

Microelectromechanical Systems (MEMS)

David King

Agenda

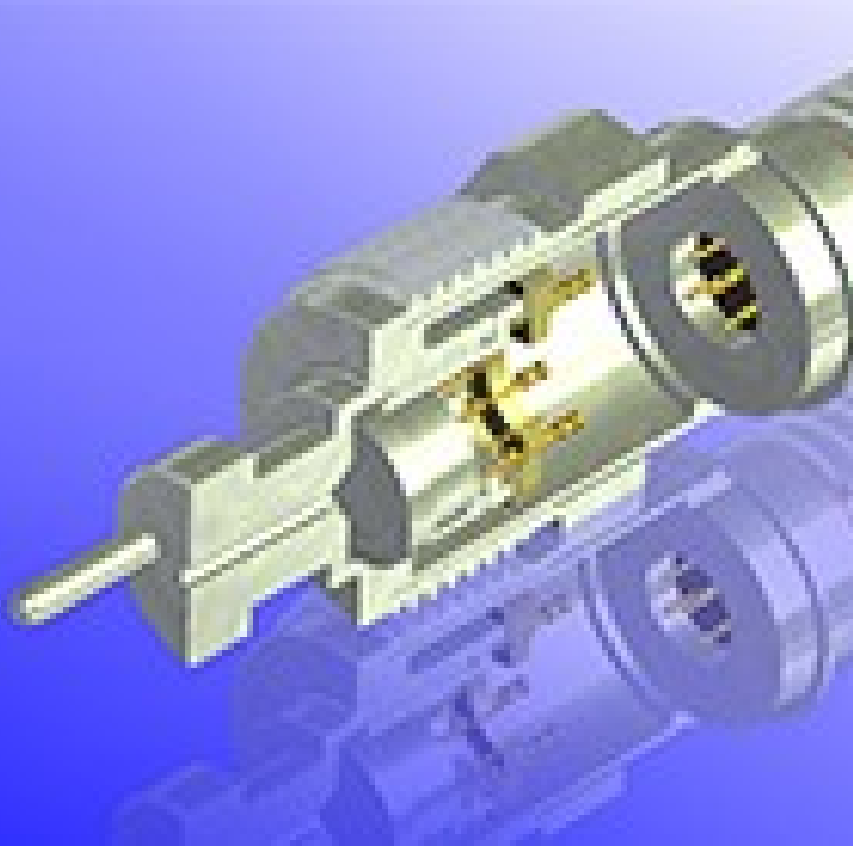
History and Evolution of MEMS Devices

Basic Operating Theory

Fabrication Process

Trends and Future Prospects

History

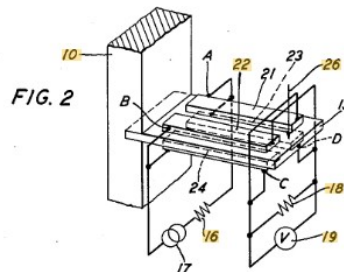
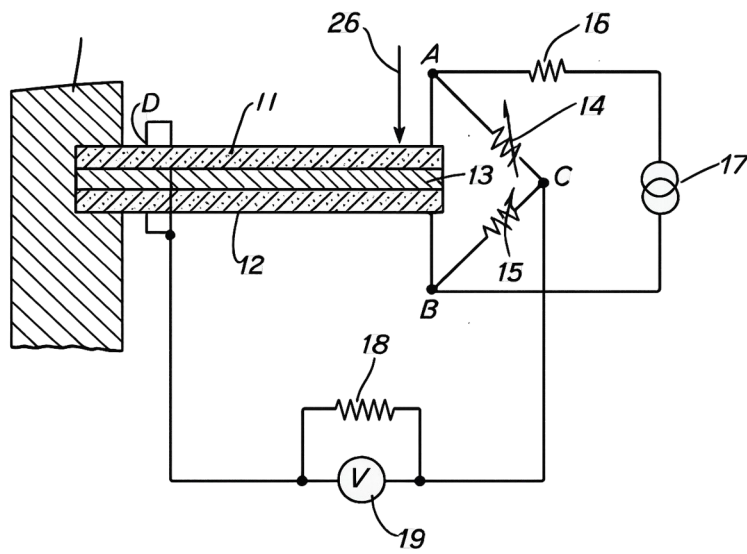


1950s: Piezoresistive Sensors Emerge

1954: Bell Labs develops first silicon/germanium piezoresistive strain gauge, enabling semiconductor sensing,

1958: Kulite becomes first licensee of Bell labs' patent, releasing first commercially offered silicon strain gauges.

First application was in jet engine testing and wind tunnel testing for high frequency pressure testing

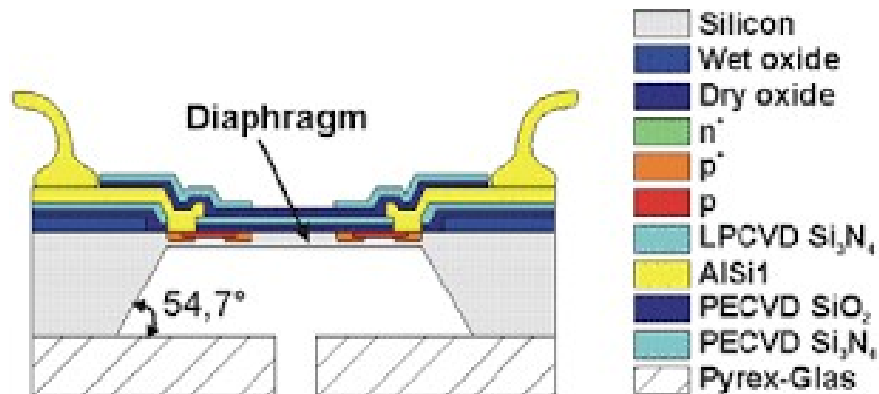
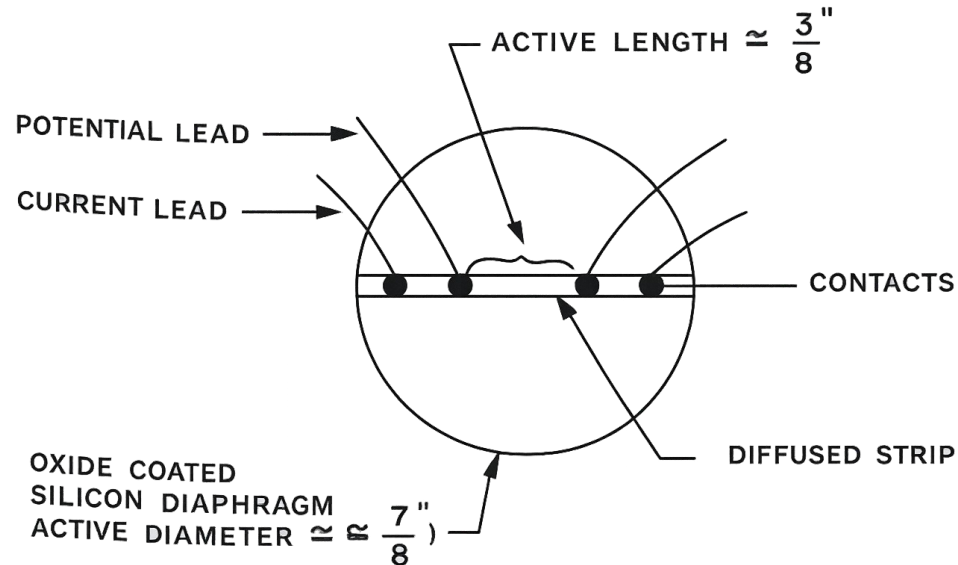


1962: First Homogeneous Silicon Pressure Sensor

First monolithic (homogeneous) silicon pressure sensor

Piezoresistive strain gauges formed by impurity diffusion directly into single-crystal silicon

No bonded gauges → sensing element and mechanical diaphragm are the same material

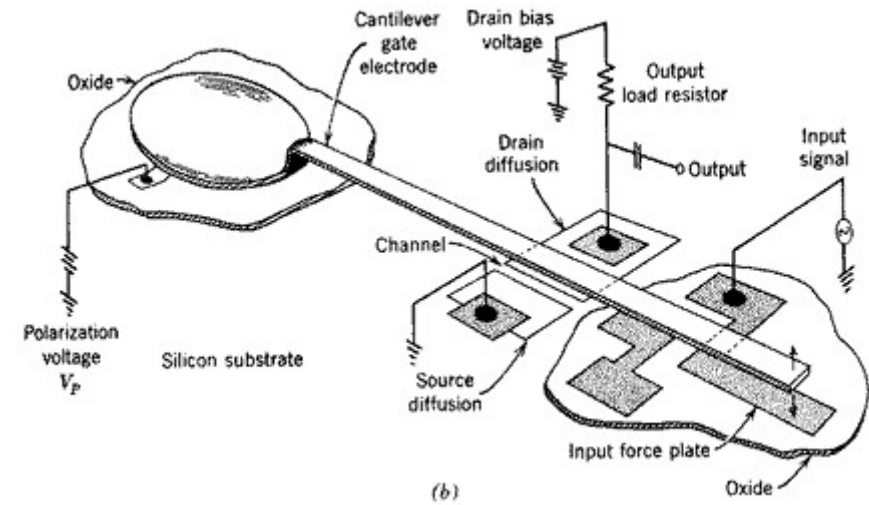


1964: The Resonant Gate Transistor

A MOS transistor with a mechanically resonant gate.

Considered first MEMS device by most standards, as it was the first to be surface micromachined.

Marks the transition from passive silicon sensors to active microelectromechanical systems.

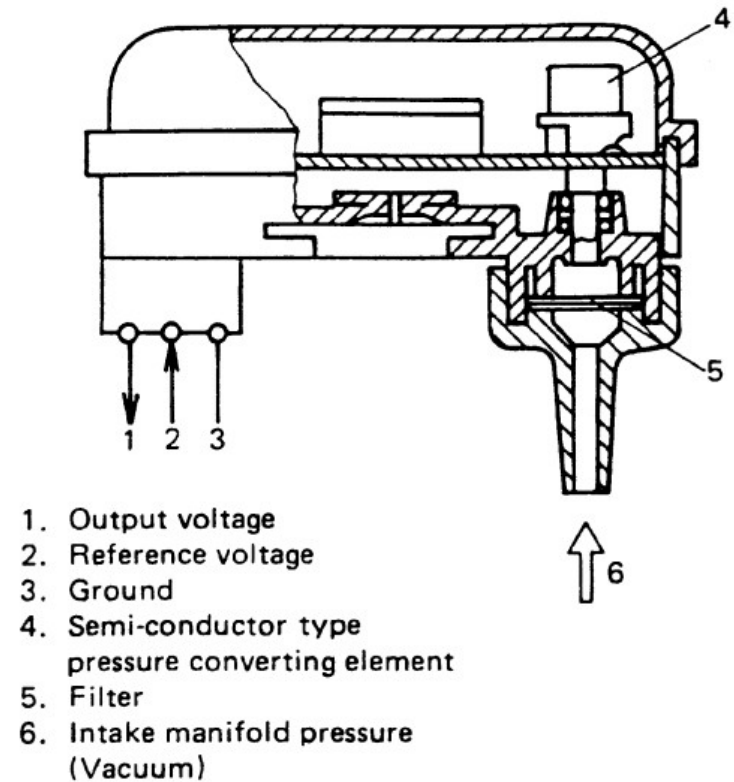


1970s: Automotive Breakthrough

Silicon micromachined/piezoresistive pressure sensing matured from low-volume instrumentation into high-volume automotive

A wave of dedicated sensor companies, IC Transducers / Foxboro ICT, Transensory Devices, IC Sensors, NovaSensor (and peers) built product lines and manufacturing aimed specifically at automotive OEM requirements

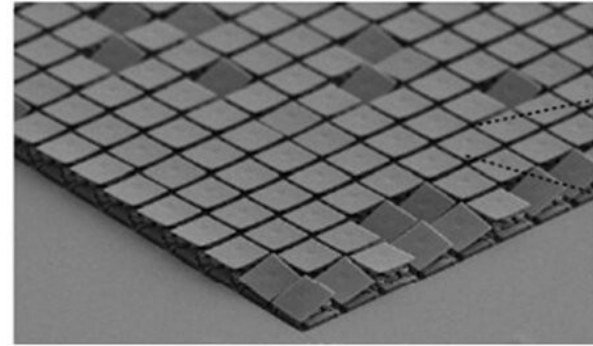
Most successful automotive application: Engine-control pressure sensing, especially MAP (manifold absolute pressure), became the first major high-volume “killer app,”



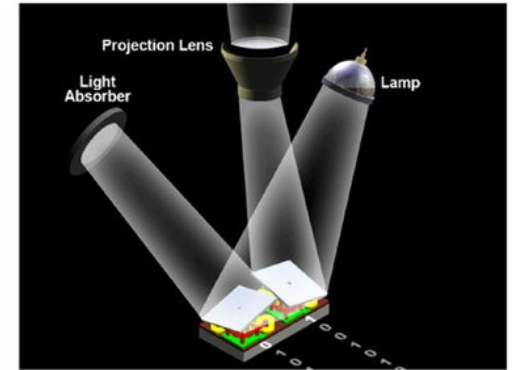
1980s: DLP Technology Created

Surface micromachining matures as a standard approach: building released structures from deposited thin films (polysilicon, oxides/nitrides).

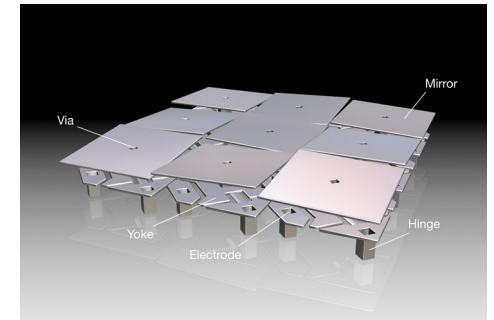
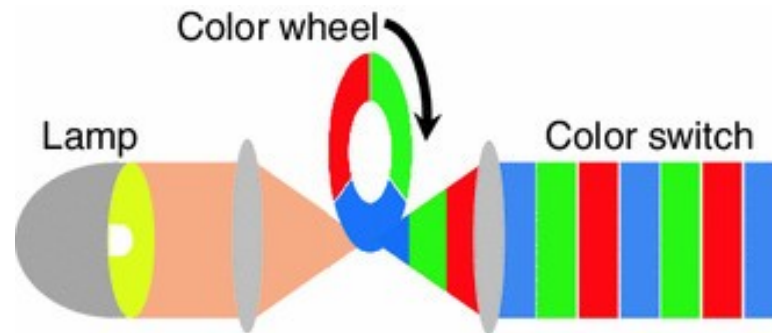
1987: TI creates the first Digital Micromirror Device (DMD) prototype (MOEMS/MEMS optics).



(a)



(b)

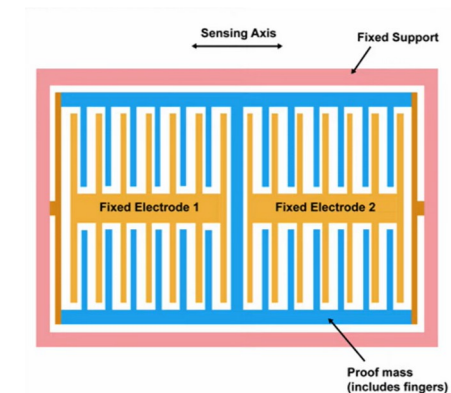
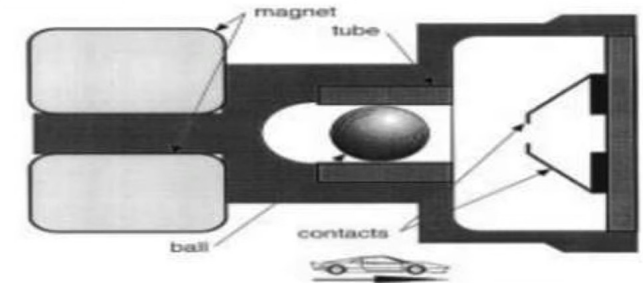


1990s

1991–1992 (commercial): TI delivers a DMD line array for the first commercial DMD product; shipments to customers start in 1992.

1991 (commercial): Analog Devices ADXL50 released; widely cited as the first successfully commercialized MEMS accelerometer product.

1993 (process milestone): DRIE introduced (Bosch process), a major enabler for high-aspect-ratio silicon MEMS structures.

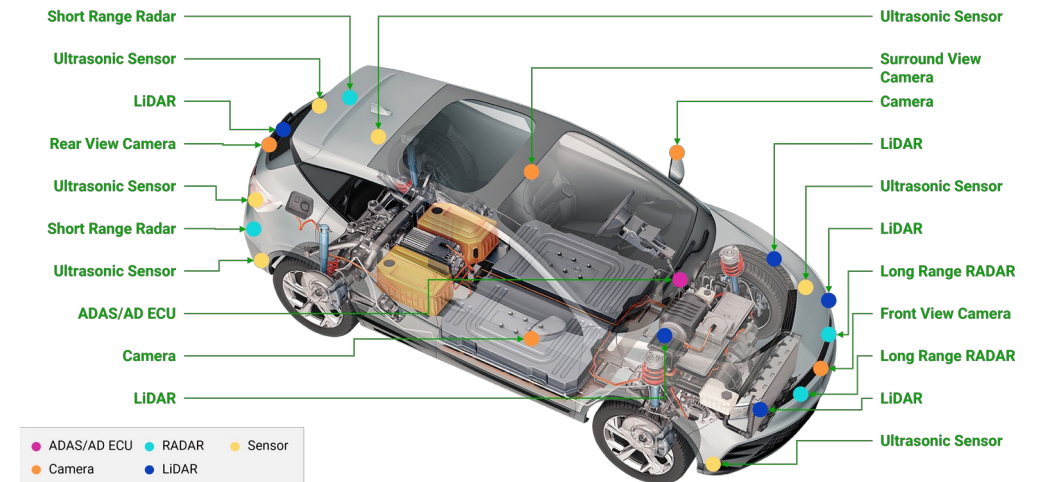
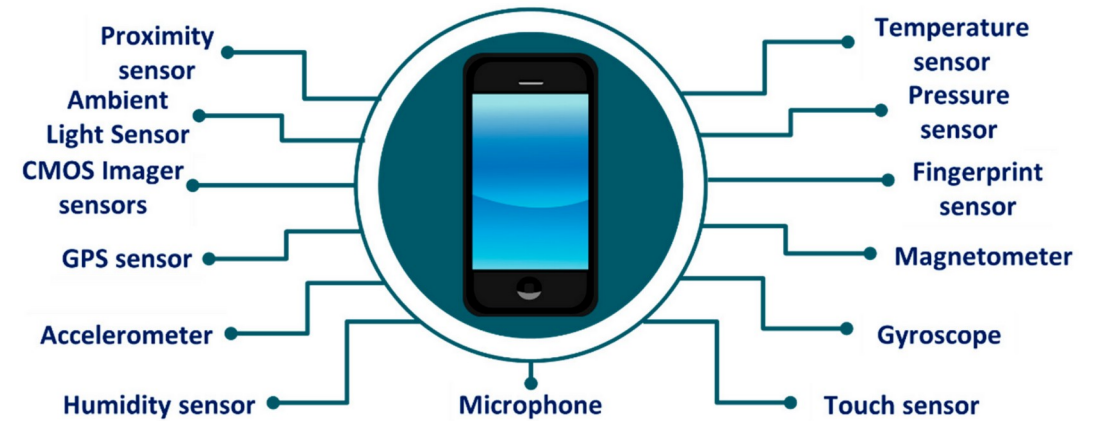
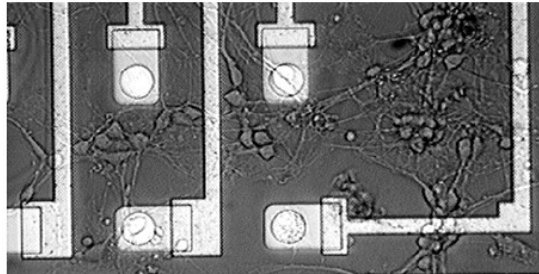


2000s

High-volume consumer MEMS continues to scale, led by IMUs, microphones, and pressure sensors

Wafer-level packaging (WLP) enables low cost, small form factor, and high throughput

Multi-sensor MEMS modules increasingly replace single-sensor components



Basic Theory and Operation

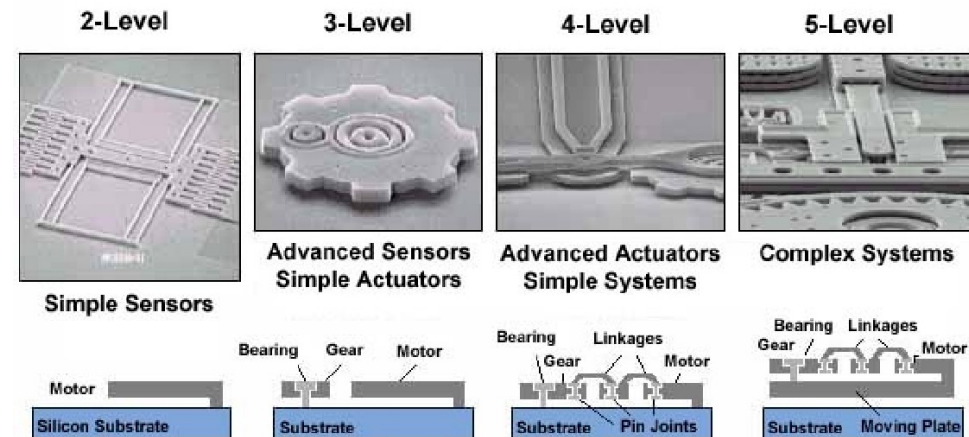
Basic Operating Principle of MEMS

MEMS interface the physical world with electronics

Physical stimulus → mechanical response → electrical signal

Operation governed by scaling laws at the microscale

Same physics as macrosystems, different dominant forces



Energy Domains in MEMS

Electrical

Mechanical

Thermal

Magnetic

Chemical

Radiative (optical)

MEMS operate by coupling energy domains

To From	Electrical	Magnetic	Mechanical	Thermal	Chemical	Radiative
Electrical		Ampere's Law	Electrostatics, Electrophoresis	Resistive Heating	Electrolysis, Ionization	EM Transmission
Magnetic	Hall Effect, Mag. Resistance		Magnetostatics, Magnetostriiction	Eddy Currents Hysteretic Loss	Magnetic Separation	Magneto-optics
Mechanical	Variable Cap. Piezoresistance Piezoelectricity	Magnetostriction		Friction	Phase Change	Tribo- luminescence
Thermal	Thermoelectric	Curie Point	Thermal Expansion		Reaction Rate Ignition	Thermal Radiation
Chemical	Electrochemical Potential	Chemomagnetic	Phase Change	Combustion		Chemo- luminescence
Radiative	Photoconductor, EM Receiving	Magneto-optics	Radiation Hardening	Photothermal	Photochemical	

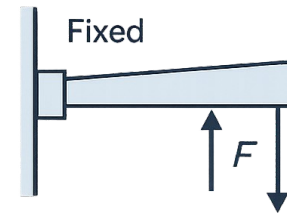
Transduction

Transduction: conversion between energy forms

Sensors: physical $\rightarrow$ electrical

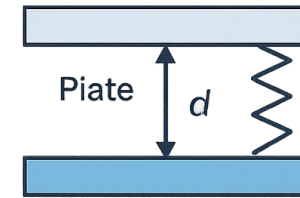
Actuators: electrical $\rightarrow$ physical

Often multiple transduction steps in series



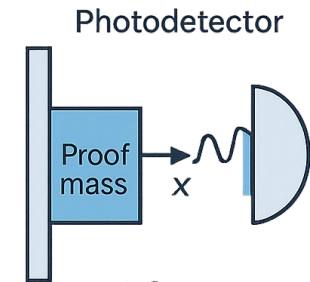
$$\Delta R = \pi \sigma$$

(a) Piezoresistive



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

(b) Capacitive



$$\Delta \lambda \propto x$$

(c) Optical

Mechanical Elements in MEMS

Cantilevers

Bridges

Plates

Membranes

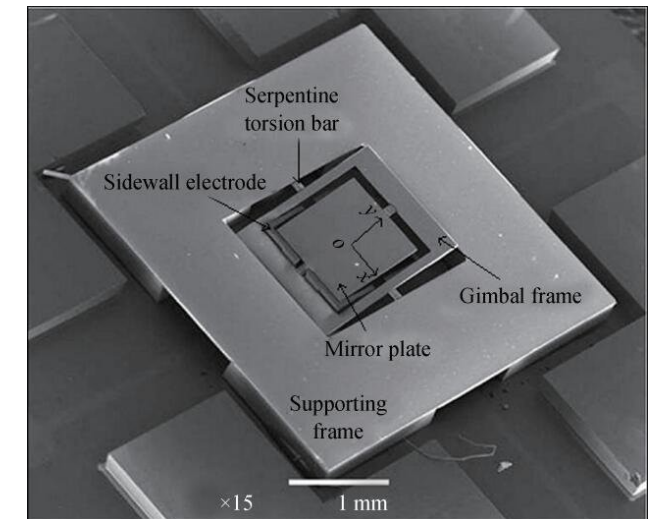
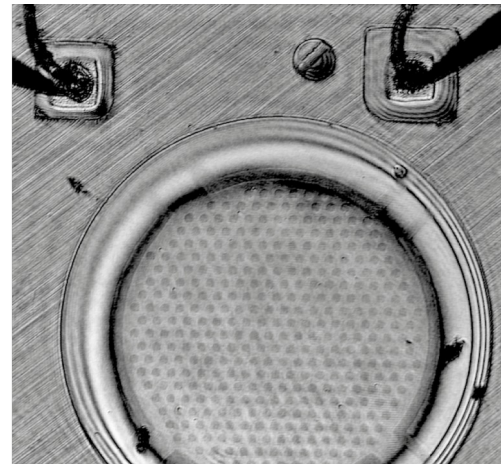
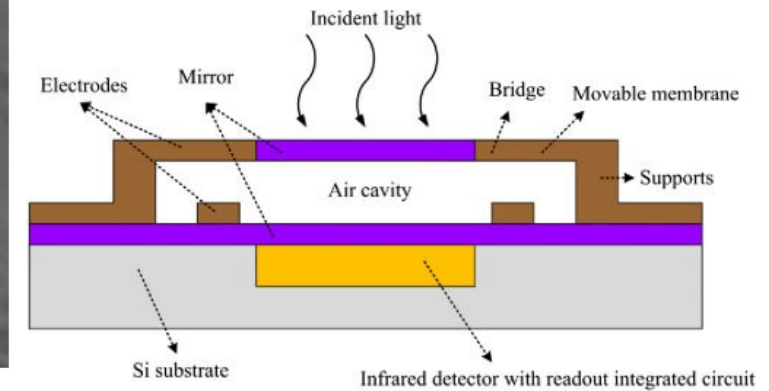
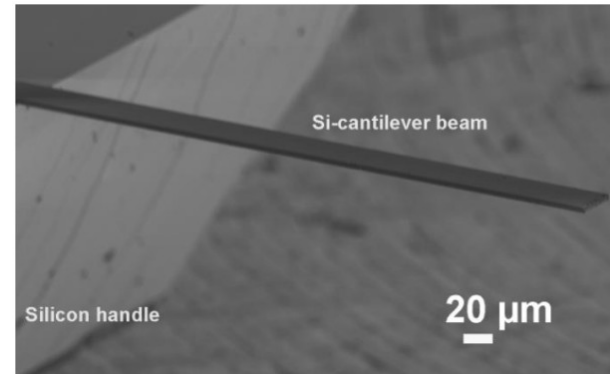
Torsion bars

Proof masses

Mechanical motion typically:

Microns or less

Elastic (not plastic)



Scaling Effects (Why MEMS Behave Differently)

Mass scales with volume ($\propto L^3$)

Stiffness scales with length ($\propto L$)

Inertial forces drop rapidly with size

Surface forces dominate over body forces

$$k = \frac{w \cdot t^3 \cdot E}{4L^3}$$

$$Re = \frac{\rho \cdot V \cdot D}{\mu}$$

$$U_{\text{electrostatic}} = \frac{1}{2} \varepsilon \cdot E^2$$

$$U_{\text{magnetostatic}} = \frac{1}{2} \left(\frac{B^2}{\mu} \right)$$

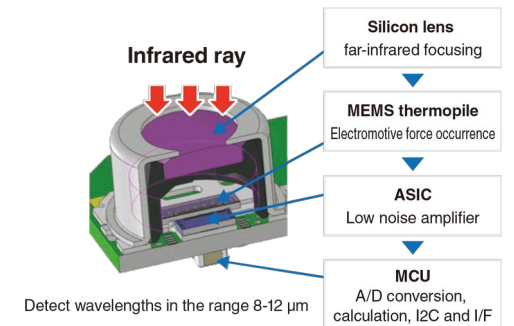
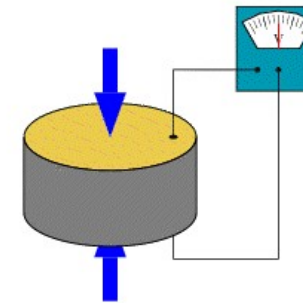
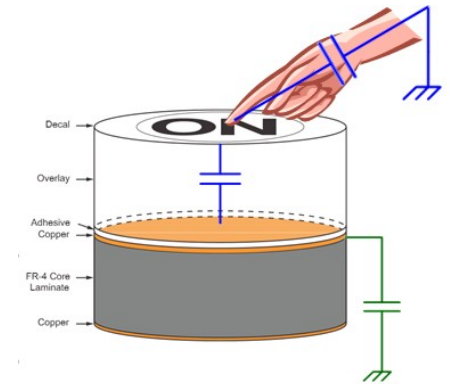
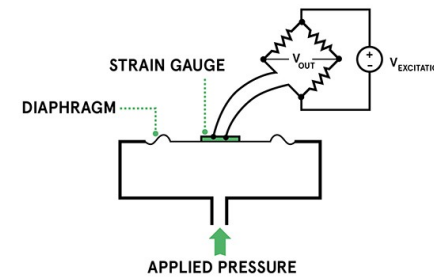
Common Sensing Mechanisms

Piezoresistive: stress $\rightarrow$ resistance change

Capacitive: displacement $\rightarrow$ capacitance change

Piezoelectric: stress $\rightarrow$ charge generation

Thermal: temperature $\rightarrow$ resistance/voltage change



Common Actuating Mechanisms

Electrostatic

Electrothermal

Piezoelectric

Magnetic

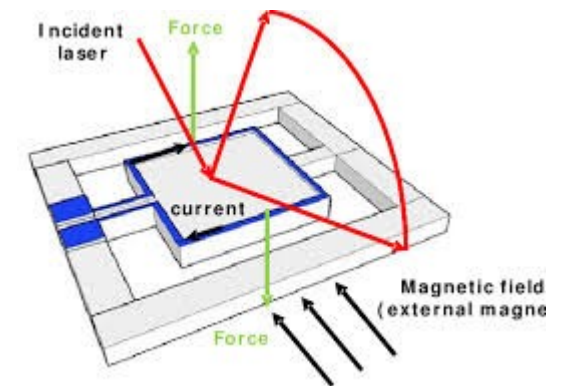
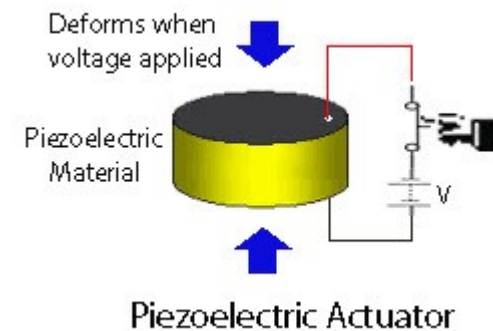
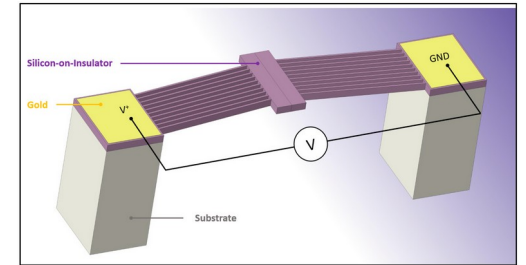
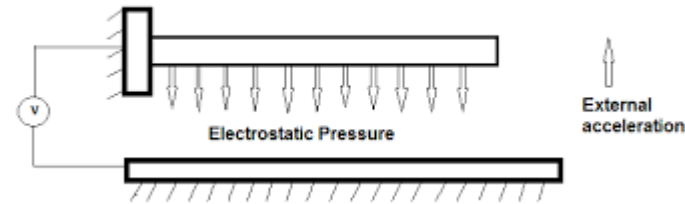
Choice driven by:

Force

Displacement

Power

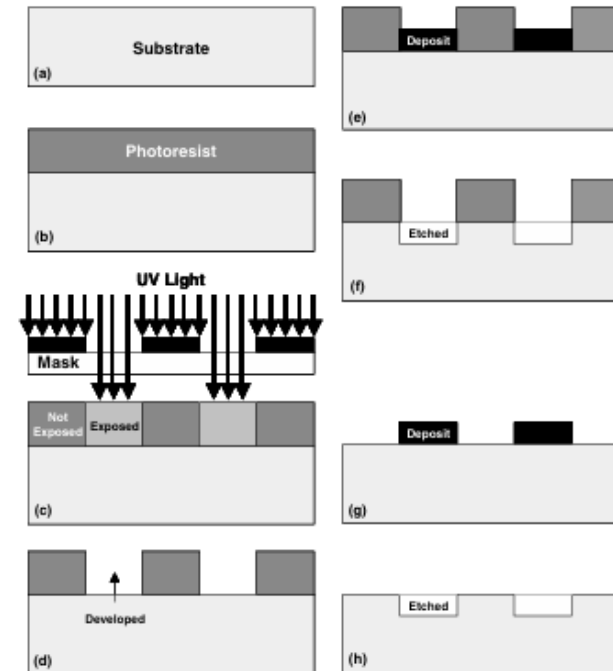
Environment



Fabrication Process

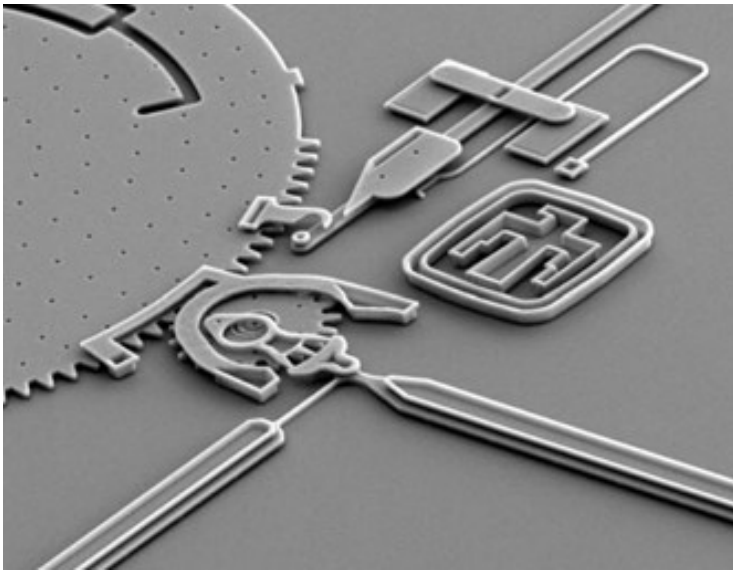
Traditional IC Fabrication (FEOL)

- MEMS inherit:
 - Photolithography
 - Thin-film deposition
 - Etching processes
- MEMS extend IC processes to:
 - Create movable structures
 - Enable 3D geometries
 - Fabrication often diverges from strict CMOS rules

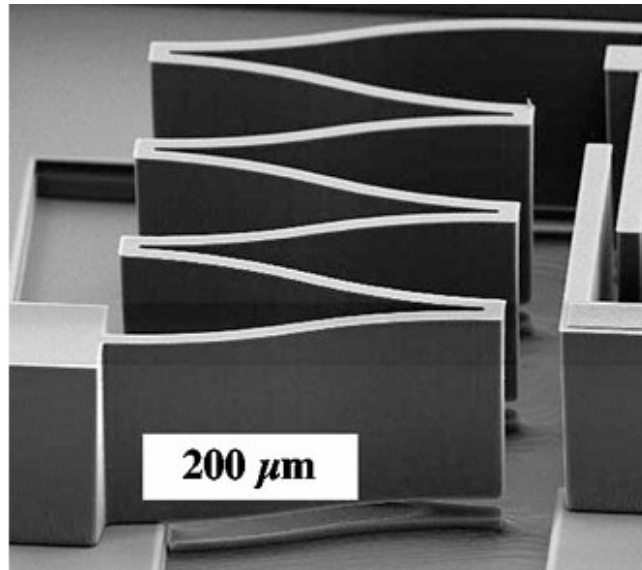


MEMS Specific Fabrication Process'

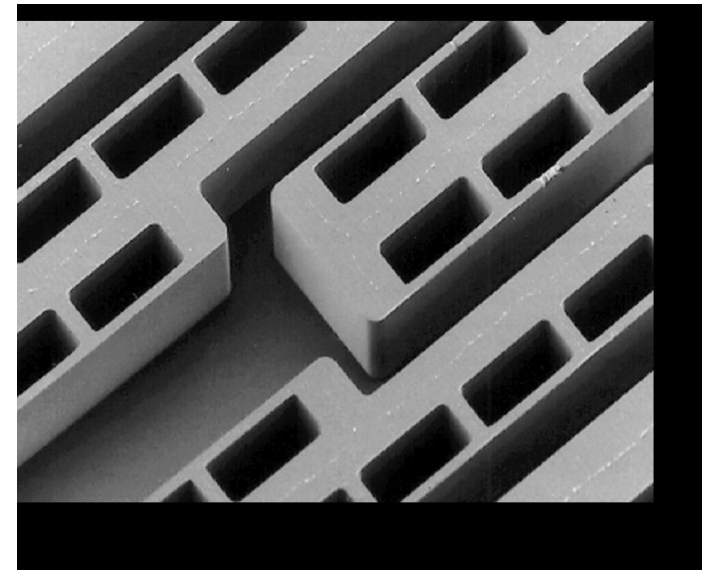
Surface Micromachining



Bulk Micromachining



LIGA



Low Aspect Ratio



High Aspect Ratio

Surface Micromachining

Structures formed from deposited films

Typical thickness: 0.1–5 μm

Excellent planarity and alignment

Limited out-of-plane thickness

Well suited for monolithic integration

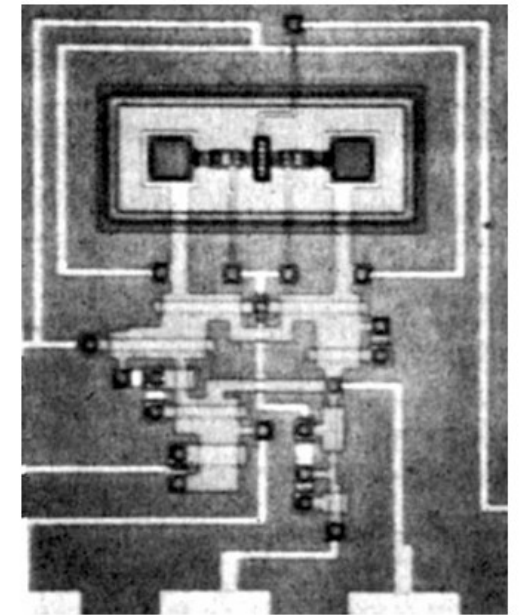
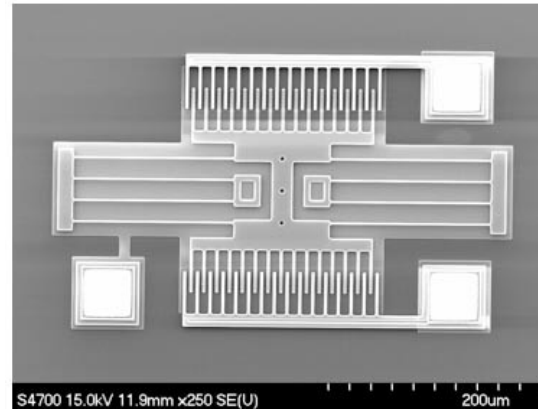
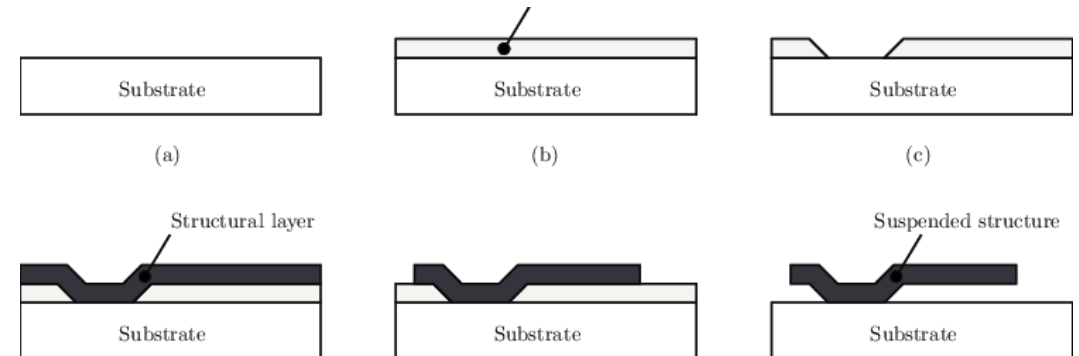
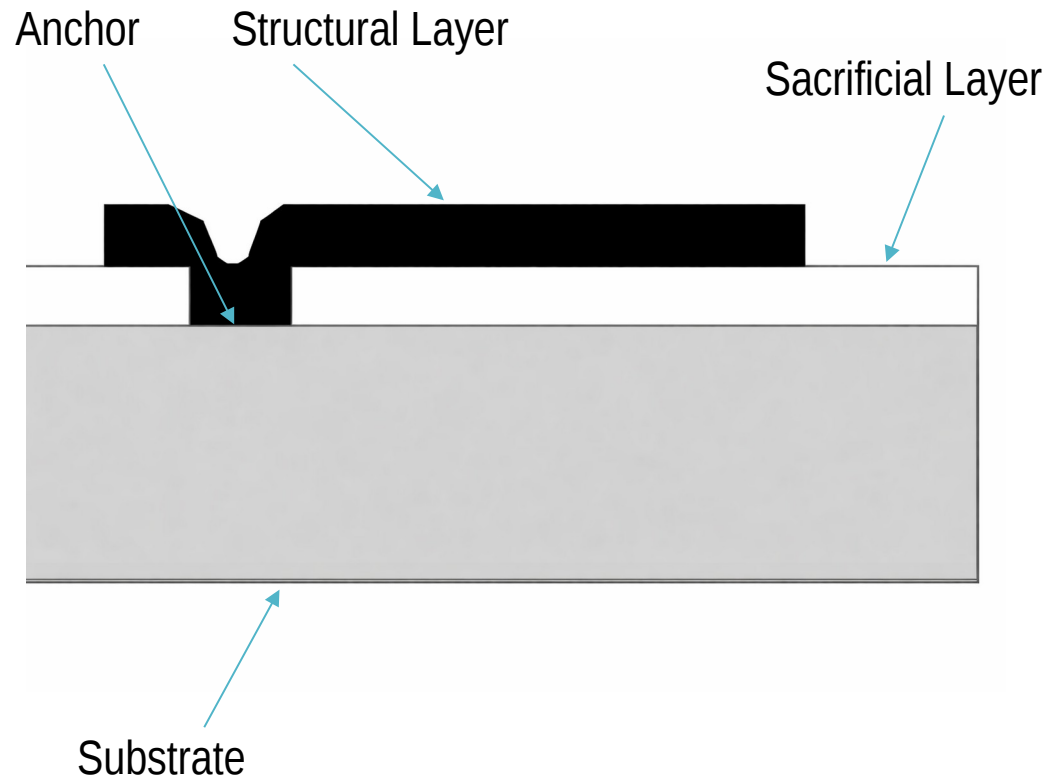


Figure 6. First polysilicon surface micromachined MEMS device integrated with circuits [29].

Surface Micromachining Process

The image depicts a microcantilever.



Bulk Micromachining

Structures formed from single-crystal silicon

Typical thickness: 10–500+ μm

High stiffness and mechanical strength

Natural 3D geometries

Substrate is a functional element

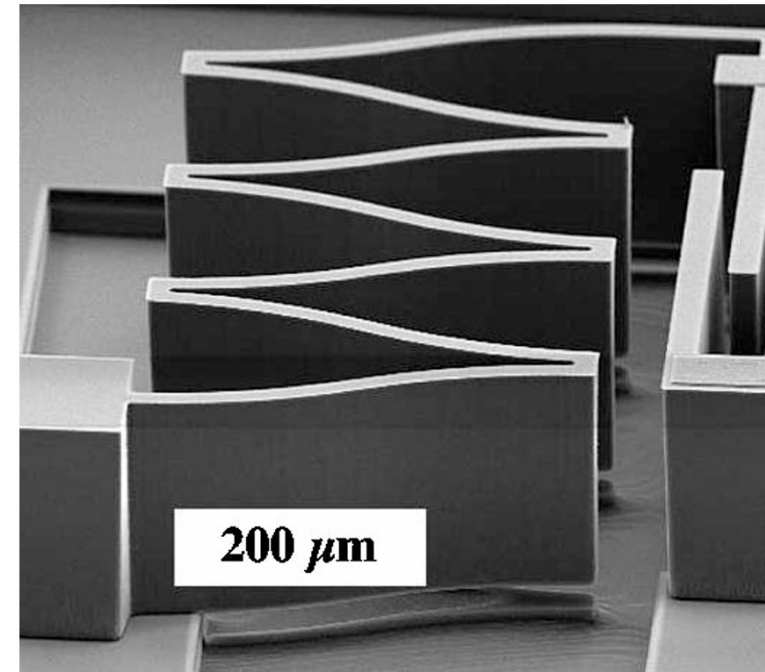


Figure 10. Microflexure created by vertical etching through a wafer with DRIE [36].

Bulk Micromachining Process

Pattern mask on silicon substrate

Remove substrate material via:

- Anisotropic wet etching

- DRIE (deep reactive ion etching)

Remaining silicon becomes structure

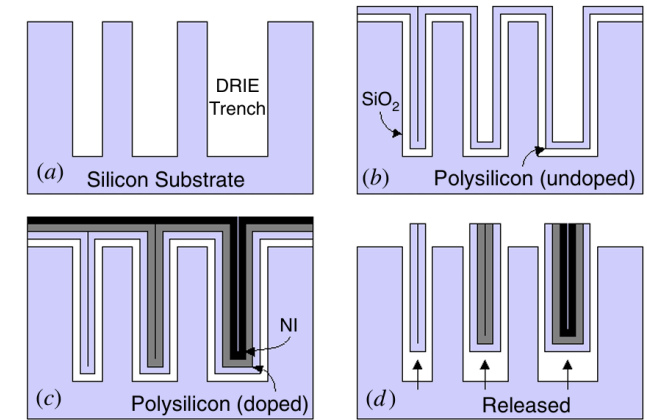
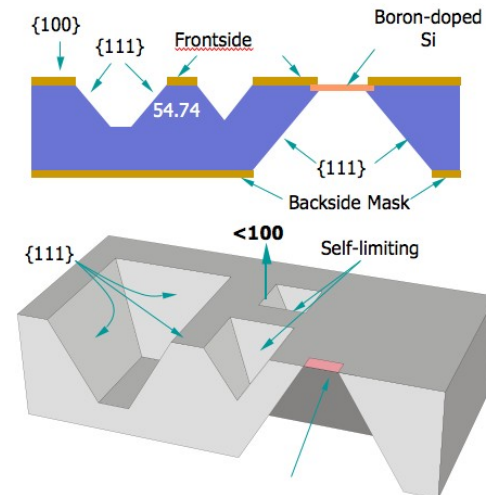
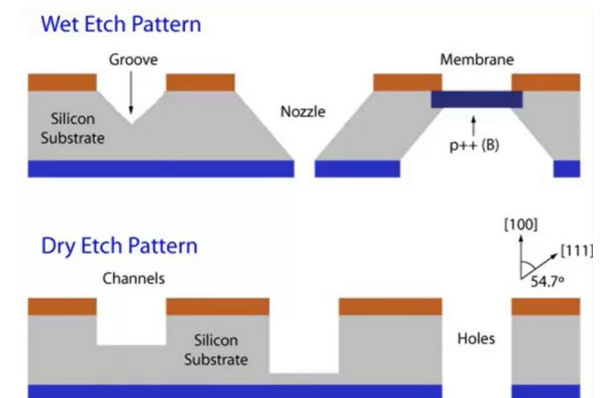


Figure 11. Micromolding process [37].



Deep Reactive-Ion Etch (Bosch Process)

Alternating etch/passivation cycles

Enables vertical sidewalls

Aspect ratios: 20:1 to >50:1

Crystallography-independent

Major enabler of modern bulk MEMS

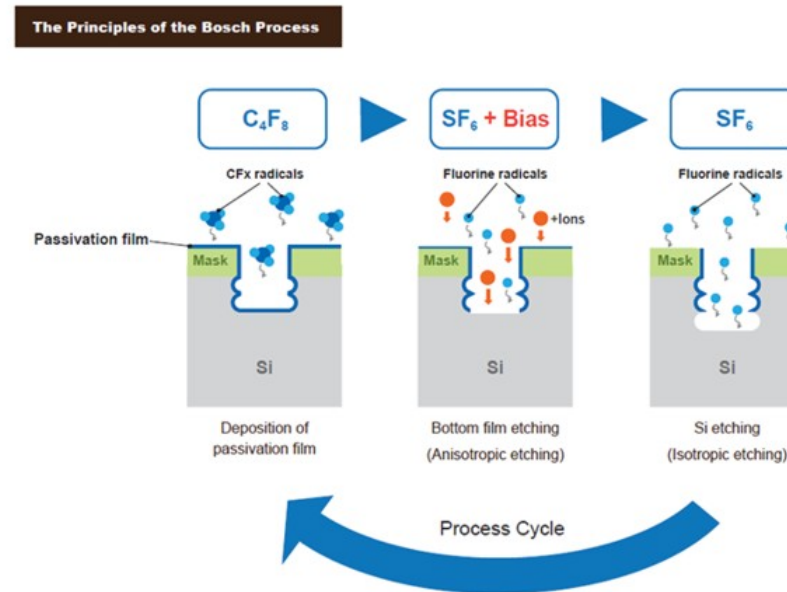


Fig. 1: The Principles of the Bosch Process

Lithographie Galvanoformung and Abformung (LIGA)

Thick resist patterned via:

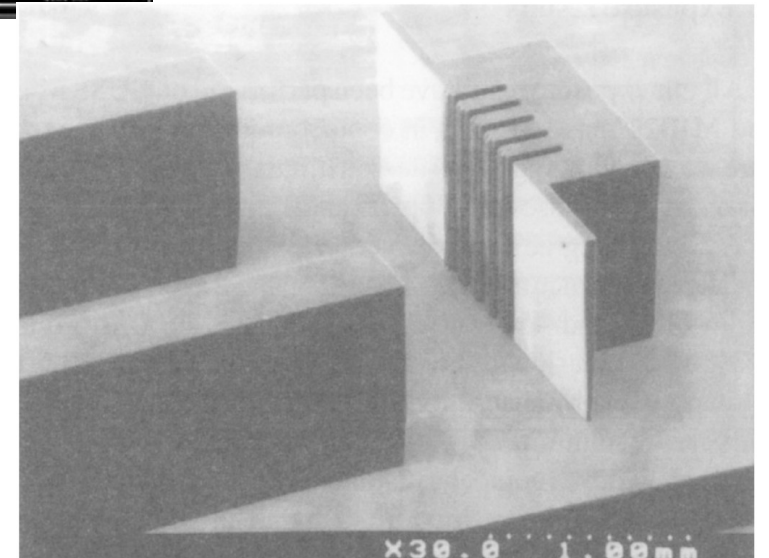
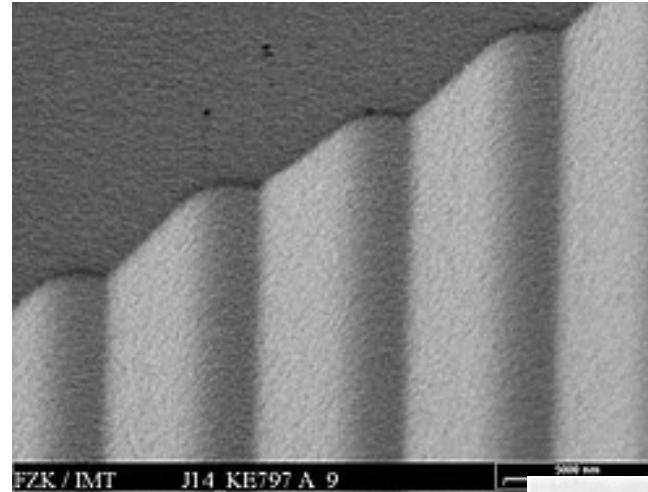
- X-ray lithography (LIGA)

- UV lithography (SU-8)

Structures formed by electroplating or molding

Enables extreme aspect ratios

Limited CMOS compatibility



LIGA Process

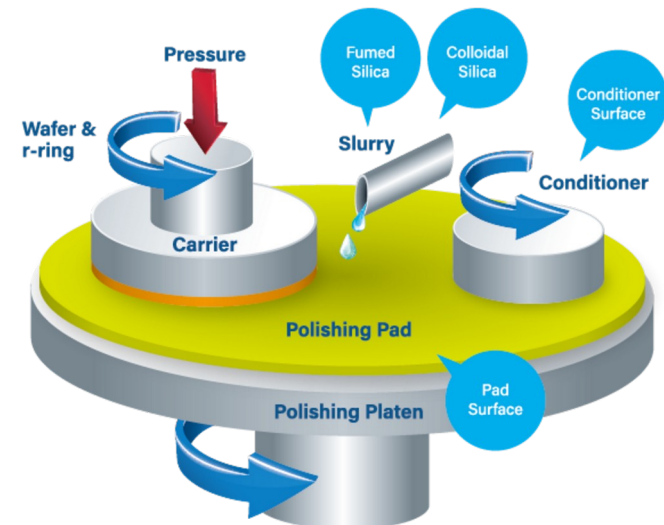
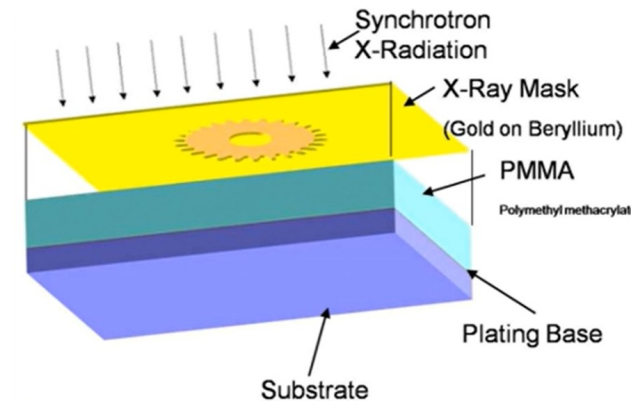
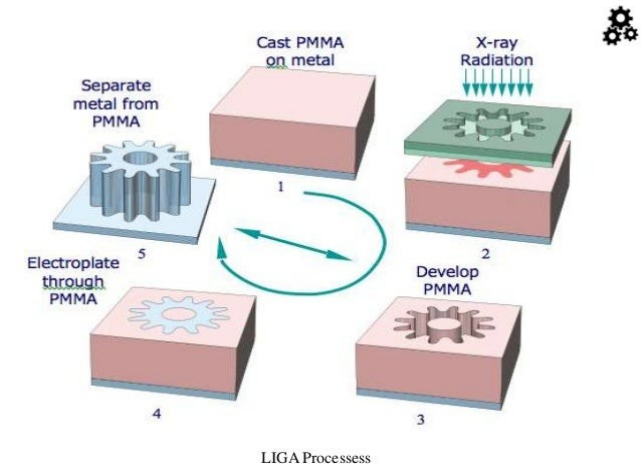
Cast PMMA on metal substrate

X-ray exposure through mask

Develop PMMA to form deep mold

Electroplate metal into mold

Remove PMMA → freestanding metal structures



LIGA Gear with Ant



Trends and Future Prospects

Heterogeneous Integration

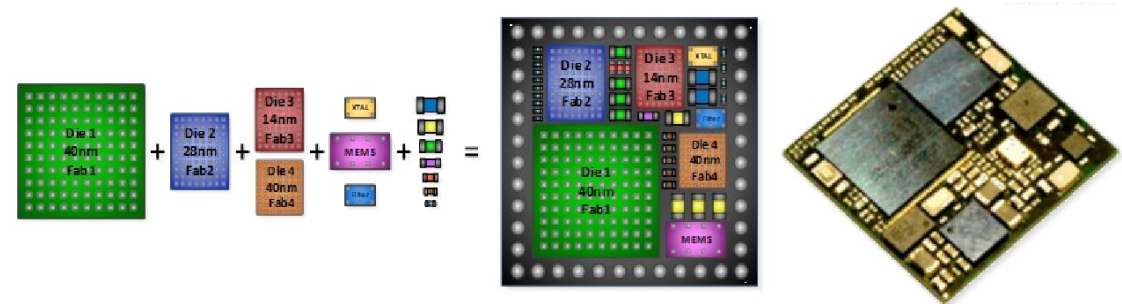
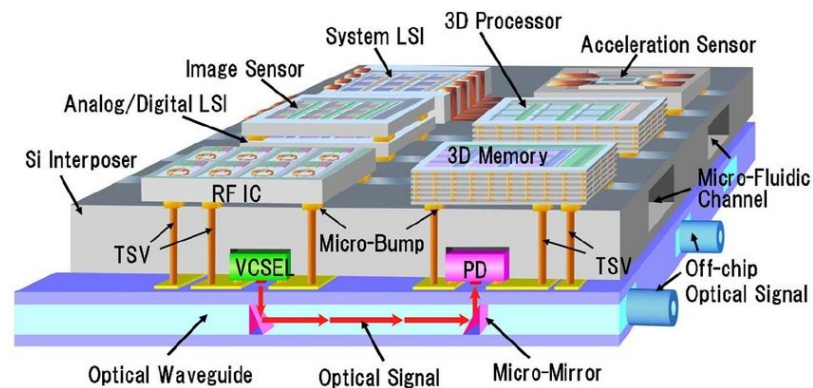
Integration of dissimilar technologies
MEMS, CMOS logic, RF, photonics,
power, and memory into a single
package or module

Benefits:

Smaller footprint, lower power, higher
performance

Improved signal integrity and reduced
parasitics

Faster time-to-market vs. full monolithic
integration



AI Focused Architecture

Raw MEMS data volume exceeds what off-chip processing can handle efficiently

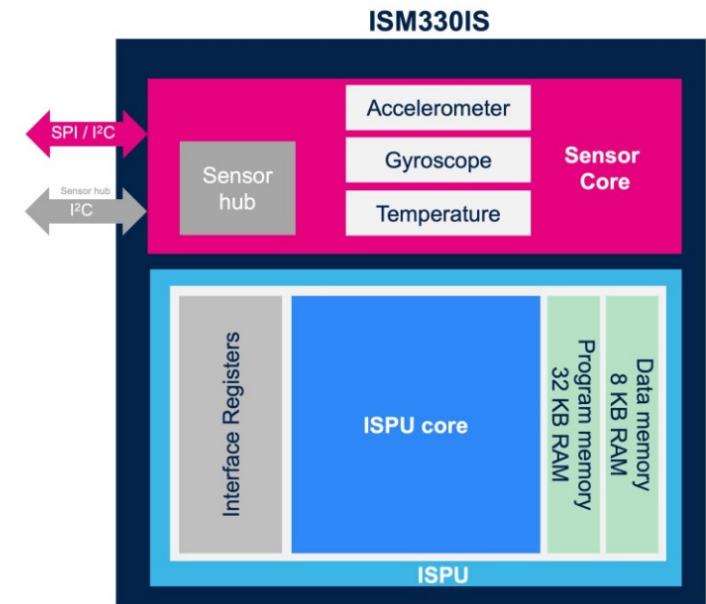
Latency, power, and bandwidth dominate system constraints

Intelligence moves closer to the sensor

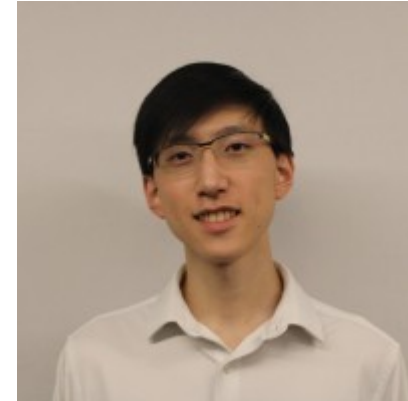
Architectural shift:

Traditional: MEMS → ADC → MCU → cloud

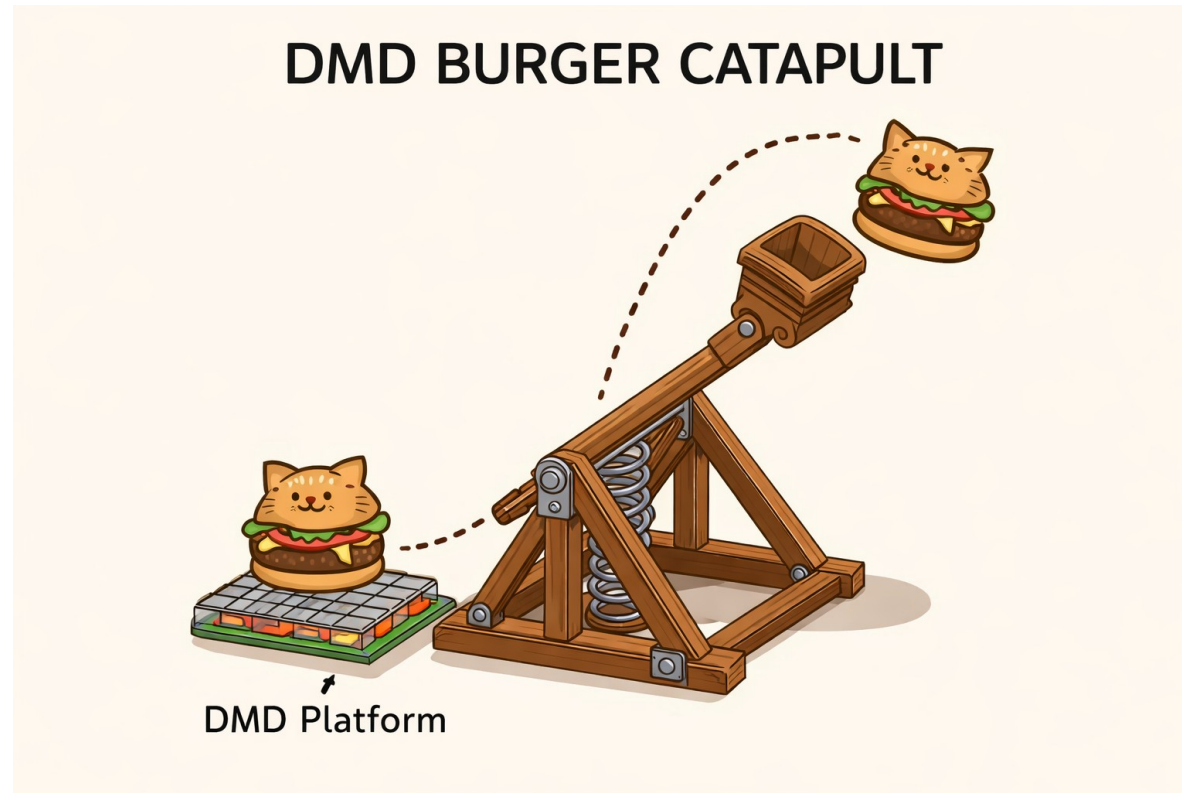
Emerging: MEMS → on-sensor preprocessing → inference → event output



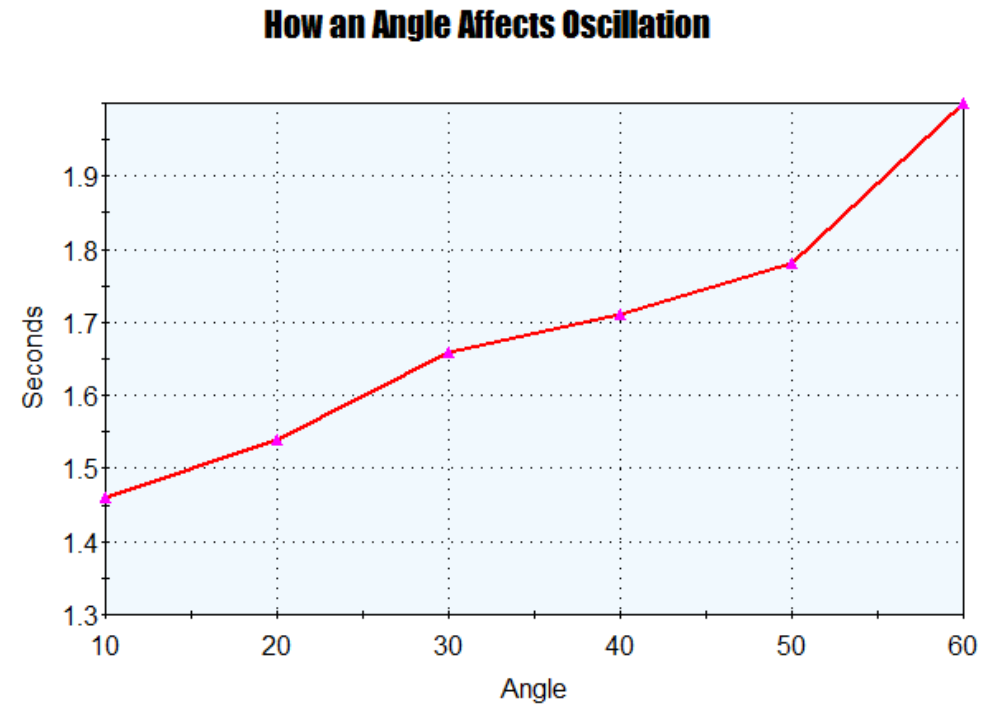
A few words from distinguished research man from industry



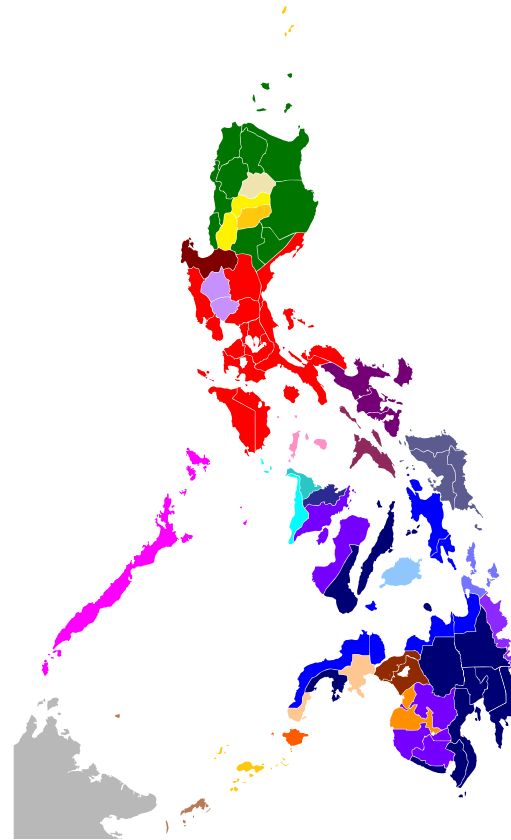
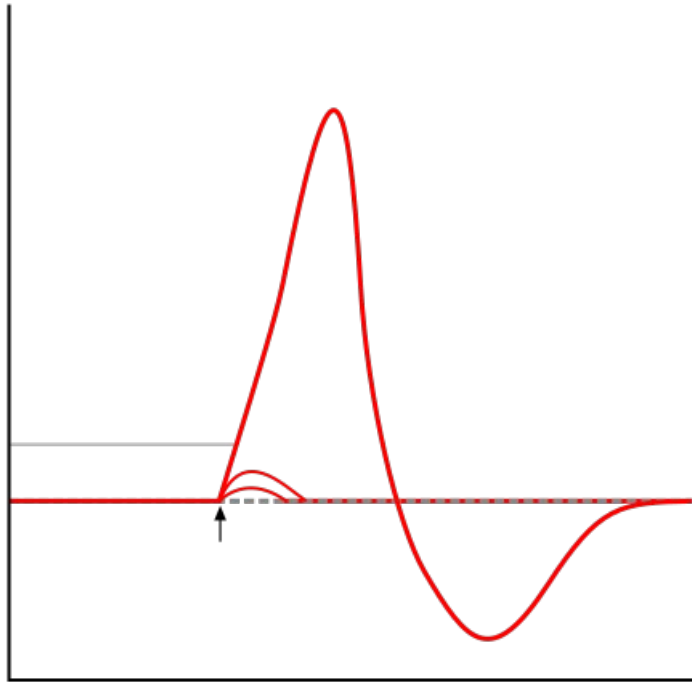
This is a massive problem



But what does the data say?



Further supporting evidence





Back to David!

That is all!

Thank you!