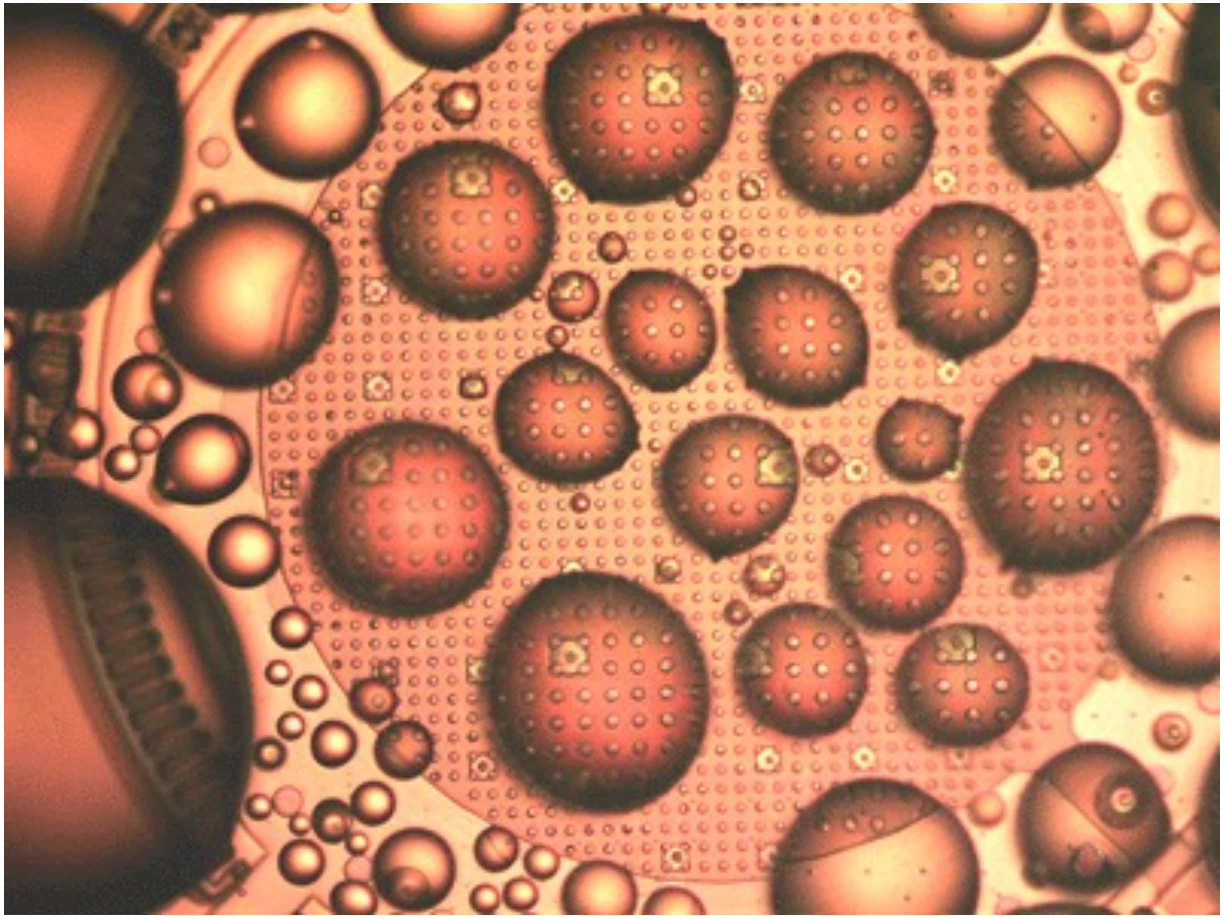
10 mask process, 1.6 mm x 1.6 mm die size, 200 mm wafers
→ 46,000 dice/wafer at 100% yield (circa 2012)
Wafer cost ~ \$1000/wafer ⇒ cost/die ~ 2.1 ¢

5 x $10^9$ microphones/year, Knowles has roughly 25% of the market
→ production rate: 34 x $10^6$ *per day*

(only around 740 wafers/day)

P. V. Loeppert and S. B. Lee, (Knowles Electronics), *Hilton Head Workshop*, June 2006.

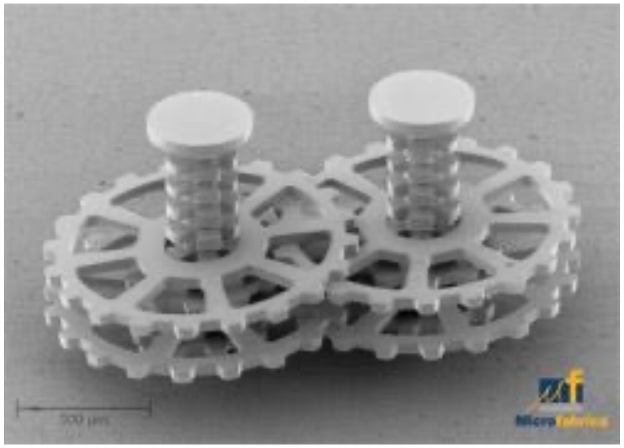
# Free-Floating Diaphragm: Preventing Stiction

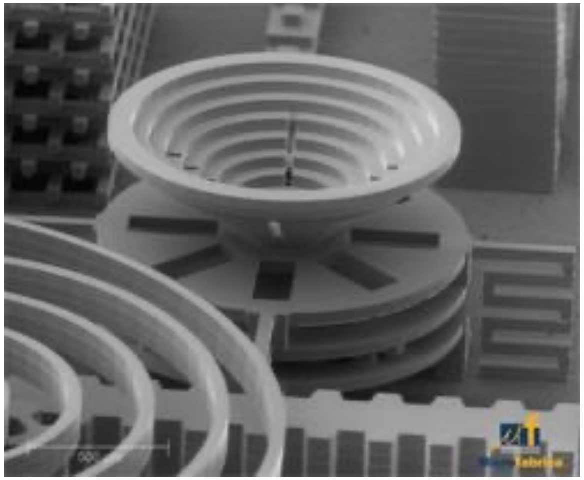


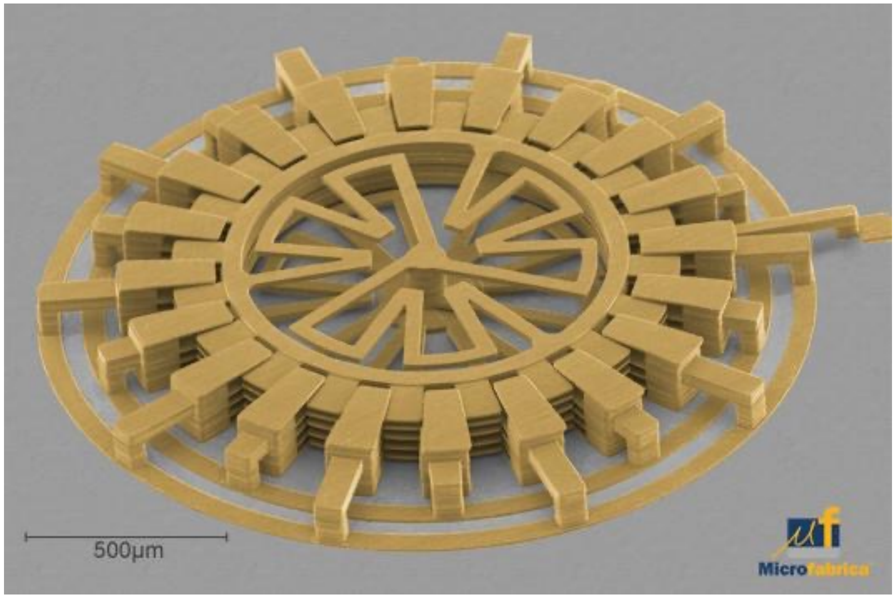
A self-assembled monolayer organic film forms an ultra-hydrophobic surface that allows the diaphragm to pop up after surface tension from drying water droplets cause its collapse

Courtesy of Peter Loeppert, Knowles Electronics.

# Metal Micro Machines







Key: polishing after each electrodeposition step

www.microfabrica.com
Van Nuys, California

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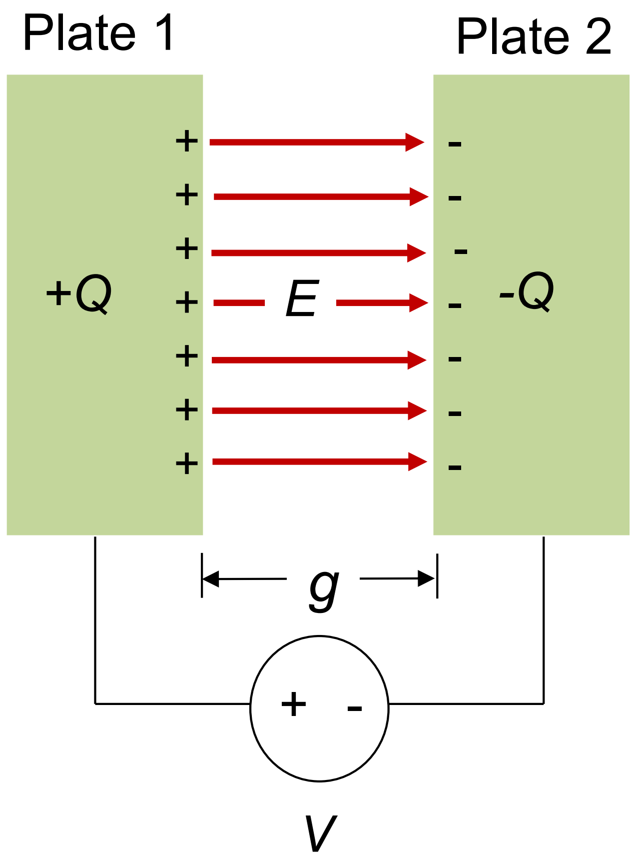
# Force Scaling with Dimension *s*

- Surface tension: $F \propto s^1$
- Electrostatics: $F \propto s^2$
- Shape memory alloy: $F \propto s^2$
- Pressure (hydraulics): $F \propto s^2$
- Electromagnetics: $F \propto s^4$

W. Trimmer and R. Jebens, Actuators for Micro Robots, *Int. Conf. on Robotics and Automation*, Scottsdale, Ariz., May 1989, pp. 1547 – 1552.

# Electrostatic Forces



Plates are made of the same conductor (silicon, polysilicon, or metal)

*Q* : electrical charge – proportional to voltage

*E* : electric field – voltage divided by the gap *g*

Resulting force is proportional to the square of the voltage and is always attractive (plates pulled together)

# Electrostatic Actuators: the Good

a) “Free” in surface micromachining processes, since isolated conductors are all that’s needed

b) Low power: parasitic $i^2R$ losses in conductors and interconnects are small since the current is small

c) Overlapping plate structures (*e.g.*, combs) can linearize the force vs. displacement function

d) Pull-in phenomenon can be exploited to make a hysteretic actuator → simplifies control

e) Scaling of the electrostatic force is favorable, since normal air breakdown processes don’t operate in the micro/nano domain

f) Same structure can be used for applying force to a structure and for position sensing.

# Electrostatic Actuators: the Bad

1. High DC voltage is often needed … or very tiny gaps to achieve high electric field and high forces
2. Coupled non-linearity with position and voltage
3. Affected by charge accumulating and drifting around on exposed insulating surfaces
4. Particles are attracted to plates connected to a voltage source
5. Collapse due to pull-in can be catastrophic if conductors touch and short-circuit. If coated with insulators, they can become charged if they touch

# Capacitive Micromachined Ultrasonic Transducers (CMUTs)

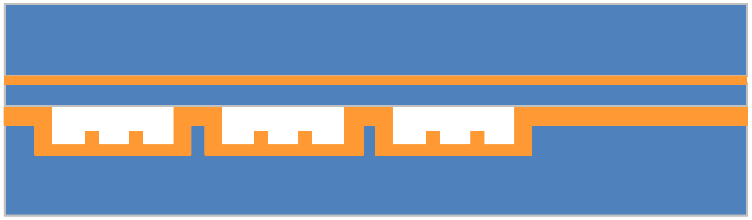
a) Silicon etch to define cavity

b) Thermal oxidation

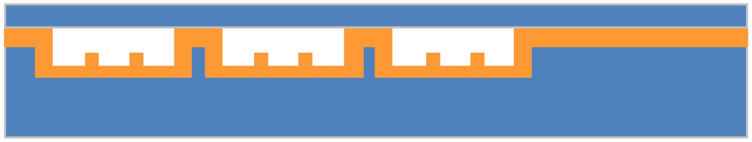
c) Oxide etch to define the bumpers

d) Thermal oxidation to form an isolation layer

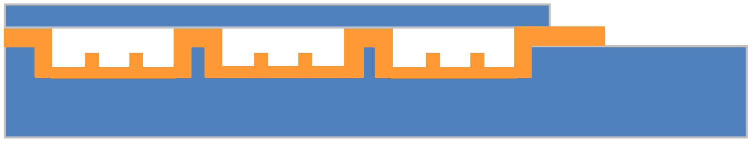
🟧 **$SiO_2$** 🟦 **Al** 🟦 **Si**



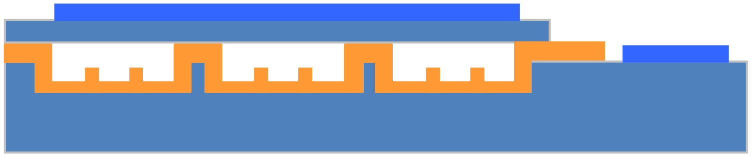
e) Silicon wafer bonding



f) Silicon etch-back to form the membrane



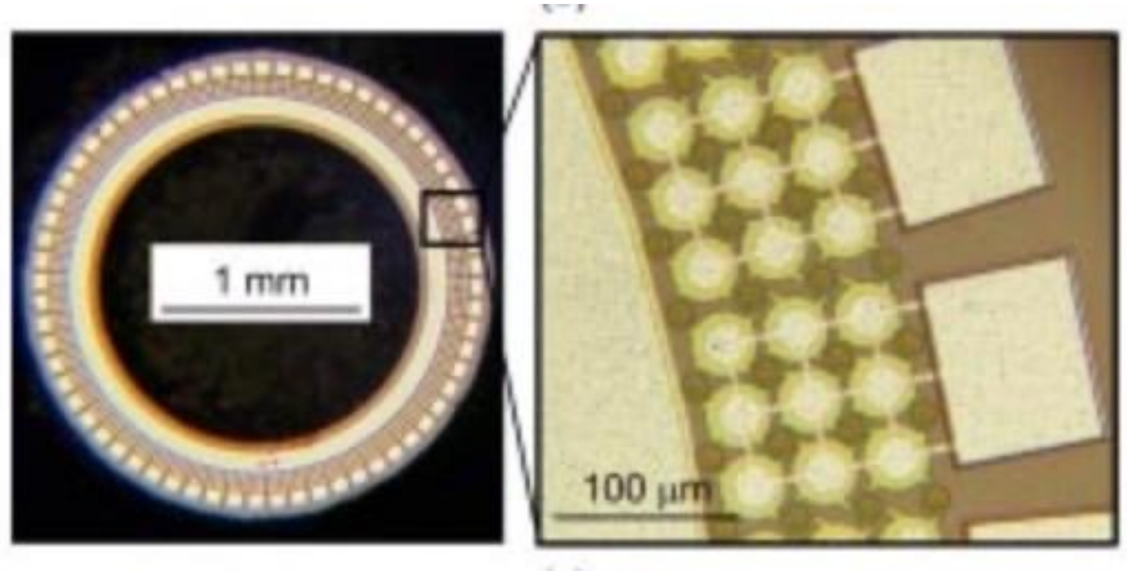
g) Via etch



h) Al deposition and patternning

# Annular CMUT Transducers

- A major advantage of MEMS fabrication is the ability to design custom arrays, such as this annular array for endoscopic imaging



64 element (each with 9 CMUTs) annular array:
10 MHz, 100 µm x 100 µm element area

Current work: high power CMUTs for ultrasonic surgery

Packaging for ultrasonic imaging in a standard endoscope form factor

Pierre Khuri-Yakub group, Stanford Electrical Engineering Dept.

# Ultrasonic Communication and Power

- Recent work at by Amin Arbabian and Pierre Khuri-Yakub (Stanford EE Dept.) has shown that ultrasonics is competitive with RF for powering and communicating with sensor nodes.

A. S. Rekhi, B. T. Khuri-Yakbub, and A. Arbabian, “Wireless Power Transfer to Millimeter-Sized Nodes Using Airborne Ultrasound,” *IEEE Trans. UFFC*, 2017.

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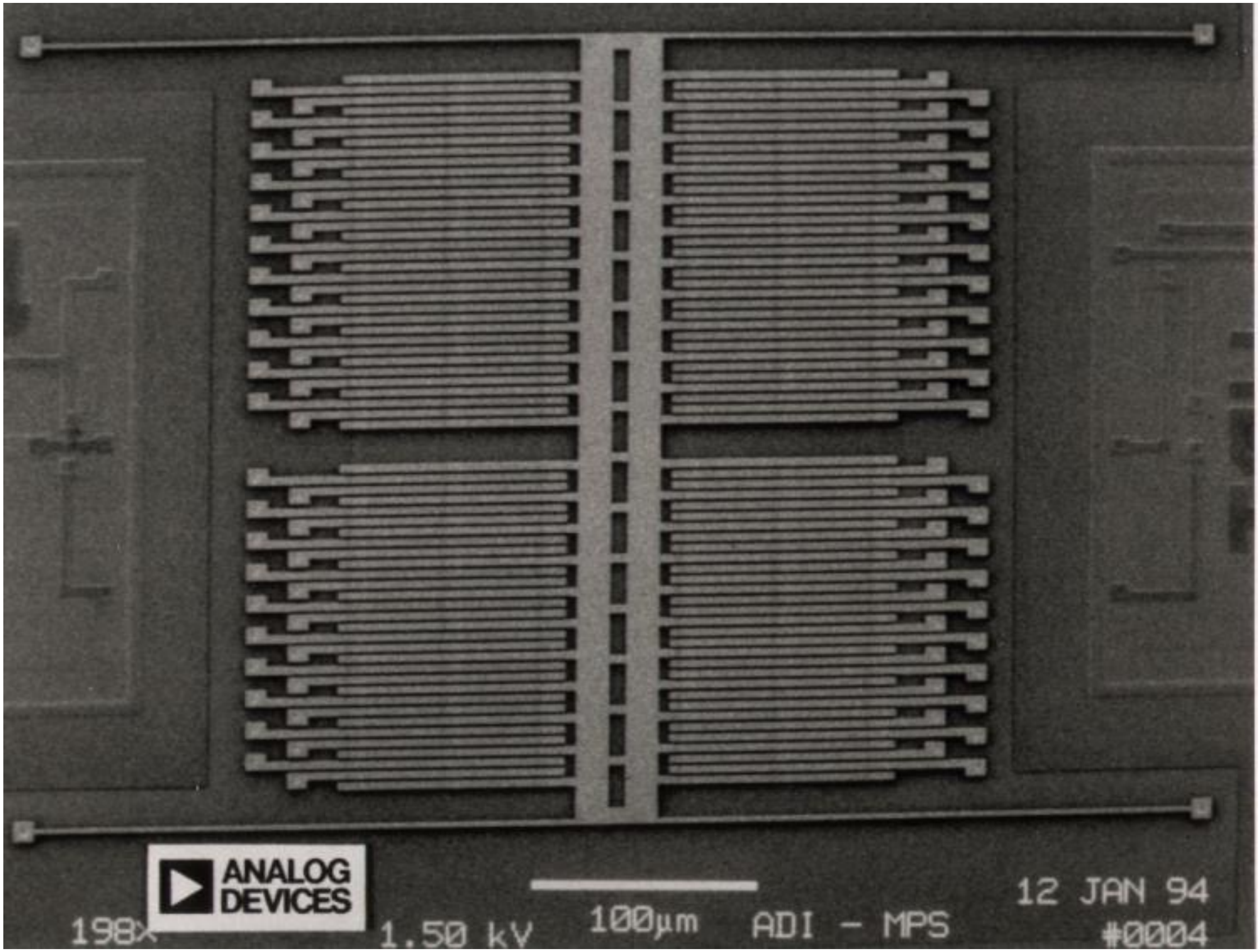
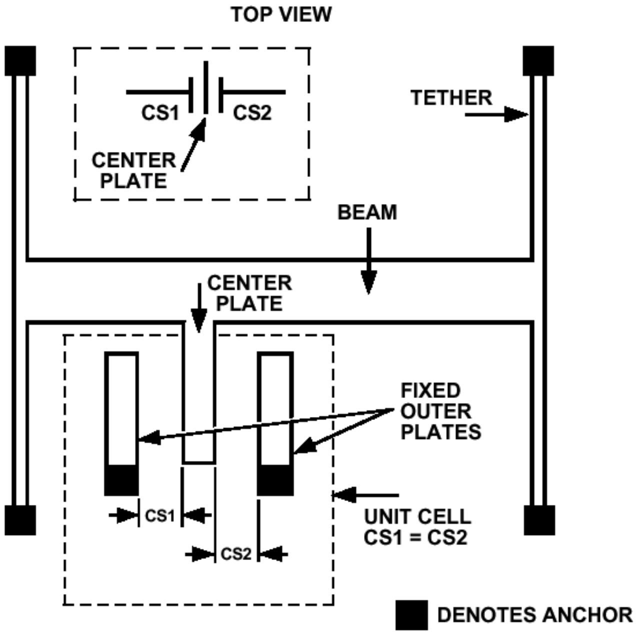
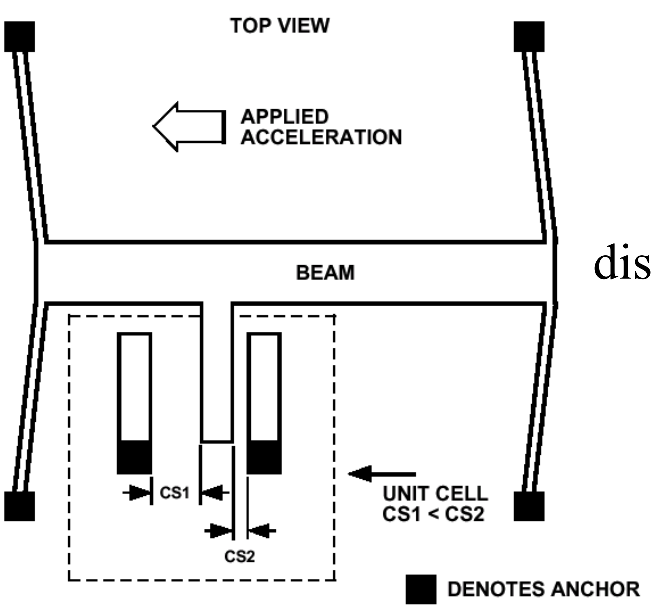
# Analog Device ADXL-50



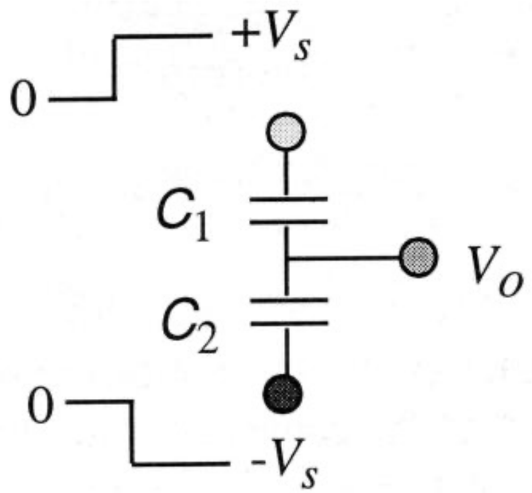
Courtesy of Richard S. Payne, Analog Devices.

# ADXL-50 Position Resolution





displacement = $x$



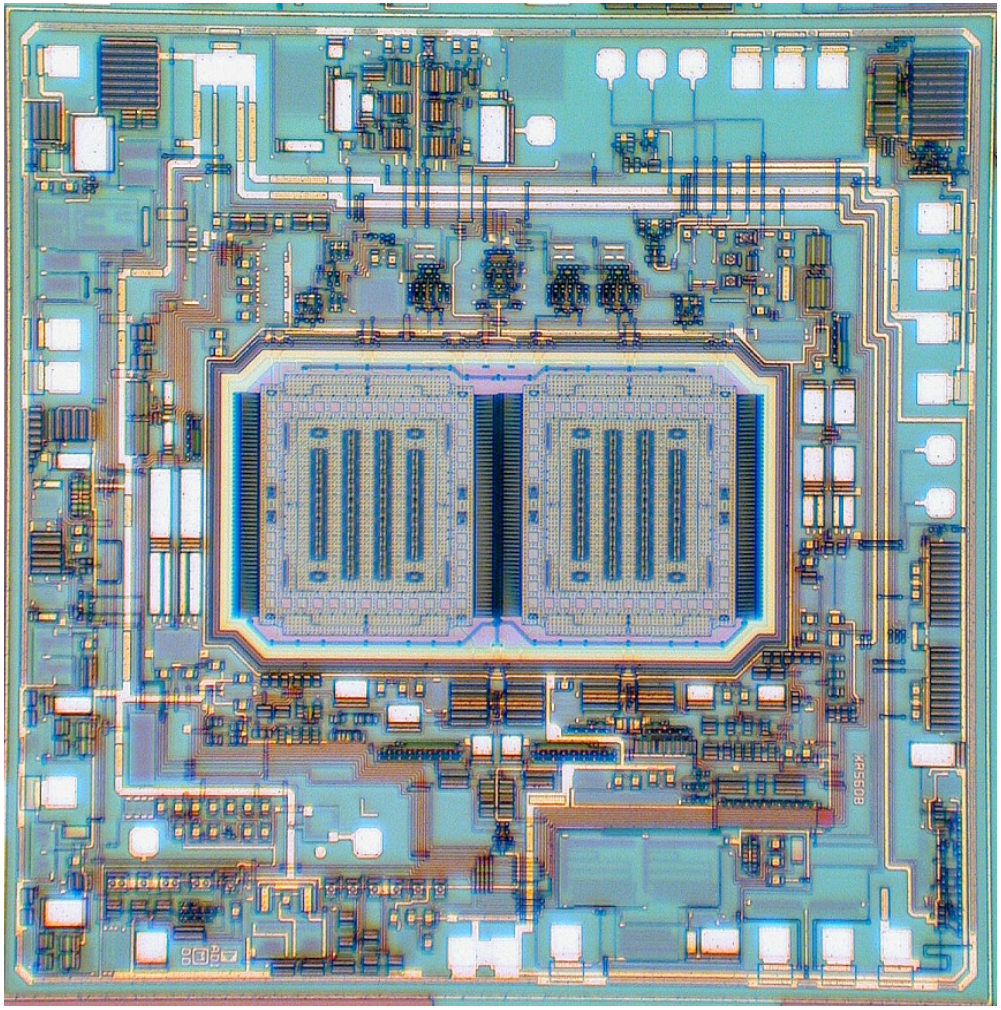
$$\left.\begin{array}{l} C_1\,,\,C_2 \approx 100\ \text{fF} \\ g_o = 1\ \mu\text{m} \\ V_+ = -V_- = 2.5\ \text{V} \end{array}\right\} \boxed{S_x = V_O / x = V_+ / g_o \approx 2.5\ \text{V}/\mu\text{m}}$$

$$V_{O\,(\text{noise})} \approx 0.1\ \text{mV} \rightarrow x_{rms} = [V_{O\,(\text{noise})}] / S_x$$

$$= [0.1\ \text{mV}] / [2.5\ \text{V}/\mu\text{m}]$$

$$\boxed{x_{rms} = 40 \times 10^{-12}\ \text{m} = \textit{15\% of the length of a silicon-silicon bond!}}$$

# Analog Devices ADRS-150 Rate Gyroscope



Full scale Coriolis-induced displacement = 2 nm

Sense capacitance ≈ 1000 fF

Minimum detectable capacitance change ≈ 12 zF = 0.012 aF

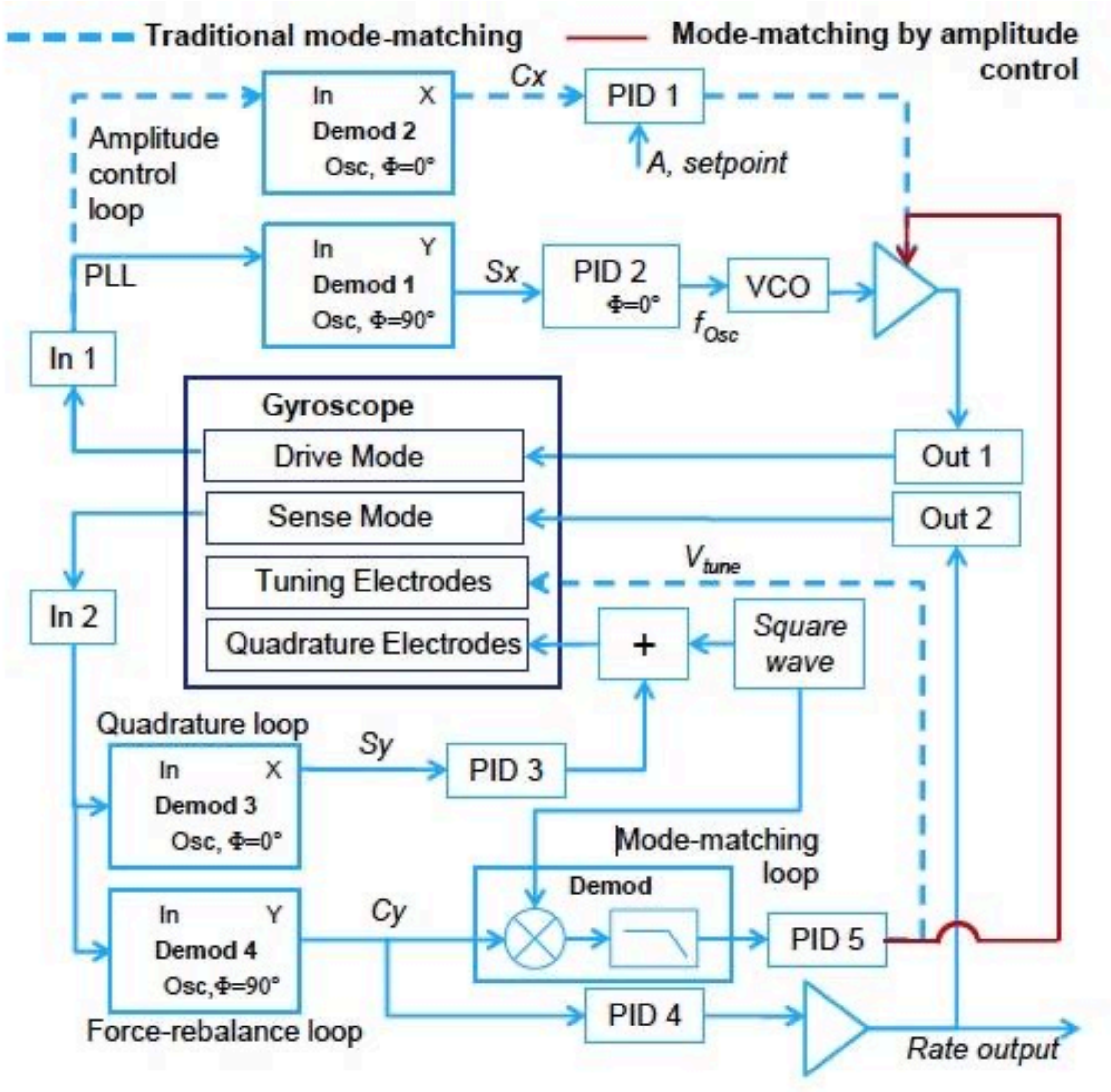
Nominal sense gap = 1.6 μm

Minimum displacement: 16 fm

< $r_e$, *the classical electron radius!*

John Geen, Steve Sherman, John Chang, and Steve Lewis,
*IEEE J. Solid-State Circuits*, **37**, Dec. 2002, 1860-1866.

# MEMS Gyro Block Diagram

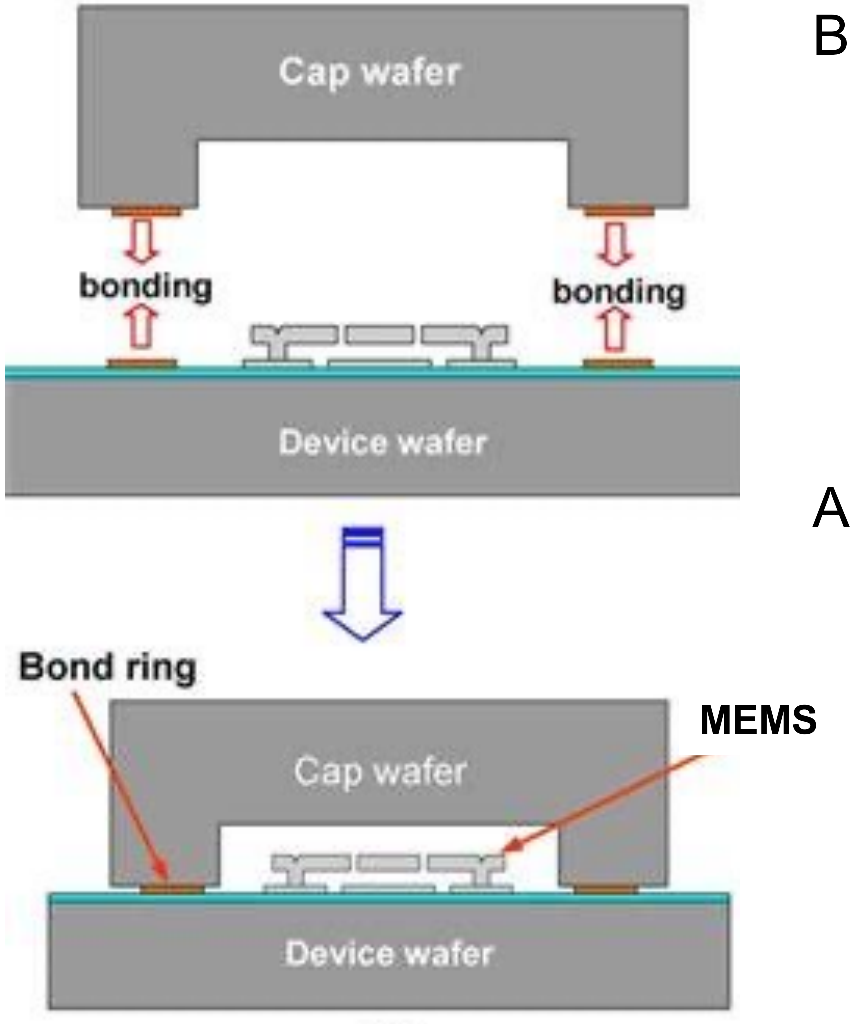


Igor Prikhodko, Sachin Nadig, J. A. Gregory, William A. Clark, and Michael W. Judy, “Half-a-Month Stable 0.2 Degree/Hour Mode-Matched MEMS Gyroscope,” *IEEE INERTIAL*, 2017.

# Outline

- Background and Stanford History
- Core Technologies
  - *Structures*: beams, diaphragms, and mechanisms
  - *Transduction*: moving energy between domains
  - *Electronics*: dealing with tiny signals
  - *Encapsulation*: taming surface phenomena
- Whither MEMS?
  - The MEMS Industry in 2022
  - New challenges: MEMS inside CMOS, intelligent structures for soft robotics

# Wafer-Level Capping



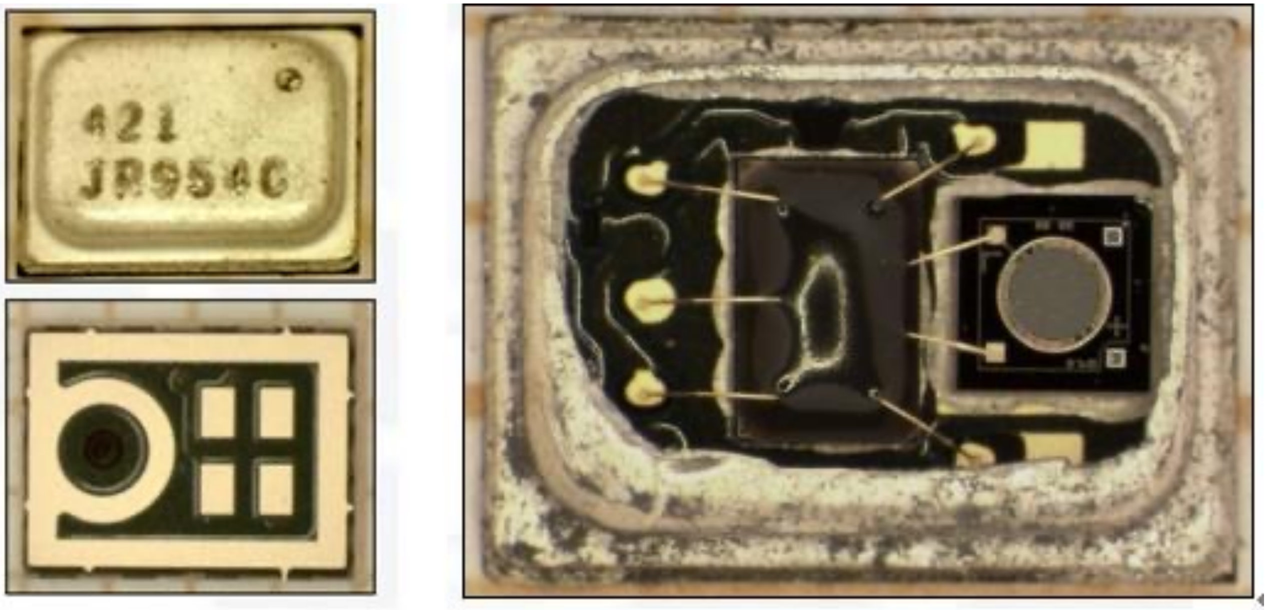
Bonding processes:

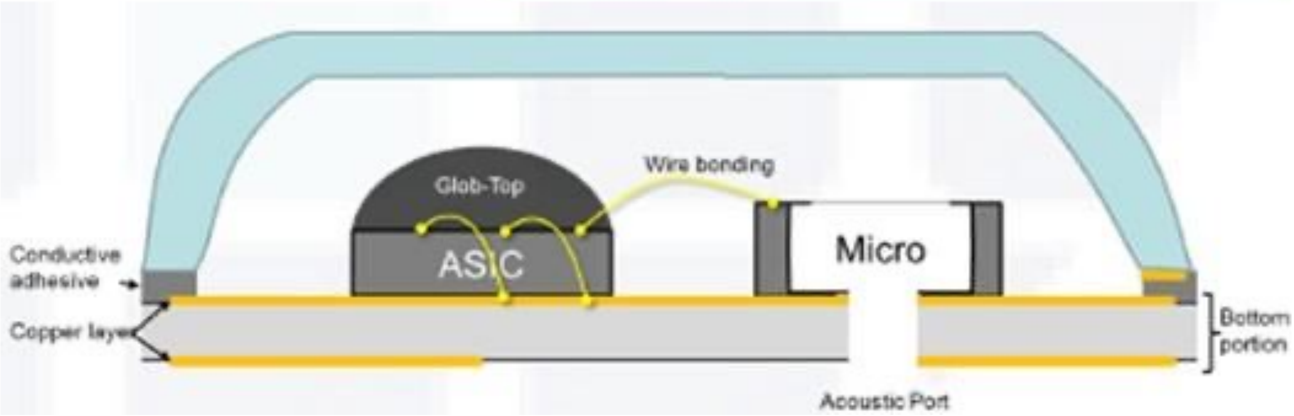
- metal-metal thermocompression
- metal-semiconductor eutectic
- silicon-silicon fusion

Ambient in package:

- pressure – high for damped resonance (accelerometers)
- pressure – low for high *Q* (resonators, gyroscopes)
- getters to scavenge oxygen, other residual gases
- anti-stiction coatings

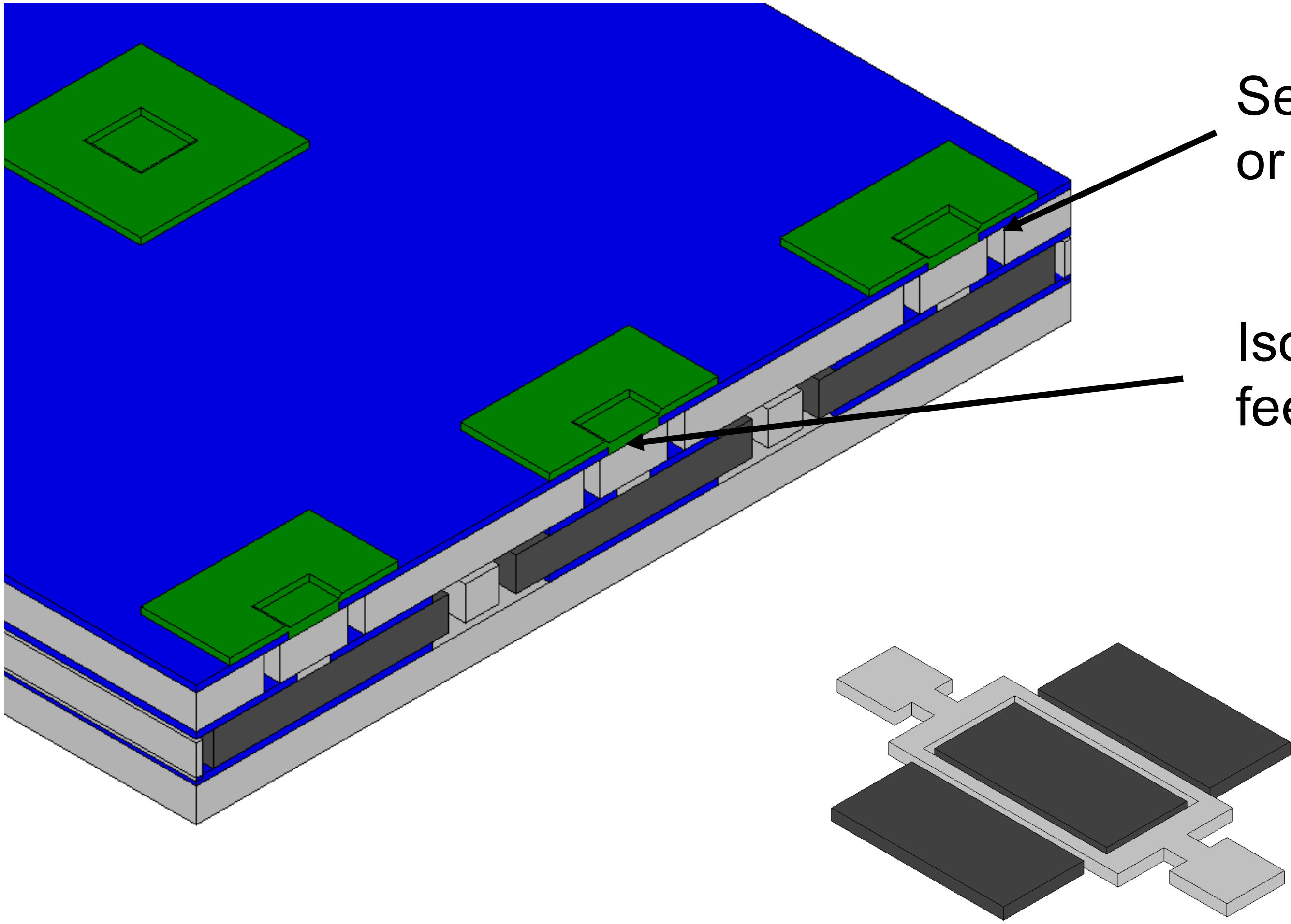
# Microphone Encapsulation





This package has a hole in it!

# Microencapsulated Silicon Resonators



Sealed with oxide
or poly-Si deposition

Isolated electrical
feedthroughs

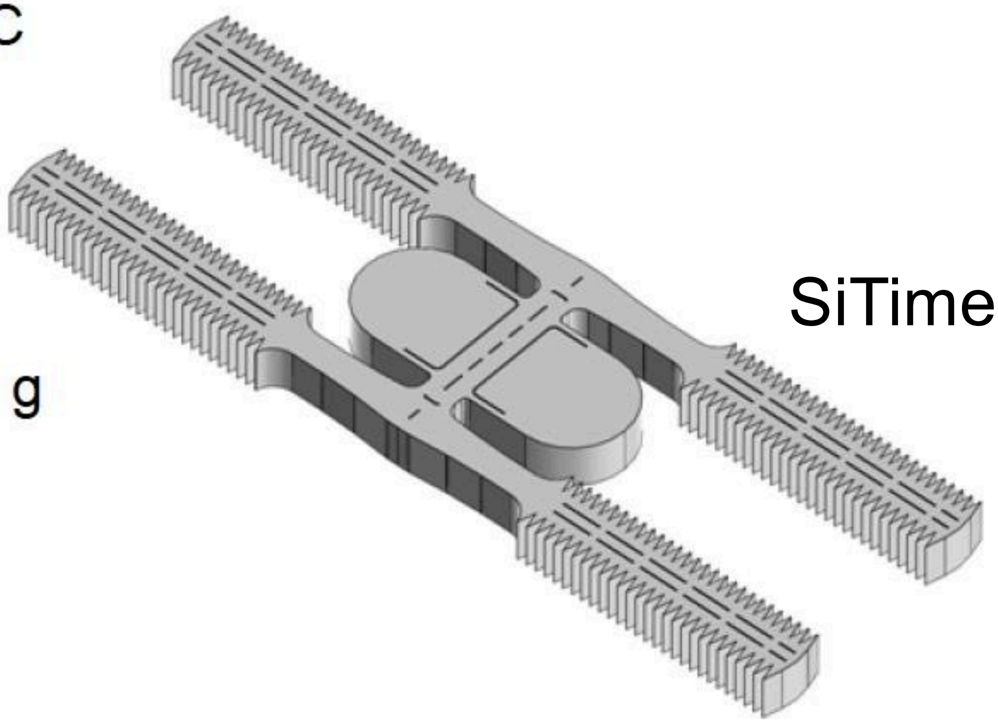
Double-ended
tuning fork micro-
resonator

Rob Candler (now UCLA ECE Dept.) and Tom Kenny, Stanford Mech. Eng. Dept.
*Transducers ’05*, Seoul, Korea

# Balanced Tuning Fork Resonator

## Features

- 524 kHz resonator for 32.768 kHz RTC
- ±100 over temp frequency stability
- ±5 ppm stability on RTC
- 50,000 quality factor
- Ultra-small size:
  420 µm x 420 µm
- 50,000 g shock and 70 g
  vibration resistance,
  10x better than quartz
- <1 µA system current

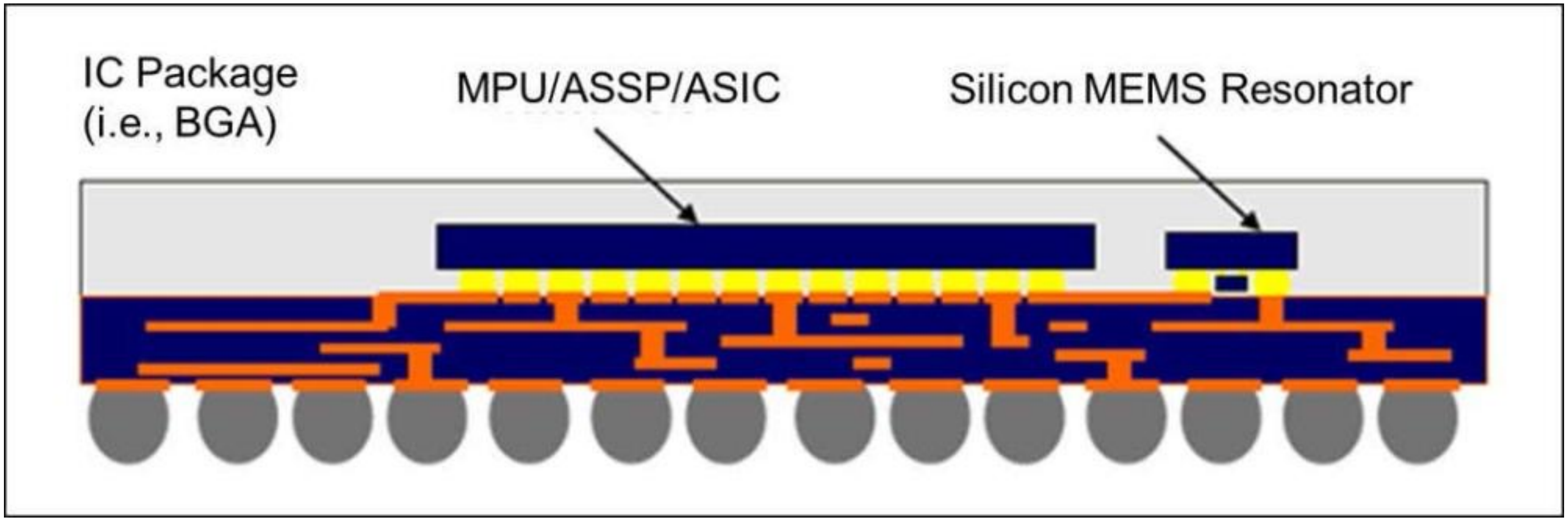


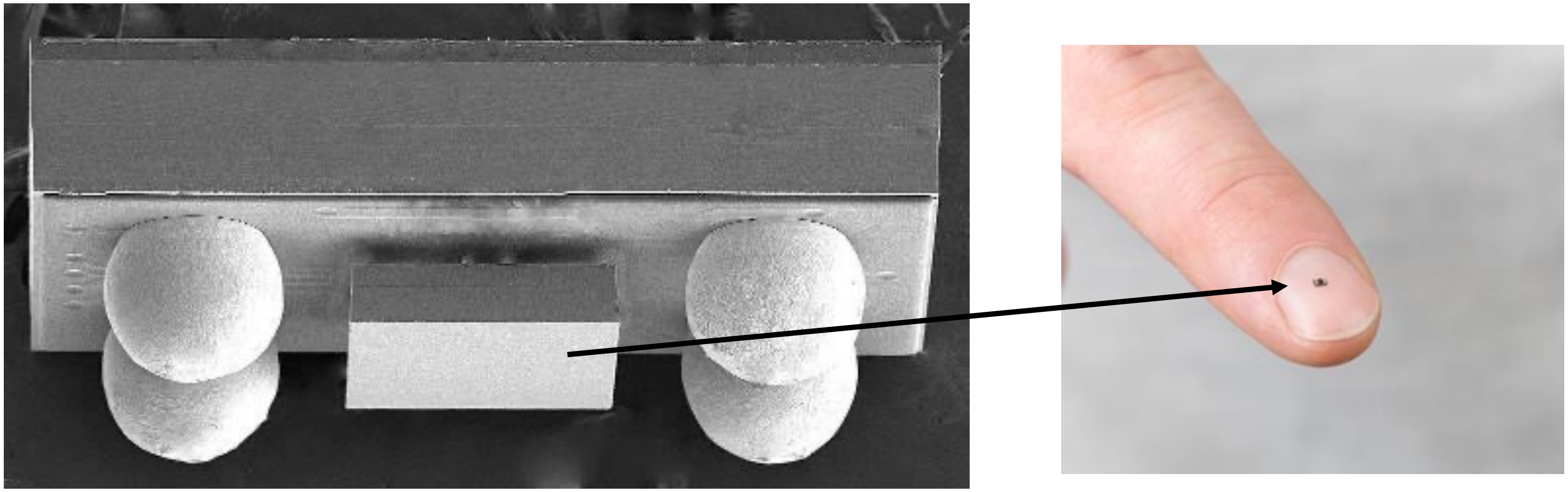
SiTime 1252

SiTime

Silicon Time (SiTime) was launched in 2005
by Markus Lutz, Aaron Partridge, Tom Kenny, and Kurt Petersen

# SiTime Timing Systems





SiTime 8021

Major application: electronic clocks for Apple Watches

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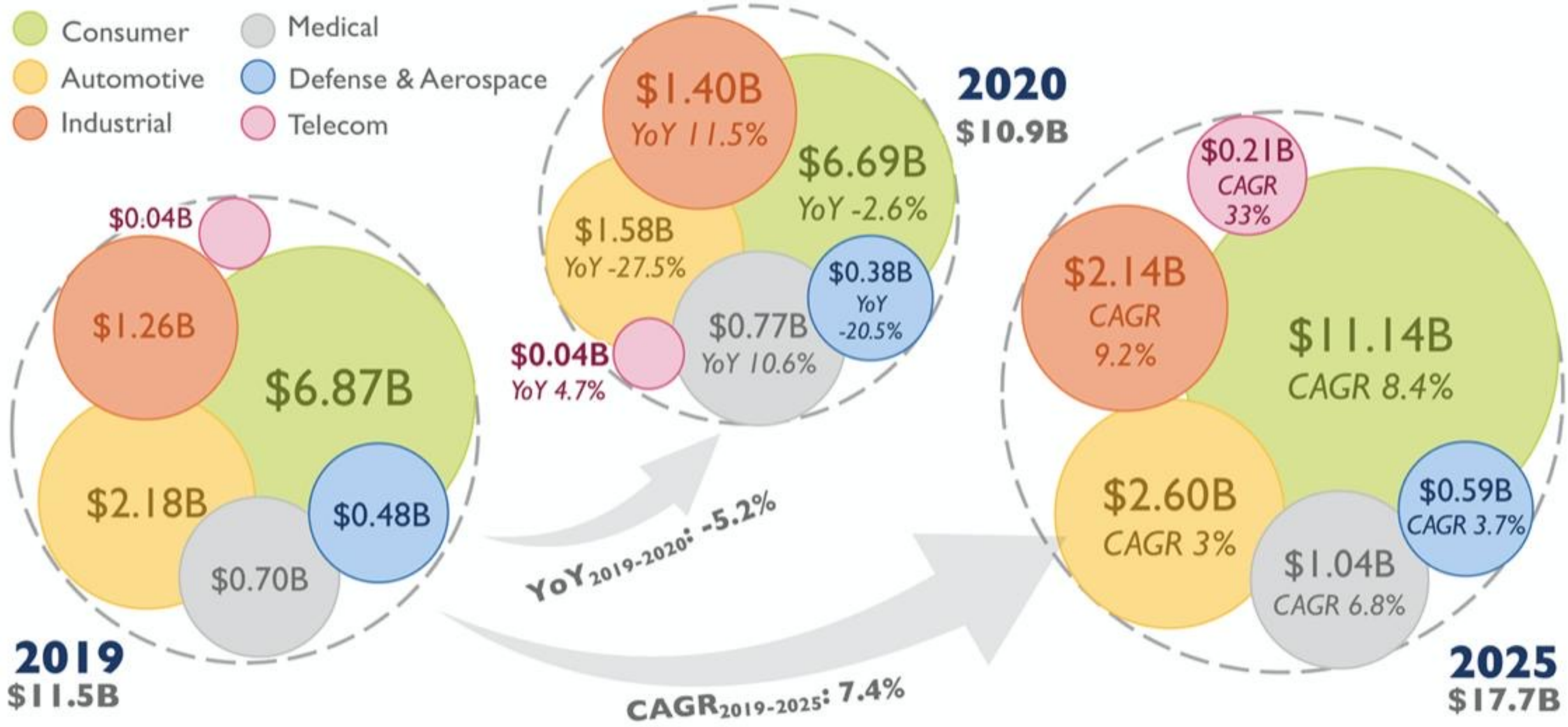
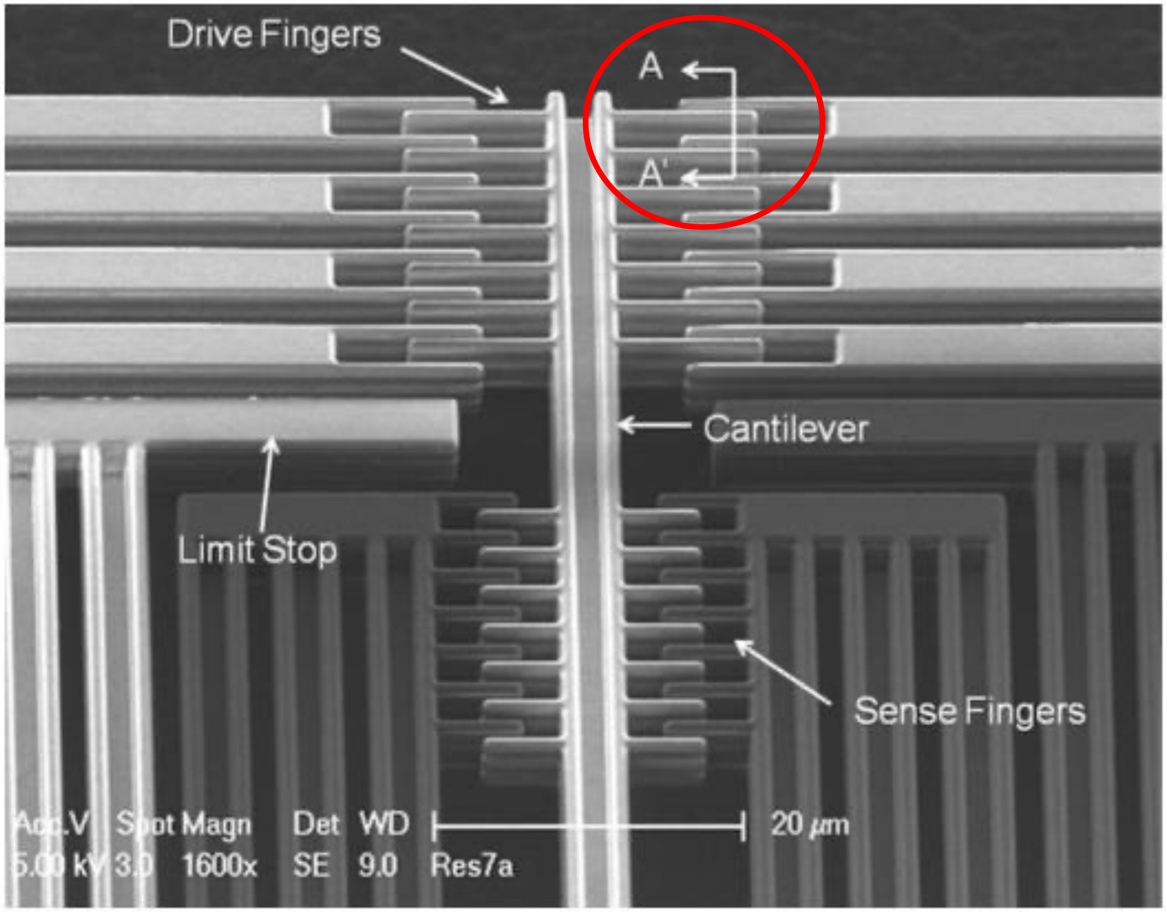
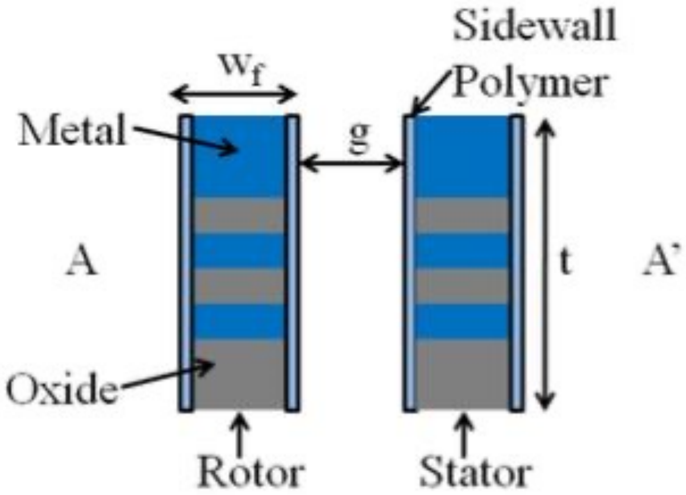
# MEMS Market: 2019 – 2025



Yole Dev., *Status of the MEMS Industry*, July 15, 2020

# MEMS inside CMOS



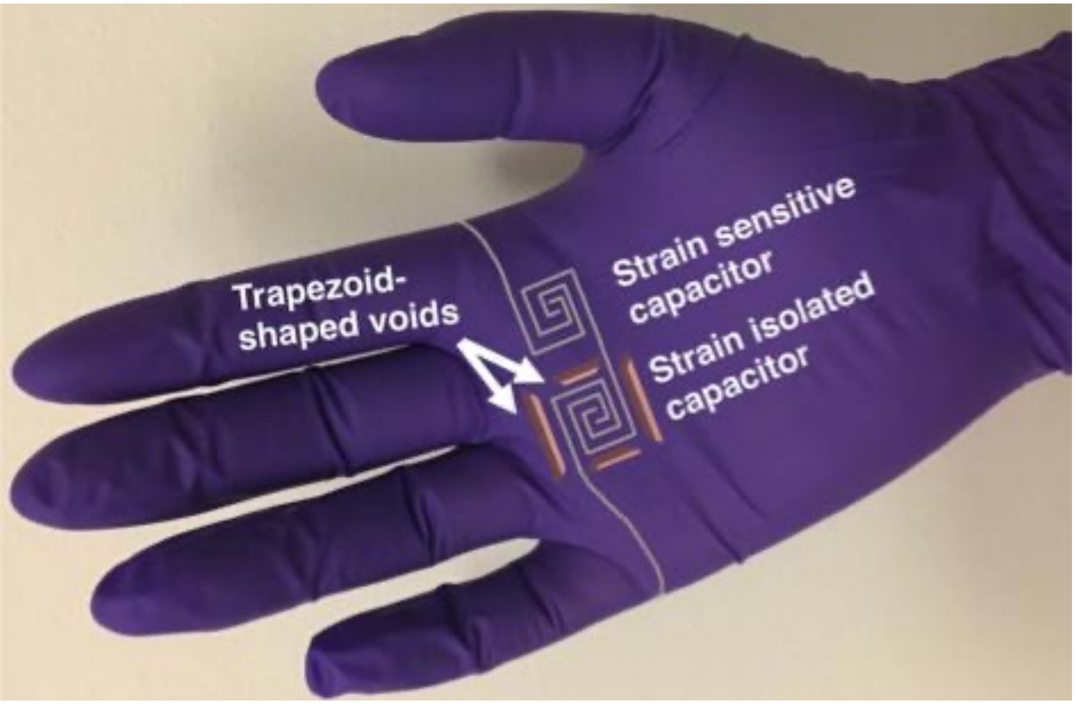


Structures are defined from the metal/oxide stack in a standard CMOS IC process

Advantage: no need for a special MEMS fab
Challenge: structures are an insulator/metal sandwich that are vulnerable to the effects of drifting charge

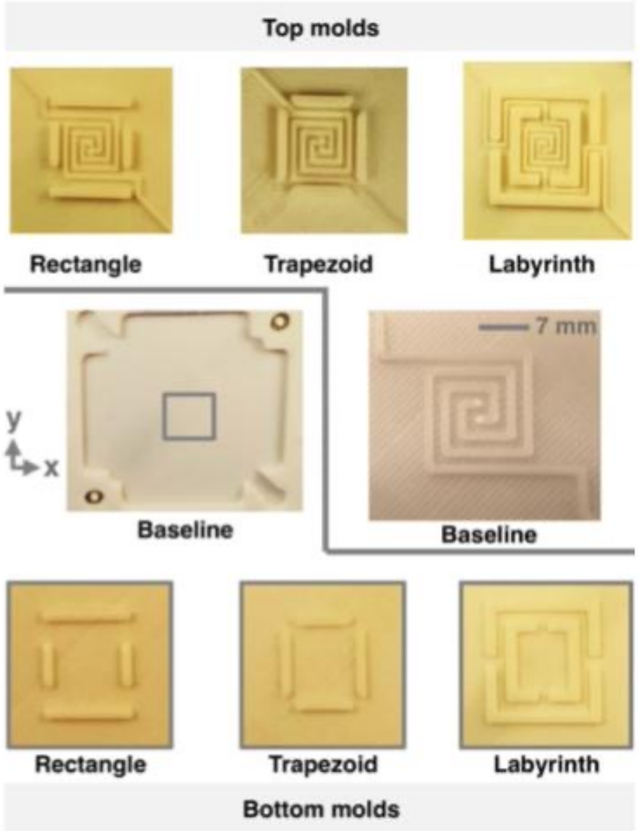
Kristen Dorsey and Gary Fedder (Carnegie-Mellon University), *Transducers 2011*, Beijing

# Next CS114 Lecture: Stretchable Structures



Concept of a glove with strain sensors

New materials, fabrication processes, electro-mechanical designs, and applications



Capacitive strain sensors: molded Eco-flex with liquid metal (e-GaIn) electrodes

Kristen L. Dorsey, *et al*, *IEEE Sensors Journal*, 2018

# Take-Aways

- MEMS helps to bridge the divide between the digital universe and the physical world
- Making MEMS borrows from 60 years of chip fabrication, with a few extra steps
- MEMS are slowly disappearing into embedded systems, giving them enhanced self-awareness
- *There's still much to do –*

Debbie Senesky (AA): harsh-environment sensors

Tom Soh (EE/Rad): implantable closed-loop therapeutics

Sindy Tang (ME): microsystems for tissue re-generation