Microelectromechanical Systems (MEMS)
An introduction to Sensors and Actuators

Wei-Chih Wang

Department of Power Mechanical Engineering

And Institute of Nanoegineering and Microsystems

National Tsinghua University

Week 2

- Introduction to MEMS and basic electricity lecture
- Water tower test (second half of the class)
- Name tag project due next Wednesday (you need to present your nametag-2 minutes max.)
- Lecture notes and project instruction can be downloaded from: http://courses.washington.edu/me557/nthu

Capturing the Good Design

Five shoulds of a good design:

- A good design should clearly represent the customer's needs and wants for the product.
- A good design should be based on engineering requirements and targets.
- A good design should follow a functional model of the product.
- A good design should subject to a decreasing number of design changes throughout the design process.
- A good design should use technology that is mature.

Other suggestion

- Keep it simple and cost effective (material, manufacturing and assembly, easier to repair)
- Blending Engineering Design with Arts (innovation and engineering aesthetic)
- Observe Nature and Surrounding
- Gadgetry (sell features we never thought we need to create a new market)
- Good marketing (e.g. social media, infomercial)
- Good networking (e.g. friends family, coworkers, social media friends)
- Good Aegis (good financial or political backing)

Other Important Factors in Achieving A Good Engineering Design:

Individual

-Self-Motivation

-Keen observation and good analytical and creative thinking (always ask question, use what you have learned, different)

Group

-Team Work (utilizing talent of each team member)

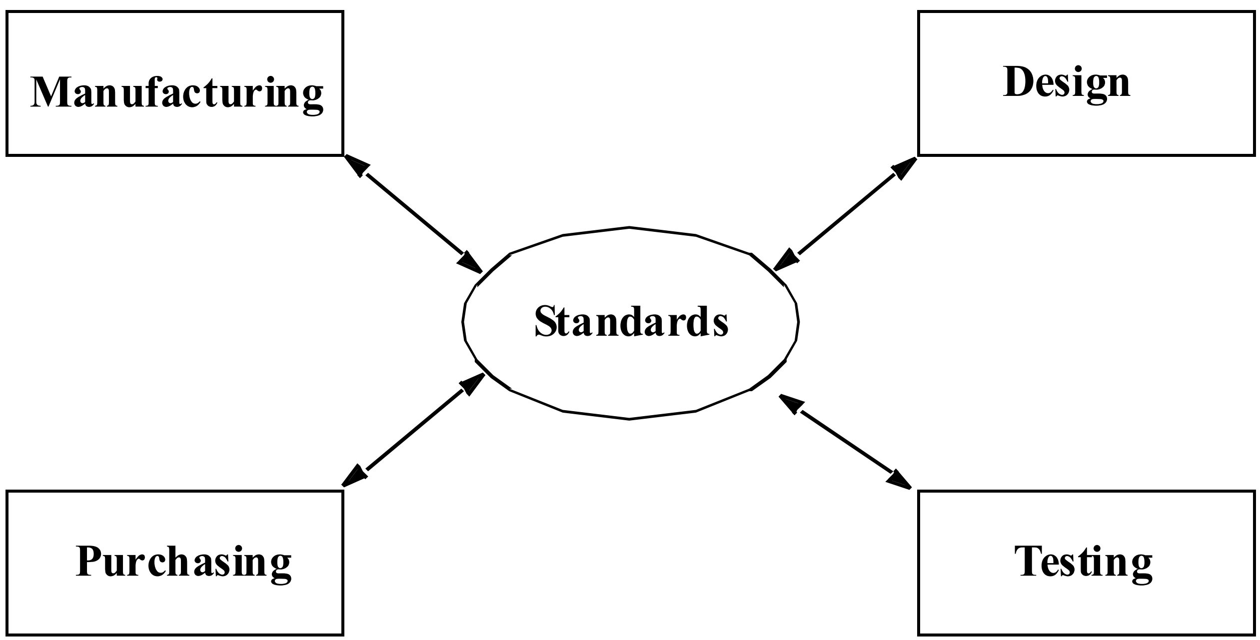
-Open-mindedness (open to ideas, encourage others to participate)

-Positive Attitude (there is no bad idea, just idea happen to be used in the wrong situation)

- Good Communication skills (types: verbal, nonverbal, written, professional public speaking, presentation, great listening and curated list: listening, reflection, openness and friendliness, confidence and honesty, brevity and clarity, accept feedback with grace, give constructive feedback, open mind respect and empathy, ability to choose the right format, body language)

What's the Advantages of Using CE?

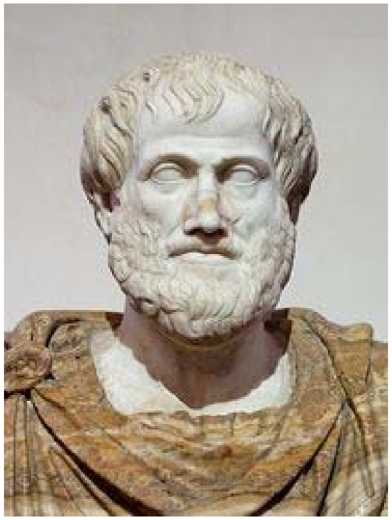
- Design in parallel leads to improvements in many areas such as communication, quality, production processes, cash flow and profitability.
- Reducing the time to market so you can have more market share



Experiential Learning (tactile learning)

- Experiential learning- learning through reflection on doing
- Tactile learning!
- How many people remember stuff you learn from Physics class?
- How many people actually apply what you learn from your class to your everyday life outside school?

Experiential Learning



"For the things we have to learn before we can do them, we learn by doing them."

— Aristotle, The Nicomachean Ethics

Experiential Learning

The general concept of learning through experience is ancient. Around 350 BCE, Aristotle wrote in the *Nichomachean Ethics* "for the things we have to learn before we can do them, we learn by doing them".[5] But as an articulated educational approach, experiential learning is of much more recent vintage. Beginning in the 1970s, David A. Kolb helped to develop the modern theory of experiential learning, drawing heavily on the work of John Dewey, Kurt Lewin, and Jean Piaget.[6]

wikipedia

True Inventor

- Sure you can choose to follow what is already effective and in popular demand, but when you do something out of the norm, then that is when the true magic can occur.

Engineer

- Problem solver
- Artist (we create, contrive)
- Maker-We make things happen (turning ideas into reality)

Takeaway

- Be nice, make friend don’t make enemy
- Be a Team Player
- Open-minded (open to ideas, encourage others to participate)
- Positive Attitude (there is no bad idea, just idea for different situation)
- Show keen observation (pay attention to detail)
- Be inquisitive (show strong analytical aptitude)
- Desire to learn (good foundation)
- Good Communication Skill
- Leadership and Management Skills

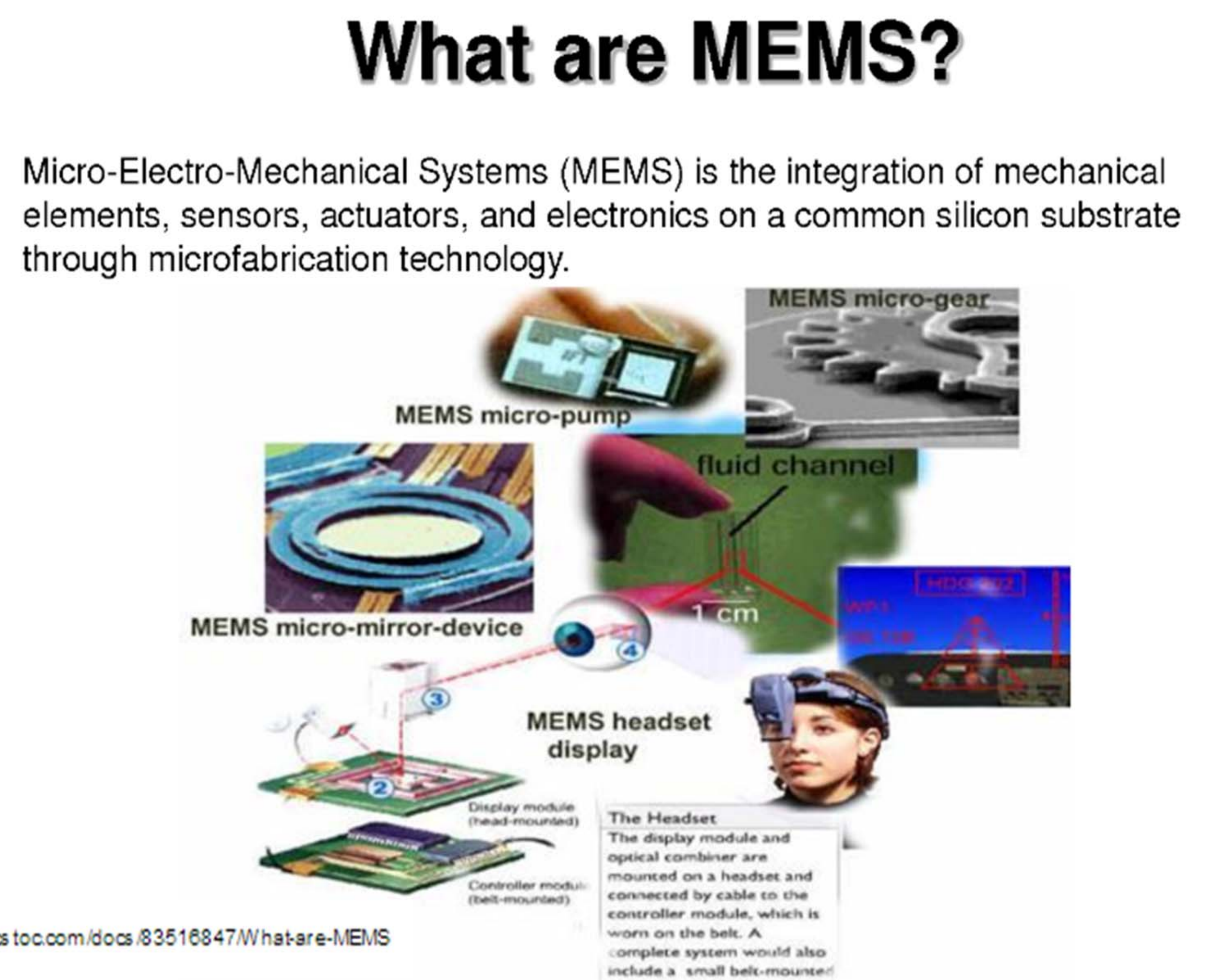
Outline

- Background and History
- MEMS Applications
- MEMS Components
- MEMS Operating principles
- Materials and Fabrication
- Markets and Future outlook

What are MEMS?

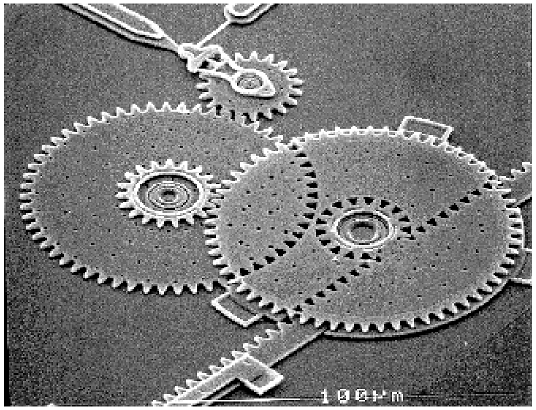
ME

- Syste ... onality fabri ... **ter.**
- Func ... **ctures,** **sens**
- One ... ements that ... ove
- Typi ... ducting chara ... lastics, ceran

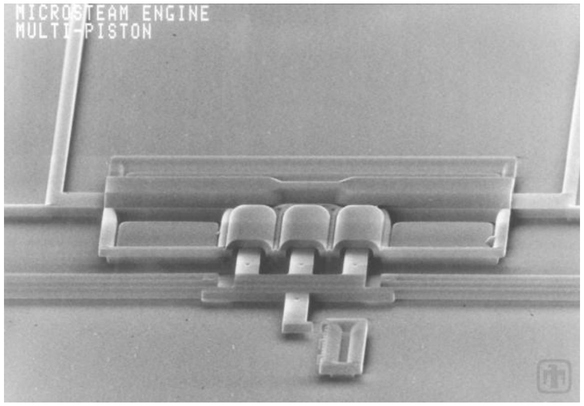


http://www.docstoc.com/docs/83516847/What-are-MEMS

3-D Micromachined Structures



Linear Rack Gear Reduction Drive

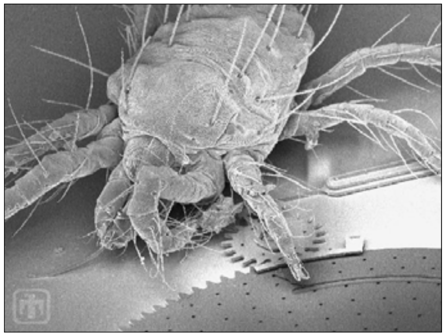


Triple-Piston Microsteam Engine

Photos from Sandia National Lab. Website: http://mems.sandia.gov

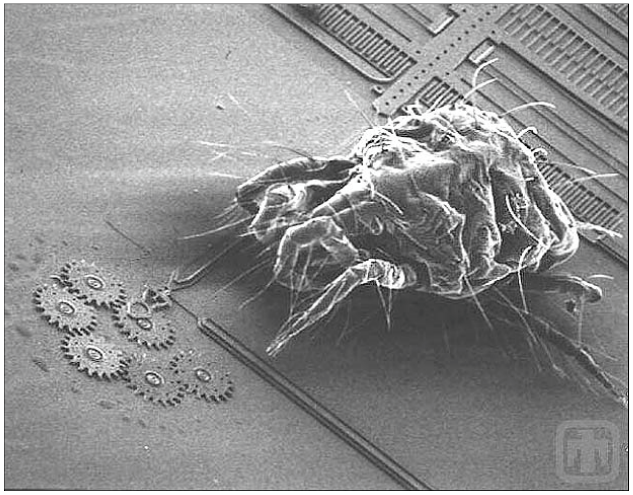
3-D Micromachined Structures

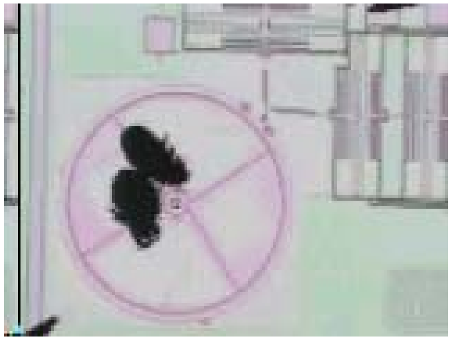
A still picture of the motor..



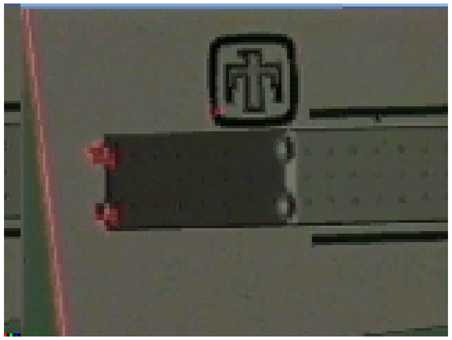
with a spider mite on it!

Another view of the engine





2 dust mites on an optical shutter

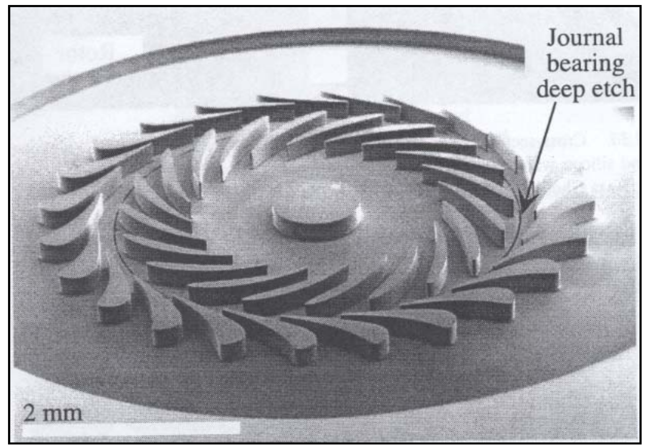


Deflection of laser light using a hinged mirror

Movies from Sandia National Lab. Website: http://mems.sandia.gov

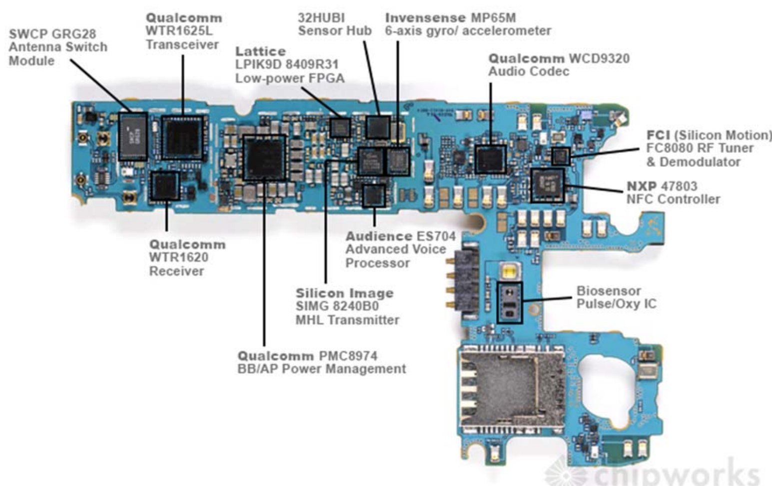
3-D Micromachined Structures

There are many other MEMS devices in development…



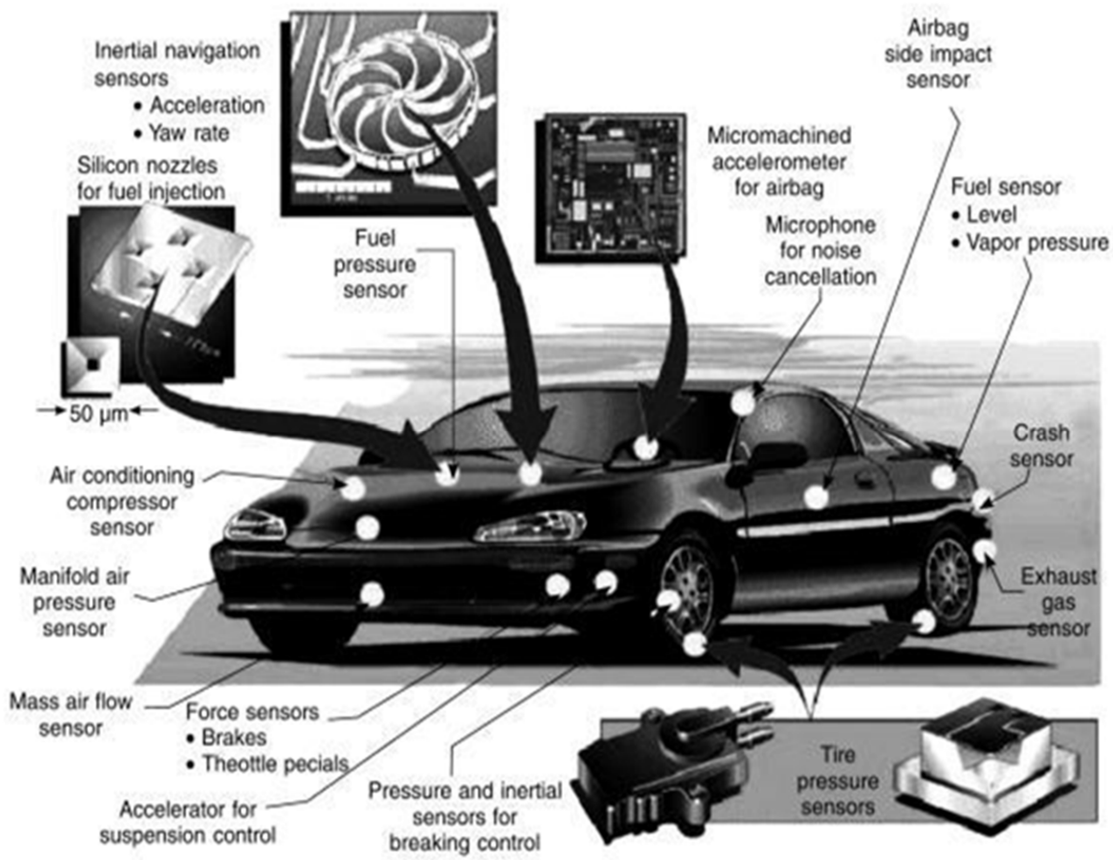
Where Are MEMS?

Smartphones, tablets, cameras, gaming devices, and many other electronics have MEMS technology inside of them



http://www.chipworks.com/en/technical-competitive-analysis/resources/blog/inside-the-samsung-galaxy-s5/

In the Car



Inertial navigation sensors
• Acceleration
• Yaw rate
Silicon nozzles for fuel injection
50 μm
Fuel pressure sensor
Micromachined accelerometer for airbag
Airbag side impact sensor
Microphone for noise cancellation
Fuel sensor
• Level
• Vapor pressure
Crash sensor
Air conditioning compressor sensor
Manifold air pressure sensor
Exhaust gas sensor
Mass air flow sensor
Force sensors
• Brakes
• Theottle pecials
Accelerator for suspension control
Pressure and inertial sensors for breaking control
Tire pressure sensors

Components

Microelectronics:

- "brain" that receives, processes, and makes decisions
- data comes from microsensors

Microsensors:

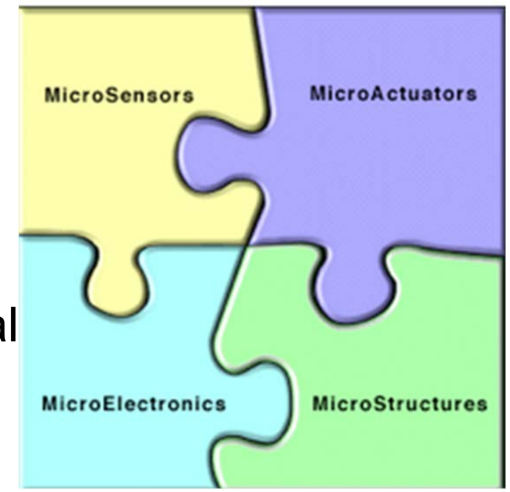
- constantly gather data from environment
- pass data to microelectronics for processing
- can monitor mechanical, thermal, biological, chemical optical, and magnetic readings

Microactuator:

- acts as trigger to activate external device
- microelectronics will tell microactuator to activate device

Microstructures:

- extremely small structures built onto surface of chip
- built right into silicon of MEMS



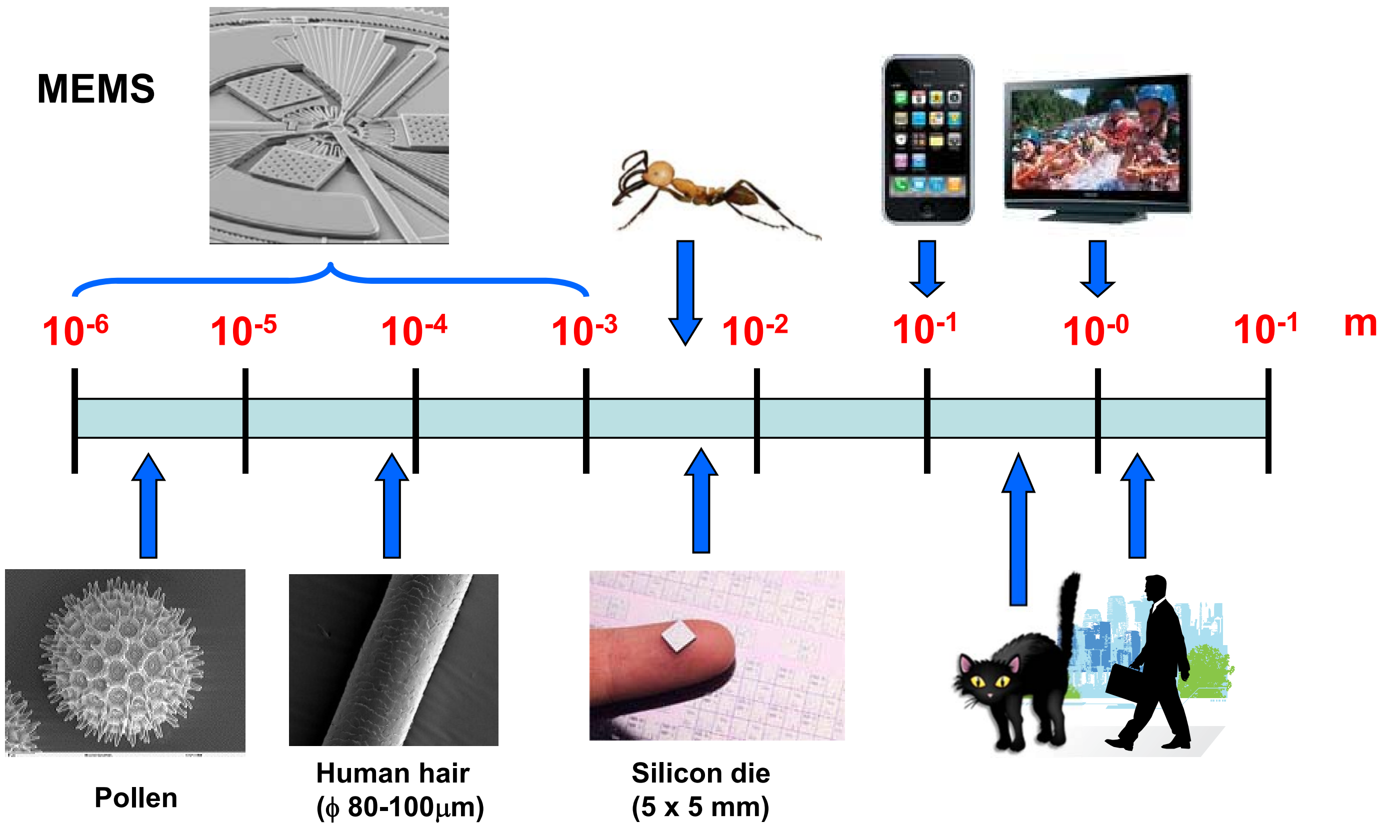
https://www.mems-exchange.org/MEMS/what-is.html

Benefits/Tradeoffs

- Much smaller area
- Cheaper than alternatives
  - In medical market, that means disposable
- Can be integrated with electronics (system on one chip)
- Speed:
  - Lower thermal time constant
  - Rapid response times(high frequency)
- Power consumption:
  - low actuation energy
  - low heating power

- Mechanize process need to be robust
- Imperfect fabrication techniques
- Difficult to design on micro scales
- Time and cost (need to be produce in large quantity)
- Expensive in prototype and design stage

Scales and Dimensions



- **Made up of components between 1-100 micrometers in size**
- **Devices vary from below one micron up to several mm**

What are some reasons that you would want to make micro-sized devices?

- Smaller devices require less material to make. (Earth has limited resources.)
- Smaller devices require less energy to run.
- Redundancy can lead to increased safety. (You can use an array of sensors instead of just one.)
- Micro devices are inexpensive (debatable?)
  - Less material
  - Can be fabricated in batch processes

What are some reasons that you would want to make micro-sized devices?

- Micro devices are minimally invasive and can be treated as disposable. (Especially good for chemical and medical applications.)

- Many physical phenomena are favored at small scales.

Small Scaling Effect

Activity – Demo with key and key ring

Water spills out of key ring, but it stays in the smaller holes of the key. Why?

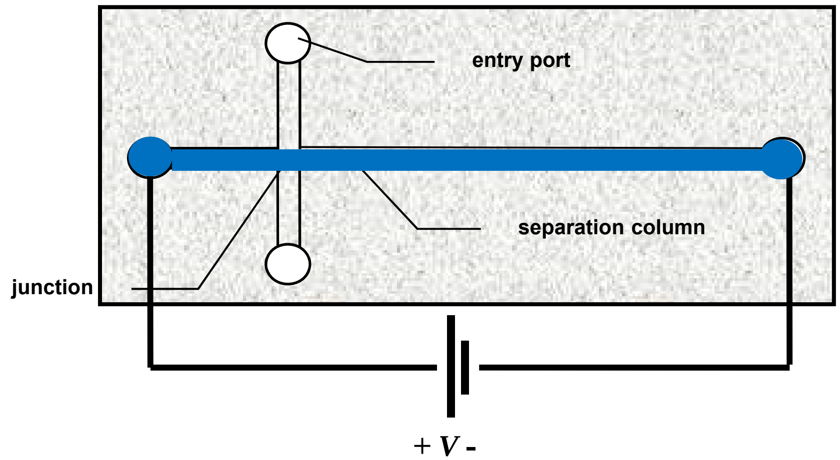
- **Gravity (weight) pulls water down. Surface tension holds water up. Which one wins?**
- **Weight depends on volume/area/length**
- **Surface tension depends on volume/area/length**
- **therefore,**

$$\frac{surface\,tension}{weight} = \frac{\sigma}{W} \sim$$

Favorable scalings at the microscale

- **Heat transfer is faster**
- **Frequency response is faster**
- **Electrostatic forces are more prominent Surface tension can move fluids**
- **And more**

Electro-osmotic flow

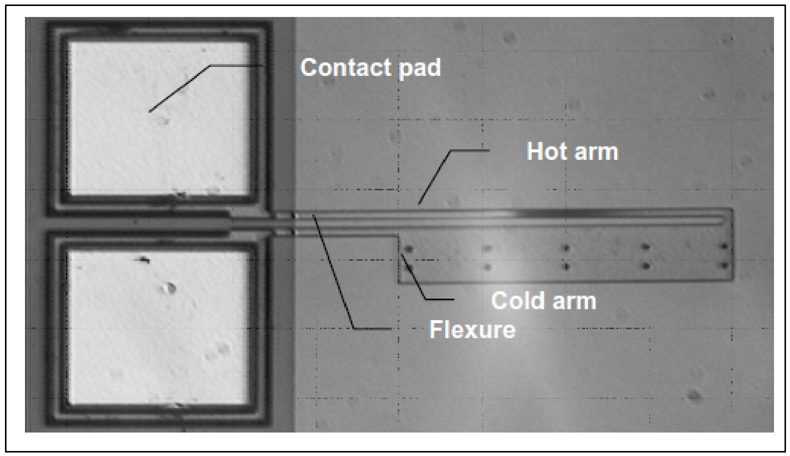


Electricity can move fluids!

Capillary effect prevent making channel too small

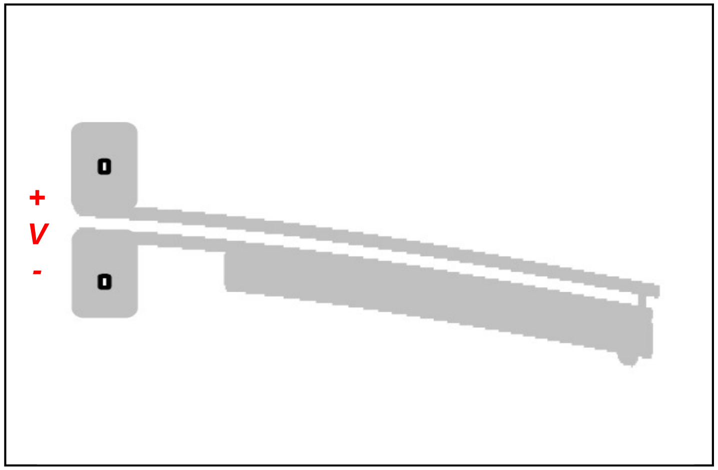
Small Scale Effect

Hot arm actuator



A poly-silicon hot-arm actuator fabricated using surface micromachining

Hot arm actuator



A poly-silicon hot-arm actuator fabricated using surface micromachining

Issues operating in Small scale devices

- Friction is greater than inertia. Capillary, electrostatic and atomic forces as well as **stiction** at a micro-level can be significant.

- **Heat dissipation** is greater than heat storage and consequently thermal transport properties could be a problem or, conversely, a great benefit.

- **Fluidic or mass transport properties are extremely important**. Tiny flow spaces are prone to blockages but can conversely regulate fluid movement.

- **Material properties** (Young's modulus, Poisson's ratio, grain structure) and mechanical theory (residual stress, wear and fatigue etc.) may be size dependent.

- **Integration with on-chip circuitry is complex and device/domain specific**. Lab-on-a- chip systems components may not scale down comparably.

- **Miniature device packaging and testing is not straightforward**. Certain MEMS sensors require environmental access as well as protection from other external influences. Testing is not rapid and is expensive in comparison with conventional IC devices.

- **Cost** – for the success of a MEMS device, it needs to leverage its IC batch fabrication resources and be mass-produced. Hence mass-market drivers must be found to generate the high volume production.

Application

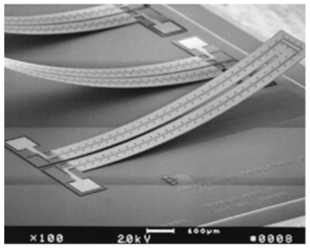
Automotive	Electronics	Medical	Communications	Defence
Internal navigation sensors	Disk drive heads	Blood pressure sensor	Fibre-optic network components	Munitions guidance
Air conditioning compressor sensor	Inkjet printer heads	Muscle stimulators & drug delivery systems	RF Relays, switches and filters	Surveillance
Brake force sensors & suspension control accelerometers	Projection screen televisions	Implanted pressure sensors	Projection displays in portable communications devices and instrumentation	Arming systems
Fuel level and vapour pressure sensors	Earthquake sensors	Prosthetics	Voltage controlled oscillators (VCOs)	Embedded sensors
Airbag sensors	Avionics pressure sensors	Miniature analytical instruments	Splitters and couplers	Data storage
"Intelligent" tyres	Mass data storage systems	Pacemakers	Tuneable lasers	Aircraft control

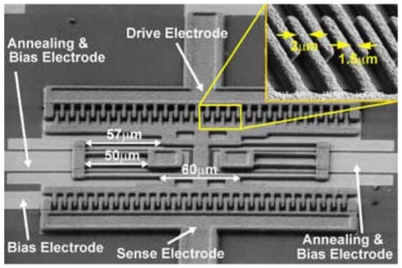
Applications

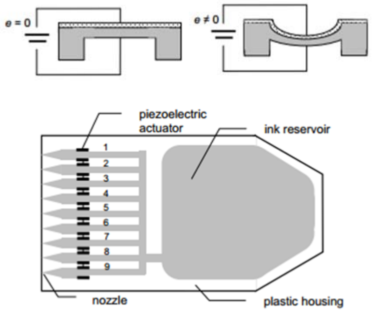
- Consumer Electronics (cell phone components-RF devices, Bluetooth dongle)
- Computer printers (Ink jet print heads)
- Computer printers (Ink jet print heads)
- Automotive (air bag sensors, tire pressure sensor)
- Lab-on-a-chip (Microfluidics)
- Optical devices (Micromirrors)
- Industrial
- Aerospace & Defense
- Healthcare
- Telecommunication
- Lots of other things

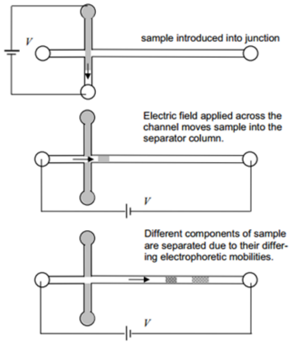
MEMS Operation

- Micro Sensors & Actuators
- Types of transducers:
  - o Electromagnetic (e.g. capacitive, electrostatic, magentic etc.)
  - o Piezoelectric (acoustic, mechanical)
  - o Thermal (bimetal, SMA, etc.)
- Additionally: Microfluidic









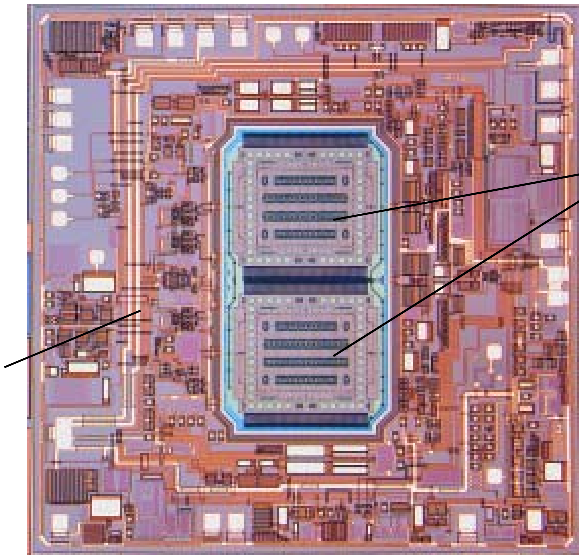
Applications: Sensors

Inertial sensors

- Acceleration
  - Air bag crash sensing
  - Seat belt tension
  - Automobile suspension control
  - Human activity for pacemaker control
- Vibration
  - Engine management
  - Security devices
  - Monitoring of seismic activity
- Angle of inclination
  - Vehicle stability and roll
  - Gyroscope for smart phone

Example 1: Inertial MEMS

ANALOG DEVICES



Signal Processing Integrated electronics

Mechanical component

Silicon substrate

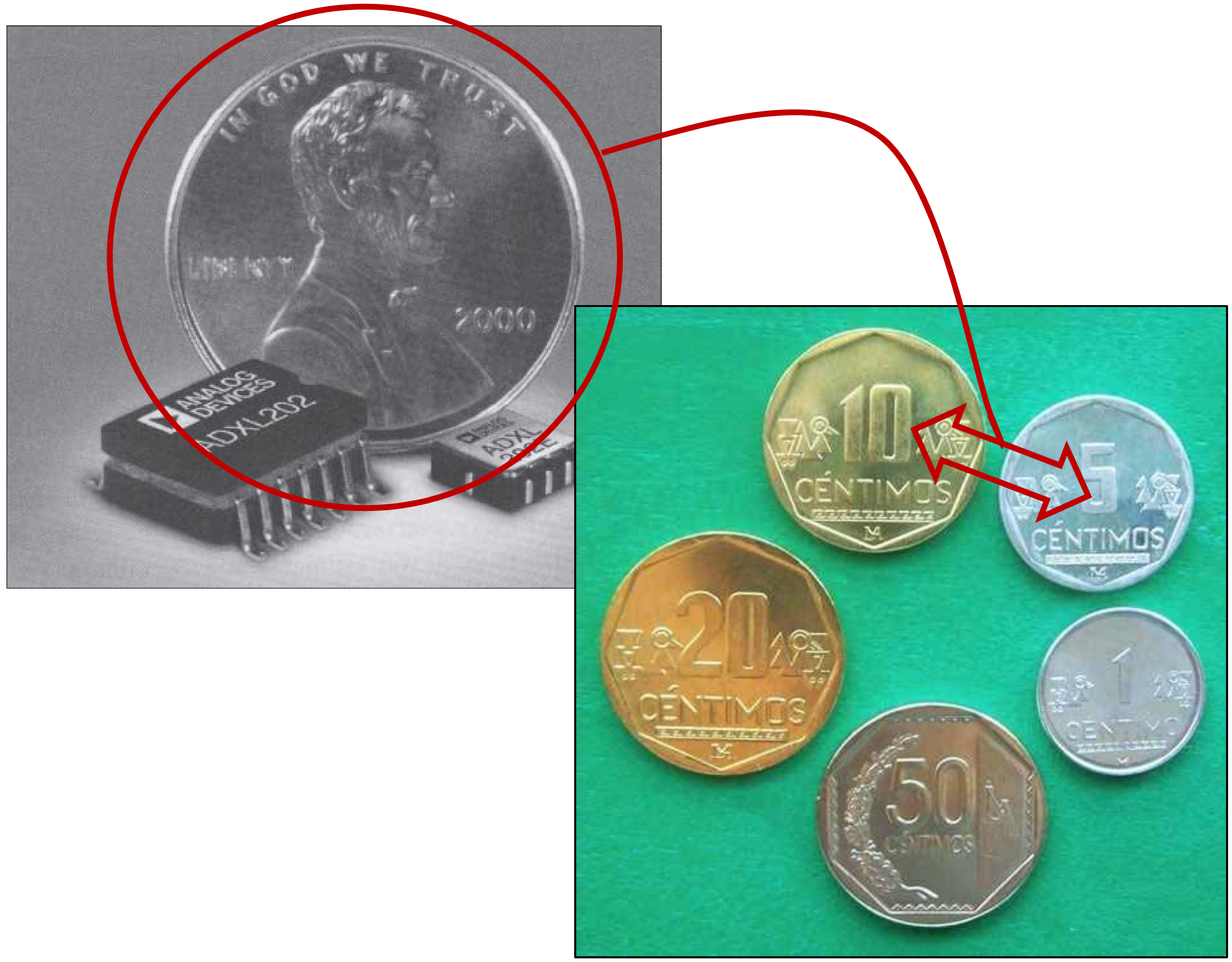
Integrated mechanical and electrical components

⇩

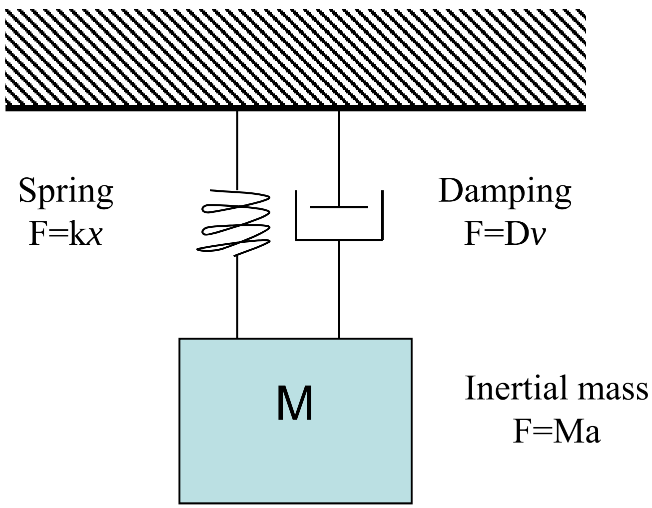
Smart microsensor systems

Analog Device Accelerometer

MEMS accelerometers are used widely to deploy airbags.



Accelerometers



Static deformation:

$$d_{static} = \frac{F}{k} = \frac{Ma}{k}$$

Dynamic behavior

$$M\frac{d^2x}{dt^2} + D\frac{dx}{dt} + kx = F_{ext} = Ma$$

$$\omega_r = \sqrt{\frac{k}{M}}$$ Resonance frequency

$$Q = \frac{\omega_r M}{D}$$ Quality factor

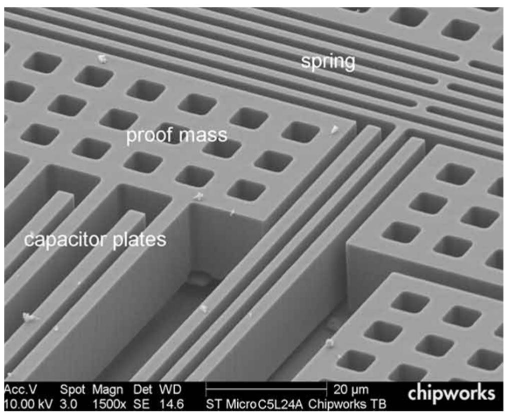
Accelerometers

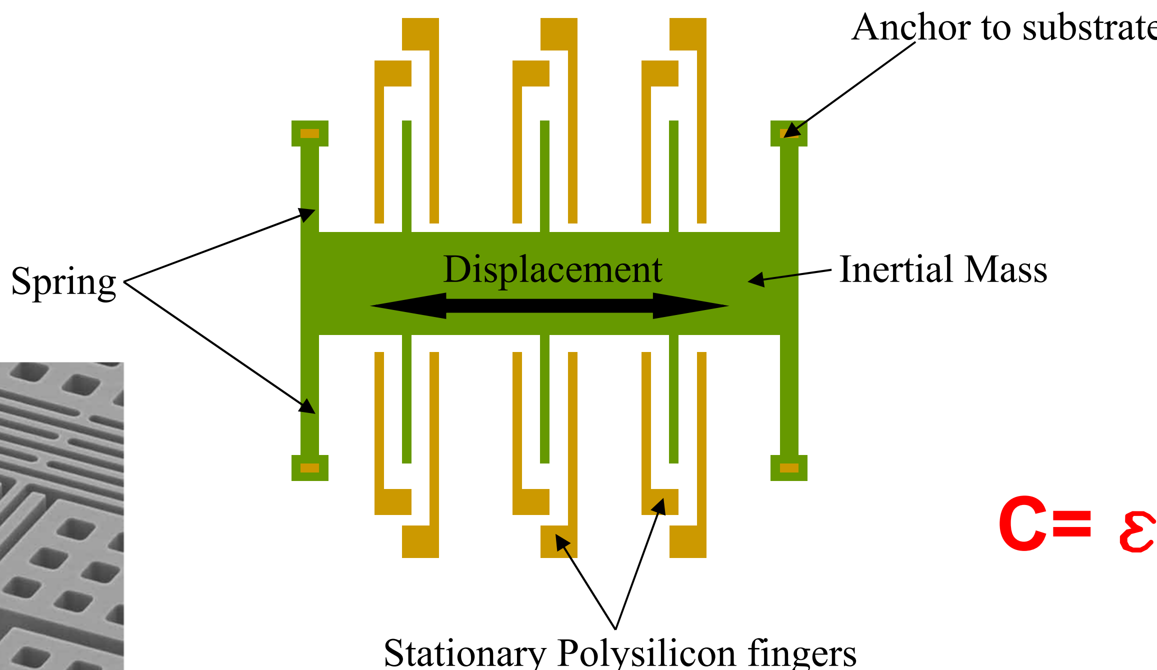
Accelerometer parameters

- acceleration range (G) (1G=9.81 m/s^2)
- sensitivity (V/G)
- resolution (G)
- bandwidth (Hz)
- cross axis sensitivity

Application	Range	Bandwidth	Comment
Air Bag Deployment	± 50 G	~ 1 kHz	
Engine vibration	± 1 G	> 10 kHz	resolve small accelerations (< 1 micro G)
Cardiac Pacemaker control	± 2 G	< 50 Hz	multiaxis, ultra-low power consumption

Capacitive Accelerometers



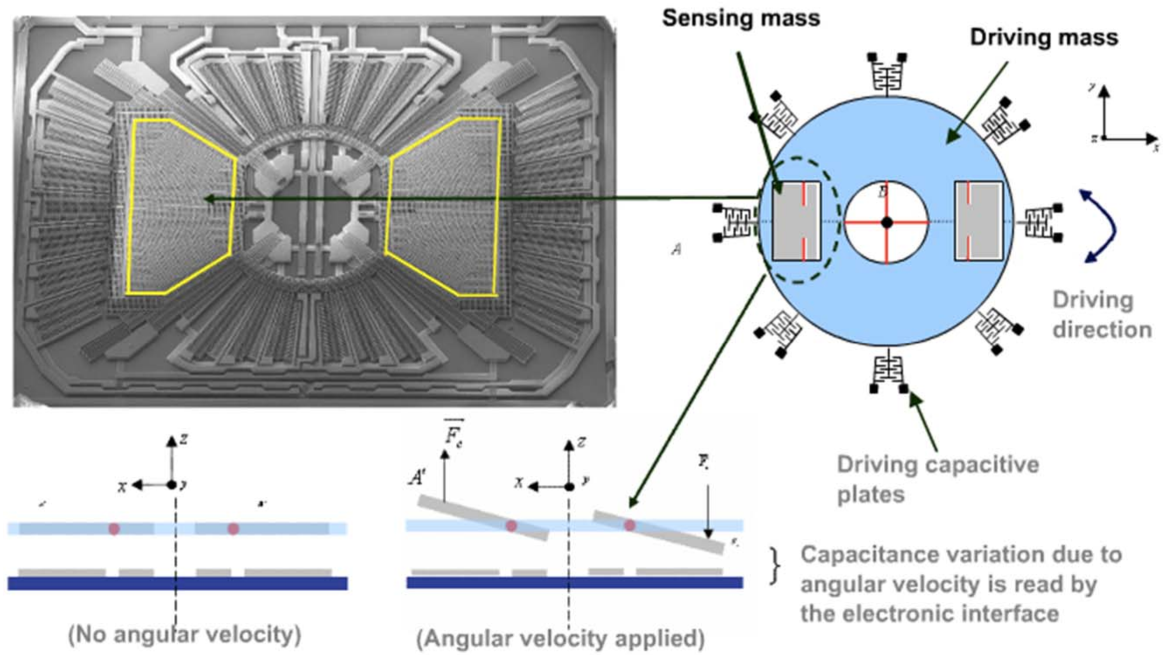


$C = \varepsilon A/d$

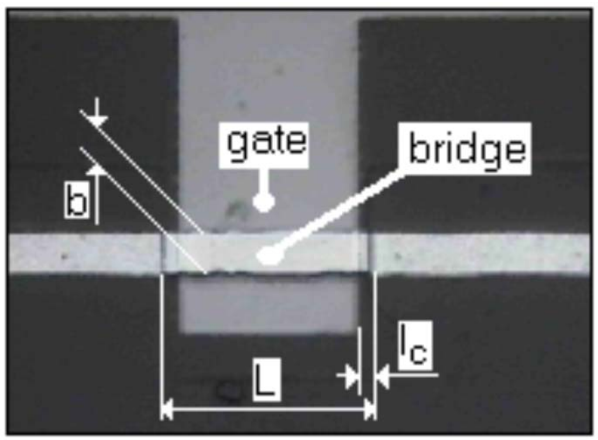
Based on ADXL accelerometers, Analog Devices, Inc.

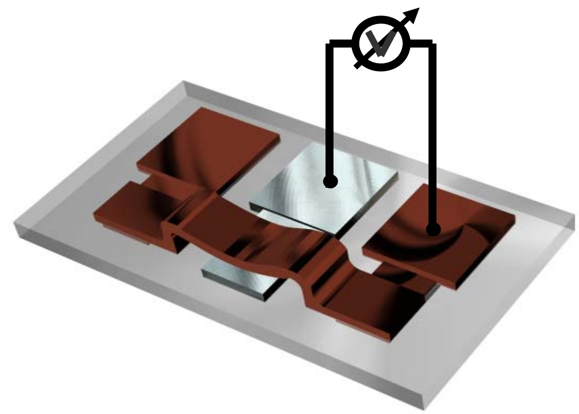
Inertial Sensors

MEMS Gyroscope



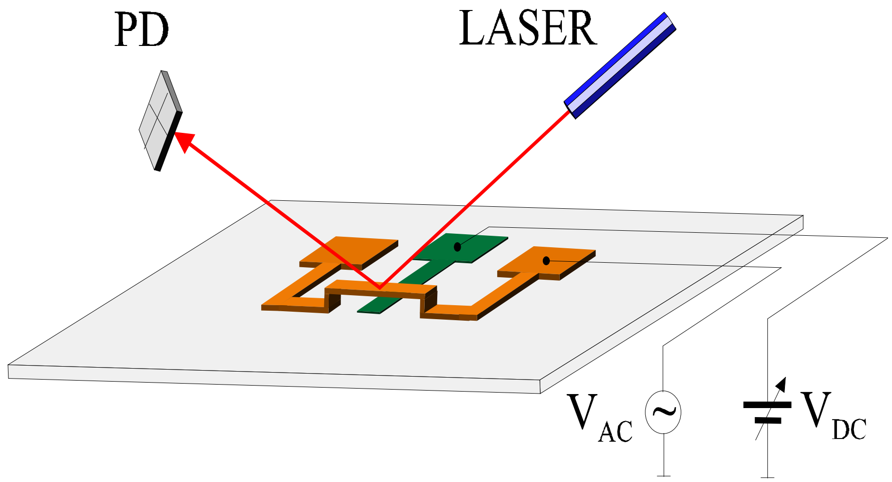
Example 2: Electrostatic Actuation





- **Electrostatic force between gate and counter-electrode**
- **Electrostatic force is always attractive**

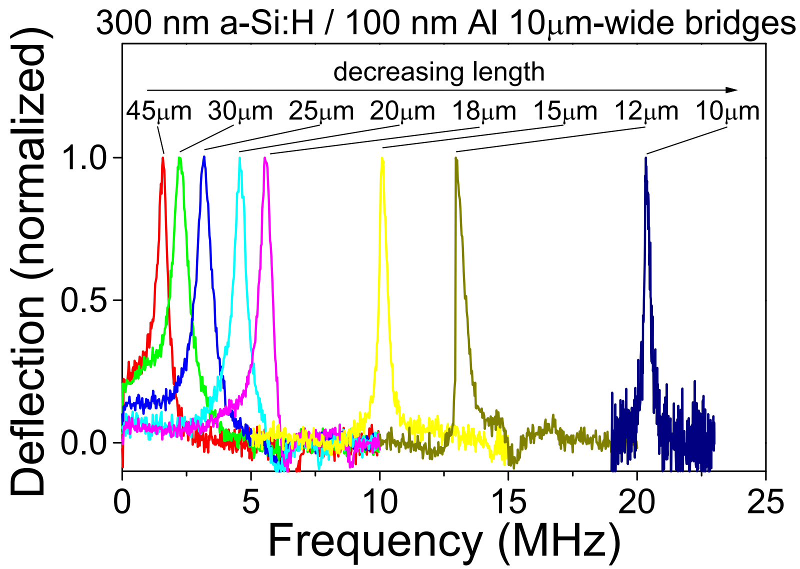
Optical detection



•A laser beam is focused on the structure and the reflected light is collected with an intensity (or quadrant) detector.

•The deviation of the beam is proportional to the deflection

Vibration Detection: Resonance frequency



$$f_r = \frac{3.52}{2\pi L^2}\left(\frac{EI}{\rho A}\right)^{1/2}$$

- Optical detection of electrical actuation
- Resonance is inversely proportional to square of the length
- 20 MHz resonances measured with 10 μm-long a-Si:H bridges (Q~100 in air; Q up to 5000 in vacuum)

W. Wang

Applications: Sensors

Pressure sensor:

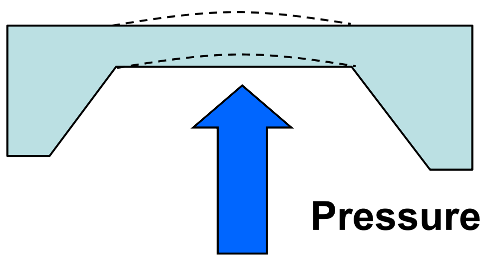
- Piezoresistive sensing
- Capacitive sensing
- Resonant sensing

Application examples:

- Manifold absolute pressure (MAP) sensor
- Disposable blood pressure sensor (Novasensor)

Example 3: Pressure Sensors

Pressure sensors utilise an thin membrane formed on or in the silicon chip.



Sensing mechanism detects the movement of the diaphragm. Signal conditioning electronics integrated on the same die.

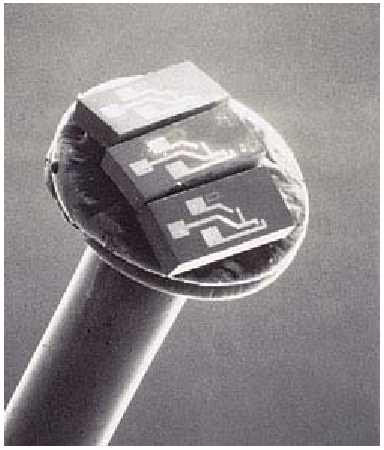
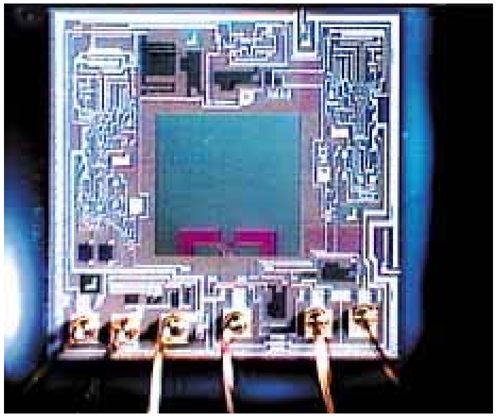
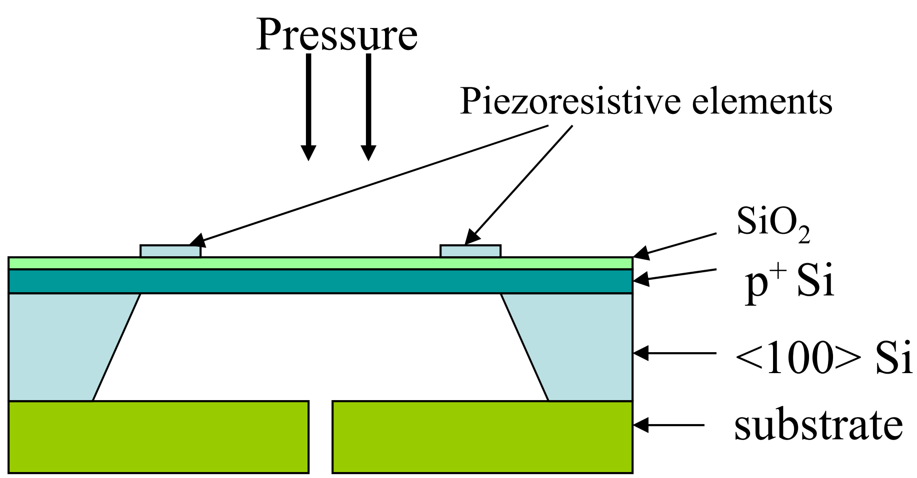


Photo from GE Novasensor – Catheter pressure sensors



Piezoresistive Pressure Sensors



Piezoresistive Pressure Sensors

Wheatstone Bridge configuration

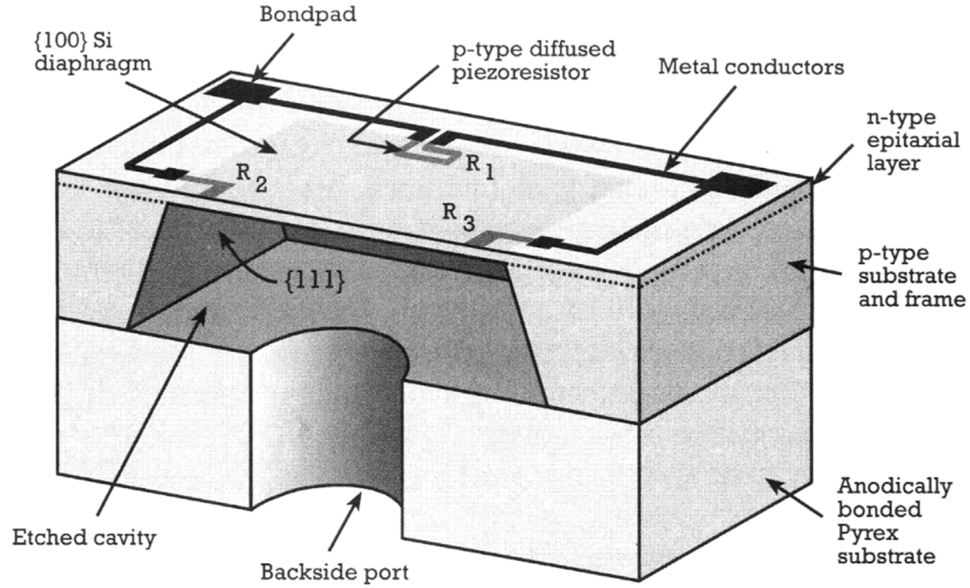


Illustration from "An Introduction to MEMS Engineering", N. Maluf

Applications: Actuators

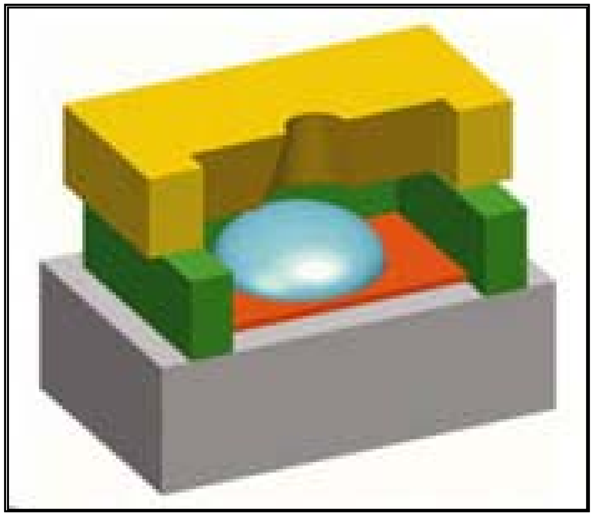
- Thermal
- Piezoelectric
- Electrostatic
- Electromagnetic

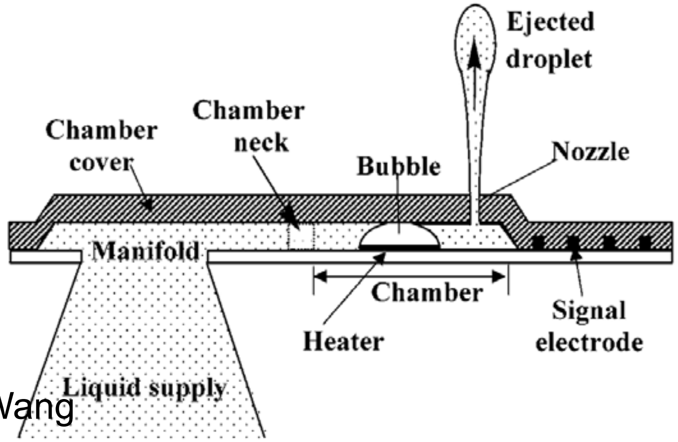
Example 5: Inkjet Print Heads

Ink dots are tiny (10-30 per mm) and so are the nozzles that fire them.

Bubble Jet (Thermal Actuator)

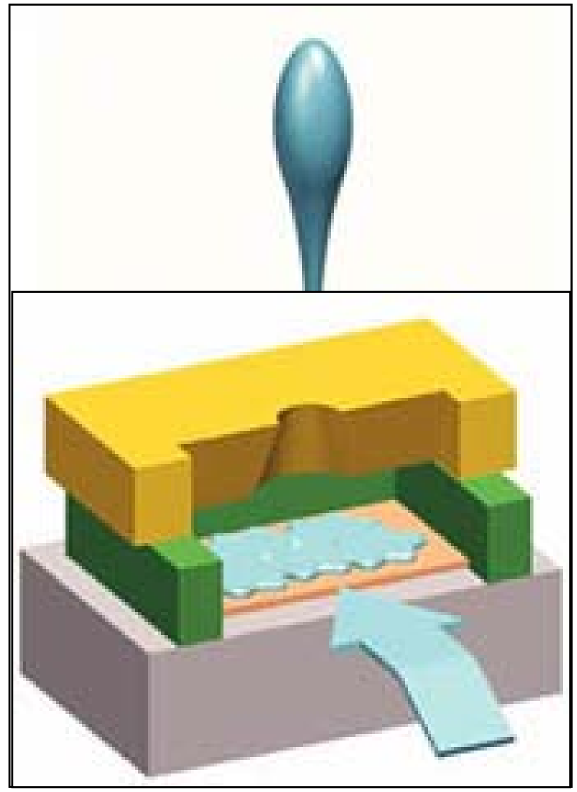
- Ink-filled chambers are heated by tiny resistive heating element
- By heating the liquid ink a bubble is generated

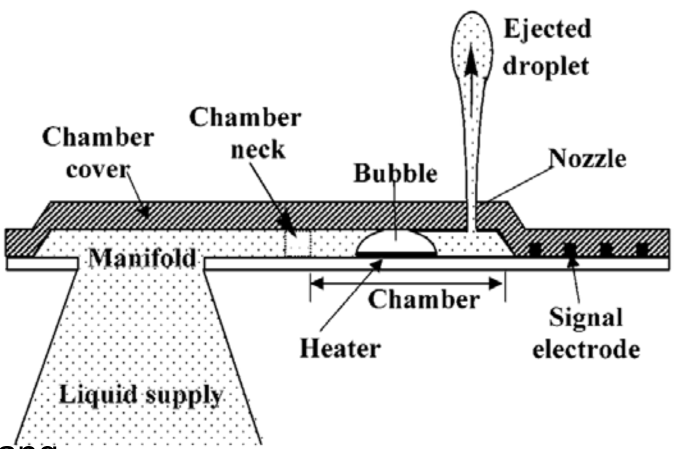




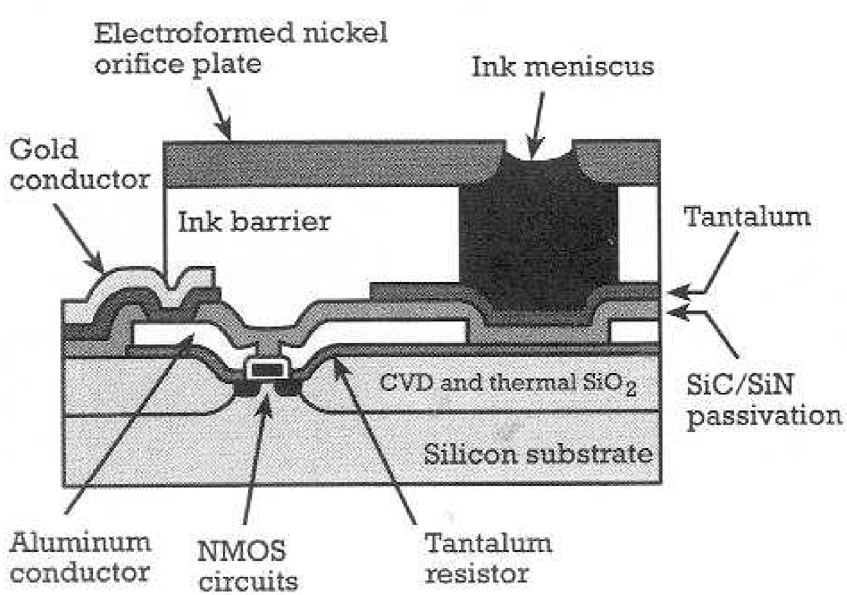
Bubble Jet

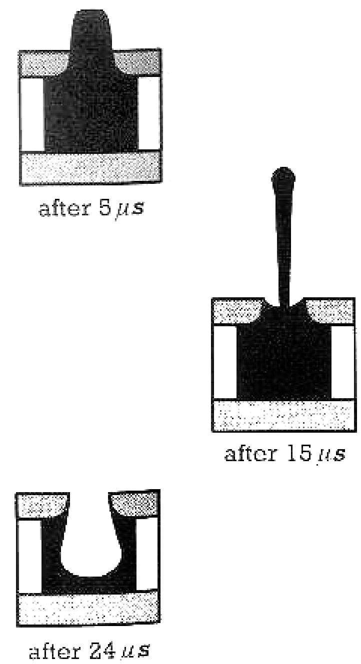
- The vaporized part of the ink is propelled towards the paper in a tiny droplet
- Chambers are filled again by the ink through microscopic channels





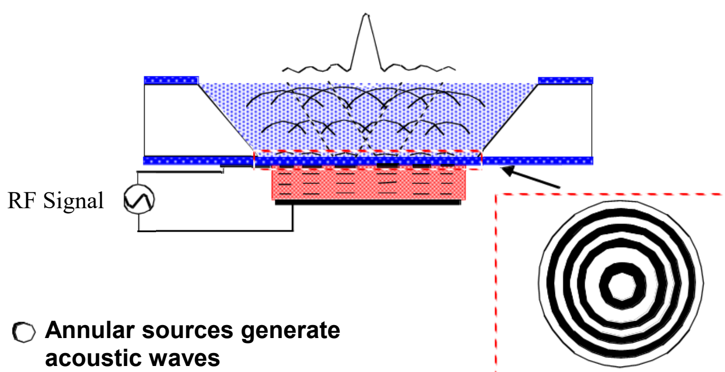
Bubble Jet
(Thermal Actuator)





Example 6: Focus Acoustic Wave Inkjet Print head (Piezoelectric)

Constructive Wave Interference



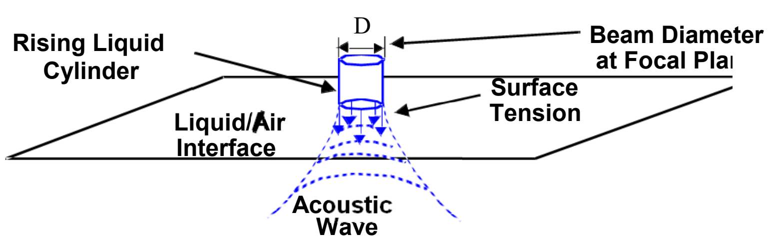
- **Annular sources generate acoustic waves**

Annular Bottom Electrodes (top view)

Transducer Specifications

- **RF Frequency: 300 MHz**
- **ZnO Thickness: 10.55 µm**
- **Focal Length: 400 µm**
- **Half-Wave-Band Sources: 7**
- **Predicted Droplet Diameter: 5 µm**

Liquid Ejector

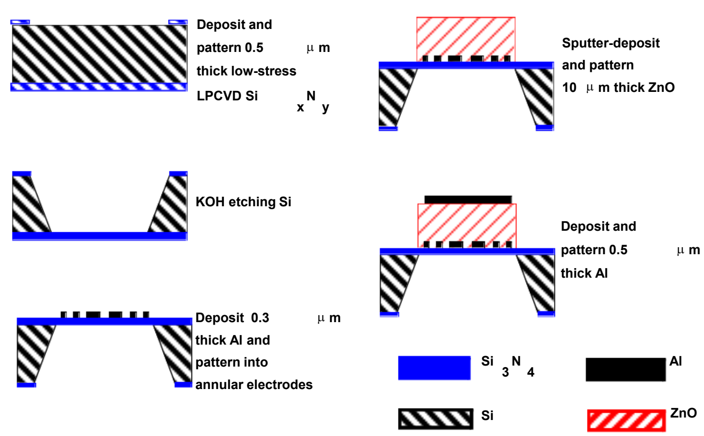


- **Droplet Formation due to Focused Acoustic Wave**
  - Function of Radiation Pressure & Surface Tension

➔ Radiation Pressure ($2I_f/V_a$)

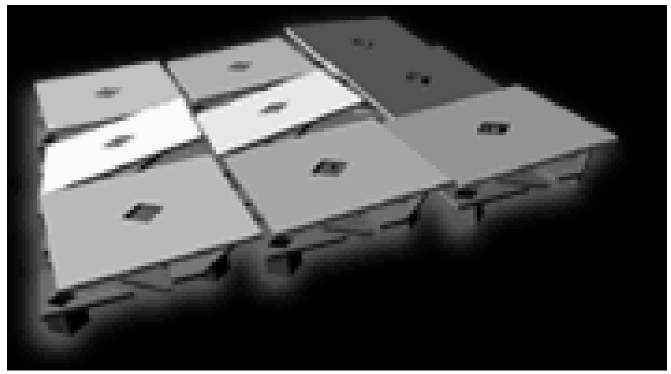
➔ Droplet Diameter ~ Beam Diameter at Focal Plane

Fabrication Steps



Example 7: Digital Micromirror (Electrostatic)

Texas Instruments Digital Micromirror Device™



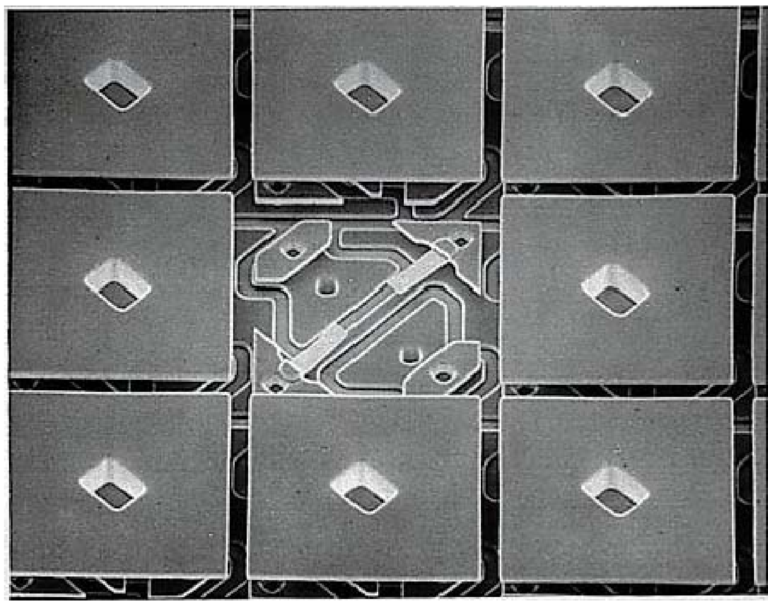
- Invented by Texas Instruments in 1986
- Array of up to 1.3 million mirrors
- Each mirror is 16 mm on a side with a pitch of 17 mm
- Resolutions: 800x600 pixels (SVGA) and 1280x1024 pixels (SXGA)

*For an animated demo of this device, go to **http://www.dlp.com/dlp_technology/***

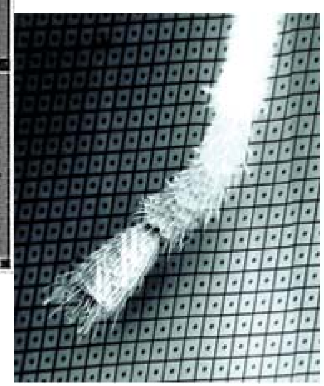
Other Applications

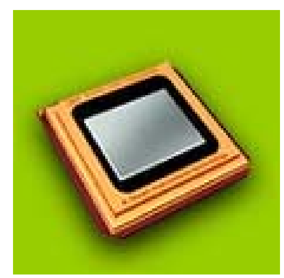
- Optical communications:
  - Optical switching, integrated optical circuit, MOEM
  - Biomedical instrument (e.g. endoscope, confocal microscope, FTS etc.)
- Mobile communications:
  - Micromechanical resonator for resonant circuits and filters (RF electronics)
- Biological applications:
  - Microfluidics
  - Lab-on-a-Chip
  - Micropumps
  - Resonant microbalances
  - Micro Total Analysis systems

Example 7: Optical MEMS - DLP



Texas Instruments
Digital Light Processors
1.3 million mirrors, 13μm
Wide, used in projectors.



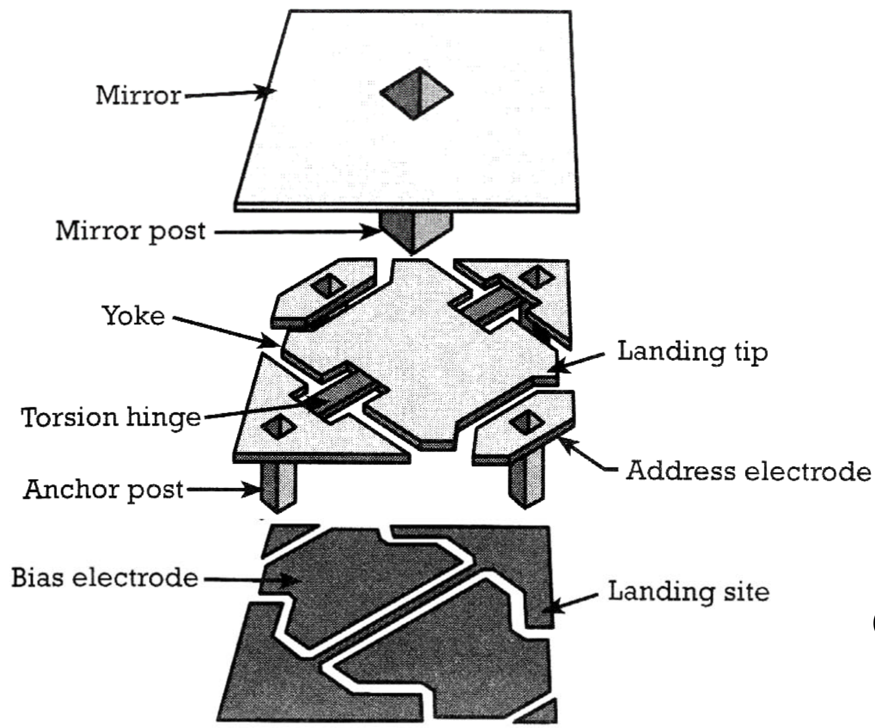


http://www.dlp.com/includes/demo_flash.aspx

TEXAS INSTRUMENTS

Digital Light Processing

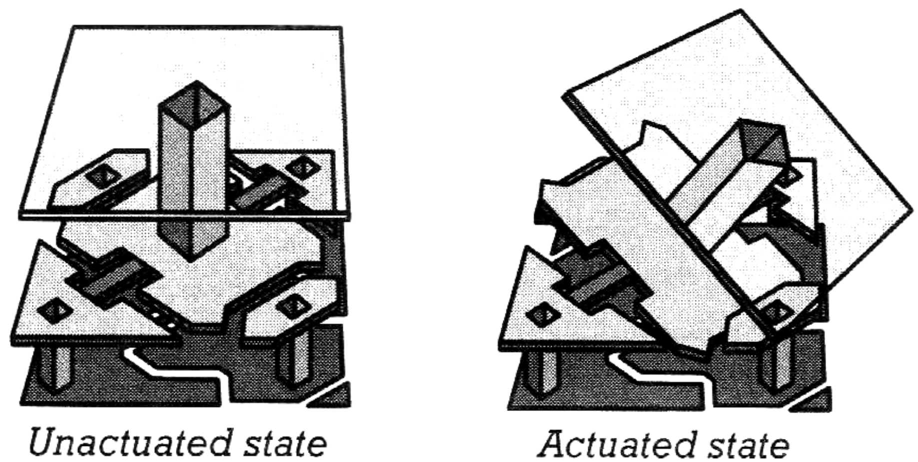
Digital Micromirror Device



Gimbal design

From "An Introduction to Microelectromechanical Systems Engineering" by Nadim Maluf

Digital Micromirror Device



- Mirror is moved by electrostatic actuation (24 V applied to bias electrode)
- Projection system consists of the DMD, electronics, light source and projection optics
- Switching time: 16 μs (about 1000 times faster than the response time of the eye)

=> Acheive grey scale by adjusting the duration of pulse

- Placing a filter wheel with the primary colors between light source and the micromirrors

=> Achieve full color by timing the reflected light to pass the wheel at the right color

From "An Introduction to Microelectromechanical Systems Engineering" by Nadim Maluf

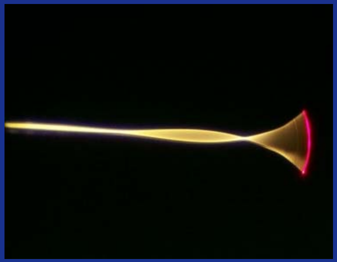
Other Applications

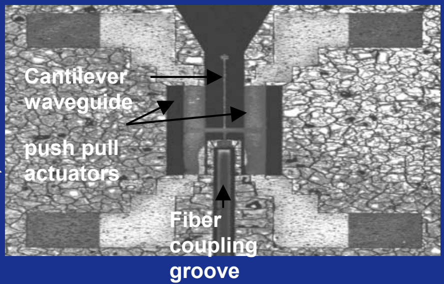
- Optical communications:
  - Optical switching, integrated optical circuit, MOEM
  - Biomedical instrument (e.g. endoscope, confocal microscope, FTS etc.)
- Mobile communications:
  - Micromechanical resonator for resonant circuits and filters (RF electronics)
- Biological applications:
  - Microfluidics
  - Lab-on-a-Chip
  - Micropumps
  - Resonant microbalances
  - Micro Total Analysis systems

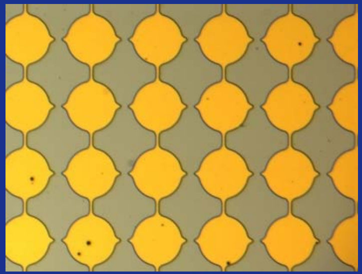
Example 8: Optical MEMS-Scanner

Scanning System

- Mechanical Resonating System
  - Fiber scanner
  - MEMS scanner
- Electro-optic Scanner
- Gradient Metamaterial

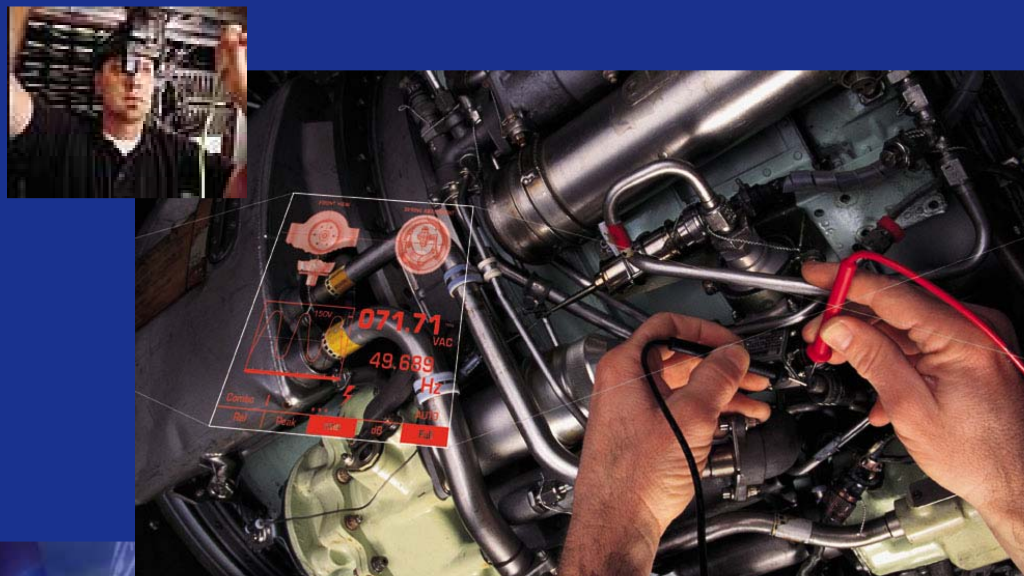




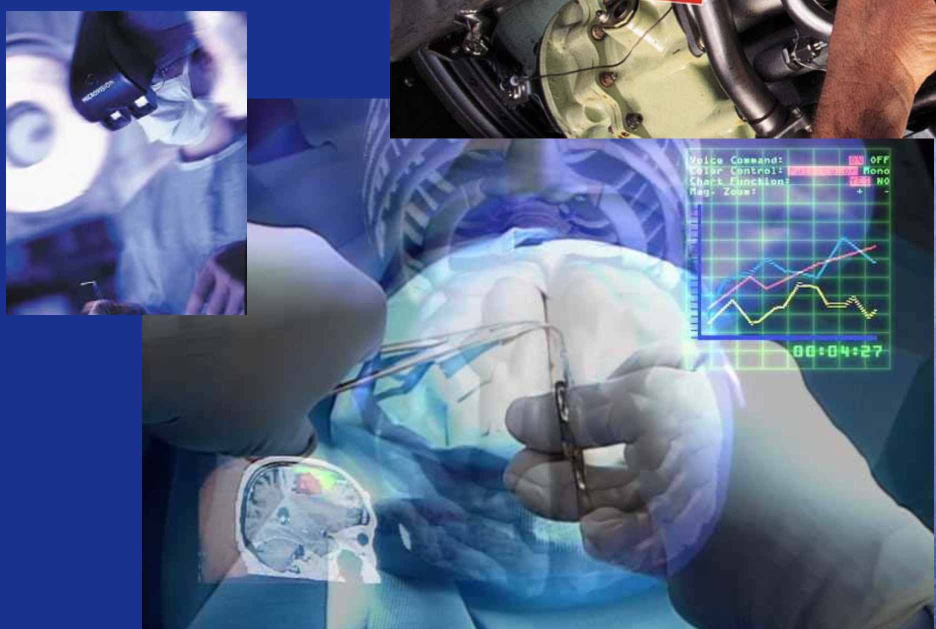


Head mount Display System

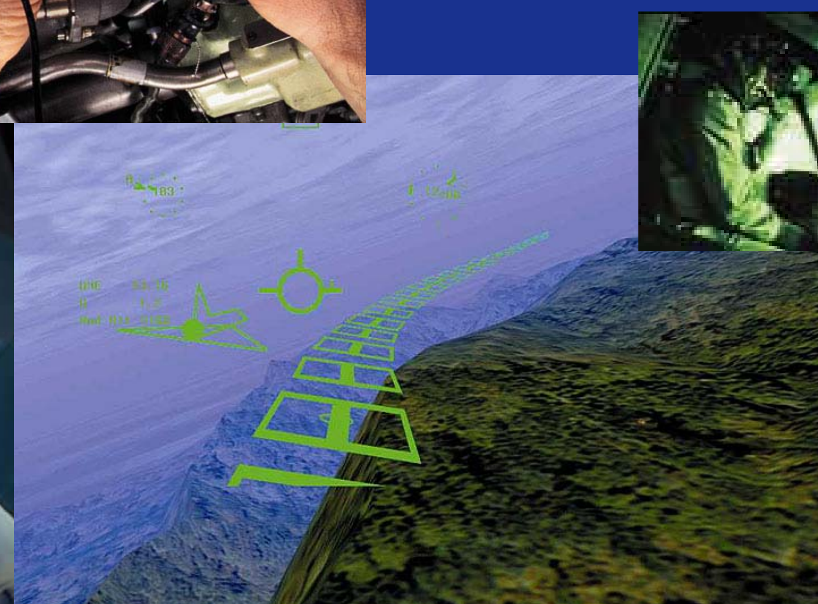
MICRO TECH LAB



Industrial application



Medical



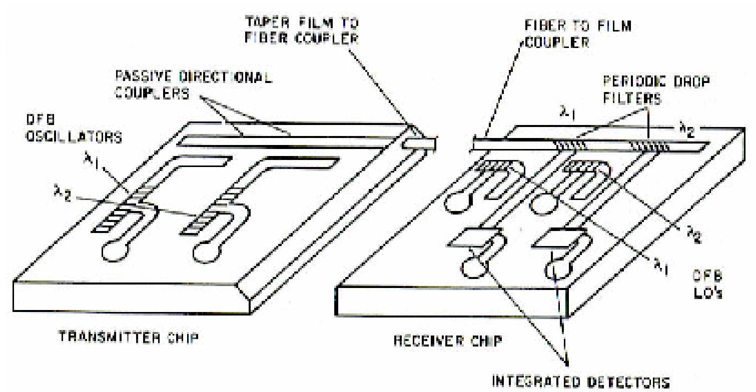
Defense and aerospace

Other Applications

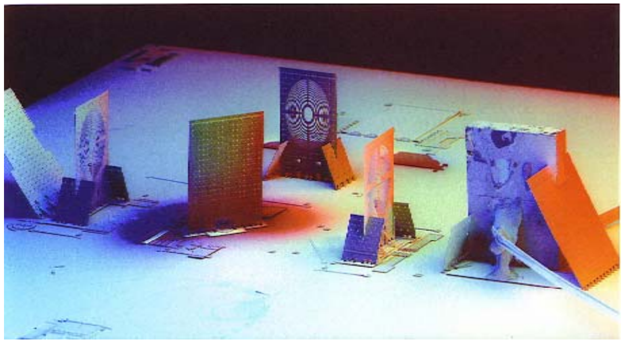
- Optical communications:
  - Optical switching, integrated optical circuit, MOEM
  - Biomedical instrument (e.g. endoscope, confocal microscope, FTS etc.)
- Mobile communications:
  - Micromechanical resonator for resonant circuits and filters (RF electronics)
- Biological applications:
  - Microfluidics
  - Lab-on-a-Chip
  - Micropumps
  - Resonant microbalances
  - Micro Total Analysis systems

Optical MEMS and Waveguide Integrated Optics

Waveguide Integrated Optics
(what's known as integrated optics in earlier day)



Optical MEMS
(can be free space or waveguide)



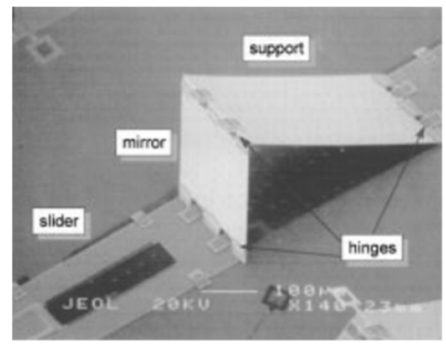
Photonic integrated circuit include optical MEMS and waveguide integrated optics

Other Applications

- Optical communications:
  - Optical switching, integrated optical circuit, MOEM
  - Biomedical instrument (e.g. endoscope, confocal microscope, FTS etc.)
- Mobile communications:
  - Micromechanical resonator for resonant circuits and filters (RF electronics)
- Biological applications:
  - Microfluidics
  - Lab-on-a-Chip
  - Micropumps
  - Resonant microbalances
  - Micro Total Analysis systems

Additional Applications

- Optical MEMS
  - Ex: optical switches, digital micromirror devices (DMD), bistable mirrors, laser scanners, optical shutters, and dynamic micromirror displays
- RF MEMS
  - Smaller, cheaper, better way to manipulate RF signals
  - Reliability is issue, but getting there



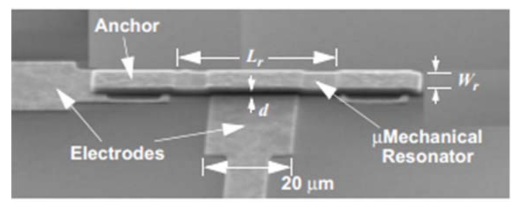
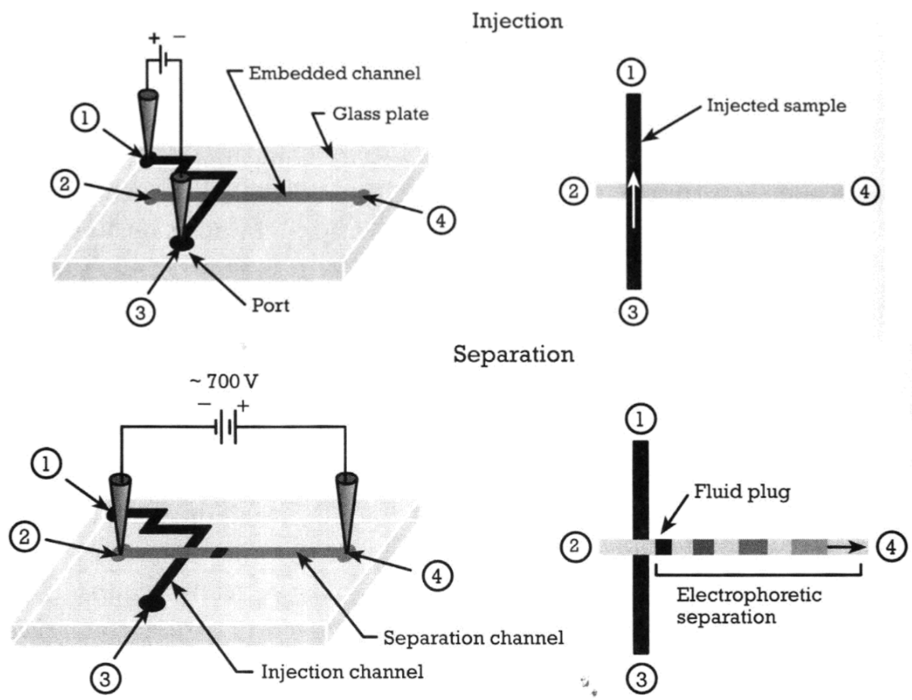


Fig. 6. SEM of an 8.5MHz clamped-clamped beam μmechanical resonator.

Other Applications

- Optical communications:
  - Optical switching, integrated optical circuit, MOEM
  - Biomedical instrument (e.g. endoscope, confocal microscope, FTS etc.)
- Mobile communications:
  - Micromechanical resonator for resonant circuits and filters (RF electronics)
- Biological applications:
  - Microfluidics
  - Lab-on-a-Chip
  - Micropumps
  - Resonant microbalances
  - Micro Total Analysis systems

Microfluidics / DNA Analysis



In the future, a complete DNA sequencing systems should include:

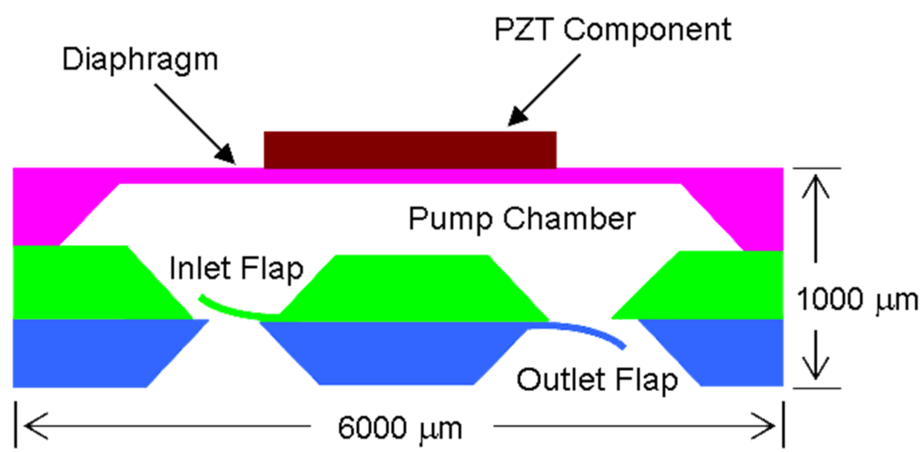
- •Amplification (PCR)
- •Detection (electrophoresis)
- •Fluid preparation and handling (pumps, valves, filters, mixing and rinsing)

→ MEMS !

Microfluidics

MEMS designed to handle or process minute quantities of liquids. Devices include micro-pumps, micro-mixers, flow channels, reaction chambers, micro-filters.

Example micro-pump



Lab-on-a-chip

Labs-on-a-chip can replace entire chemical and biological analysis laboratories.

Biomedical Applications

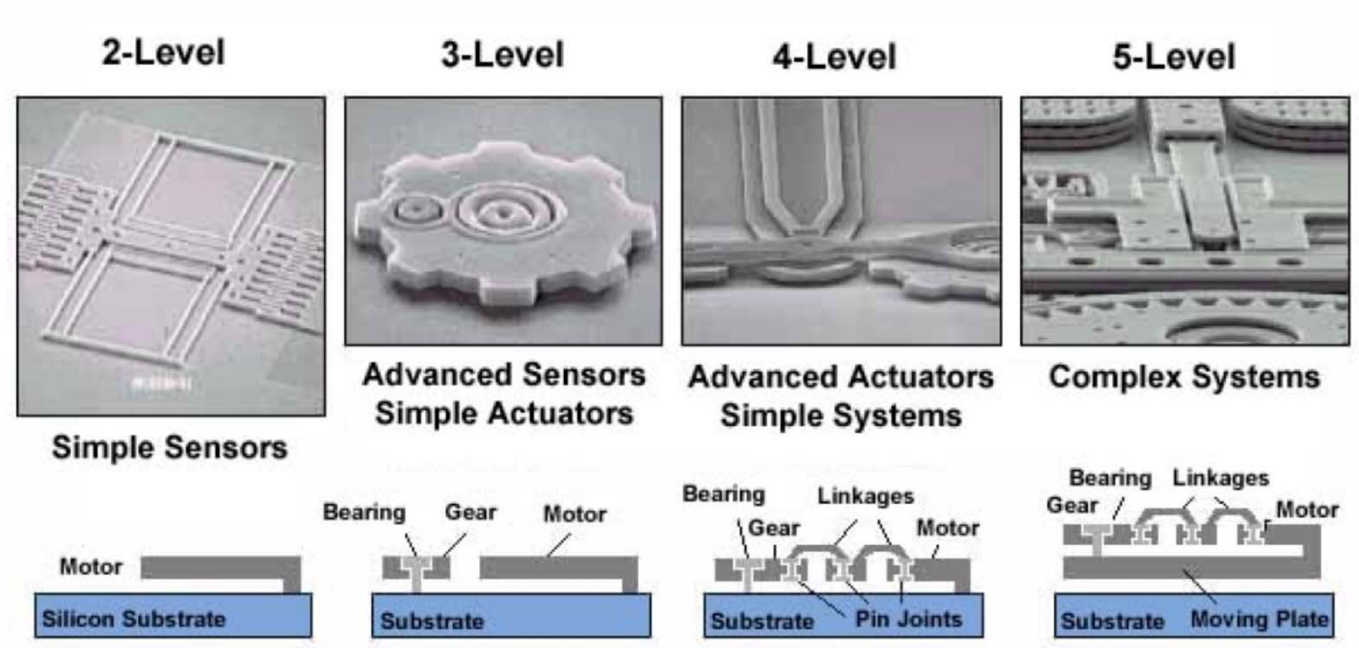
- Usually in the form of pressure sensors
  - Intracranial pressure sensors
  - Pacemaker applications
  - Implanted coronary pressure measurements
  - Intraocular pressure monitors
  - Cerebrospinal fluid pressure sensors
  - Endoscope pressure sensors
  - Infusion pump sensors
- Retinal prosthesis
- Glucose monitoring & insulin delivery
- MEMS tweezers & surgical tools
- Cell, antibody, DNA, RNA enzyme measurement devices

Blood Pressure sensor on the head of a pin

MEMS Fabrication

- The fabrication process must be considered at the outset since this defines dimensional limits and material properties.

Complexity of MEMS device by structural layers



MEMS Microfabrication

- Many techniques borrowed from integrated circuit (IC) fabrication

1. Photolithography
2. Materials for Micromachining

- Substrates (silicon)
- Additive Films and Materials

• silicon - single crystal, polycrystalline and amorphous

• silicon compounds (SixNy, SiO2, SiC etc.)

• metals and metallic compounds (Au, Cu, Al, ZnO, GaAs, IrOx, CdS)

• ceramics (Al203 and more complex ceramic compounds)

• organics (diamond, polymers, enzymes, antibodies, DNA etc.)

3. Bulk **micromachining**

- **Wet etching**
- **Dry etching**

4. Surface **micromachining**
5. Other techniques (LIGA and Wafer bonding, laser machining)

Mirofabrication
(tools and equipment used)

- Etching
  - Wet chemical etching
    - Istropic
    - Anisotropic
  - Dry etching
    - Plasma etch
    - Reactive Ion etch (RIE, DRIE)
- Deposition
  - Chemical vapor deposition (CVD/PECVD/LPCVD)
  - Epitaxy
  - Oxidation
  - Evaporation
  - Sputtering
  - Spin-on methods
- Patterning
  - Photolithography
  - X-ray lithography
  - Softlithography
  - Additive manufacturing
  - Nanomachining (AFM, Ion milling, E-beam lithography, etc.)

Micromachining

This is the process of fabricating mechanical components in the micron to millimetre size range.

- **Typically based upon silicon IC fabrication processes (see next slide). Especially true for micron scale devices.**
- **Also includes 'traditional' approaches (precision CNC machining, electroplating, molding)**
- **Variety of materials**

Denso Corporation

Silicon Micromachining Processes

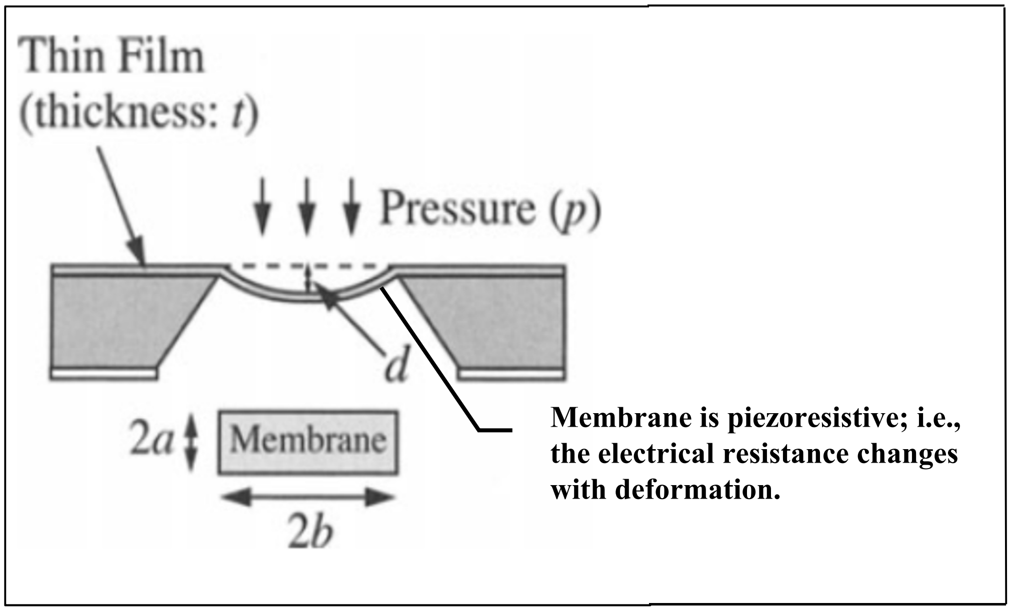
Typically based upon IC fabrication processes which enable:

- **Simultaneous device processing on each wafer**
- **Batch fabrication (many wafers simultaneously)**
- **Low cost in high volumes**
- **Inherently small size (nanometres to millimetres)**

But Beware!

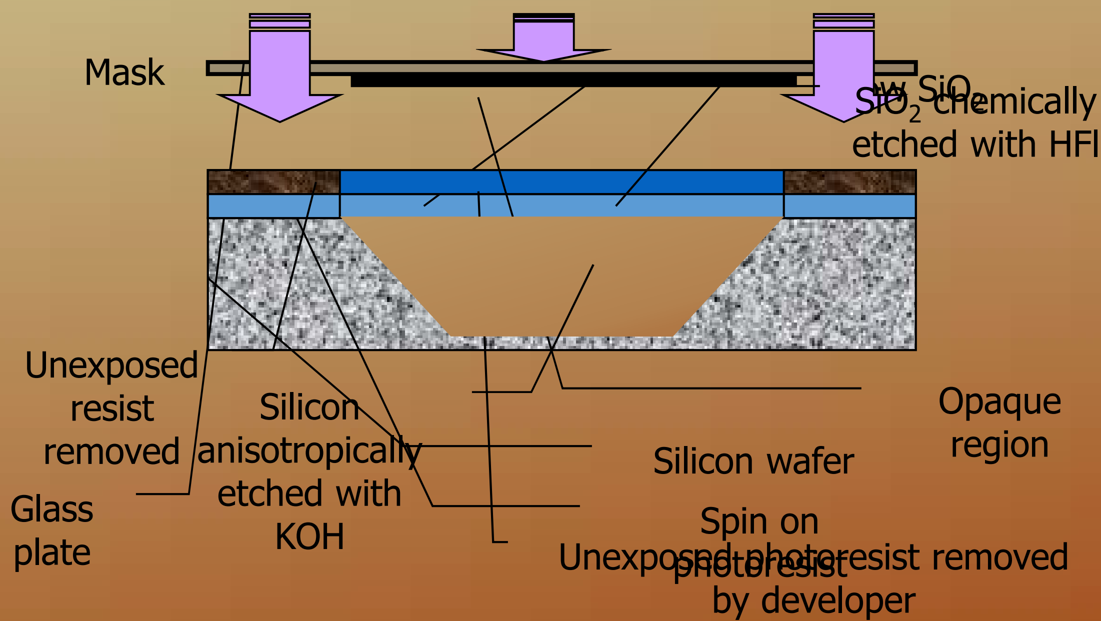
- **High cost of infrastructure (both initial and running)**
- **High cost of equipment**
- **Specialist processes often required (poor standardisation)**

Bulk micromachining example - A diaphragm for a pressure sensor



Adapted from ***MEMS: A Practical Guide to Design, Analysis, and Applications***, **Ed. Jan G. Korvink and Oliver Paul, Springer, 2006**

Bulk micromachining example - A diaphragm for a pressure sensor



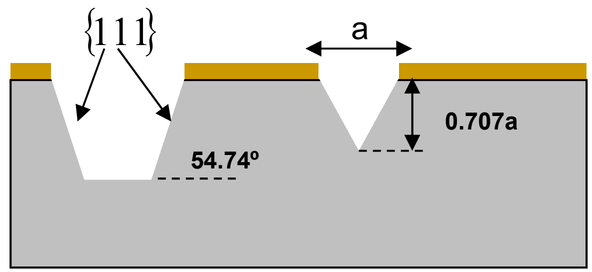
Bulk micromachining

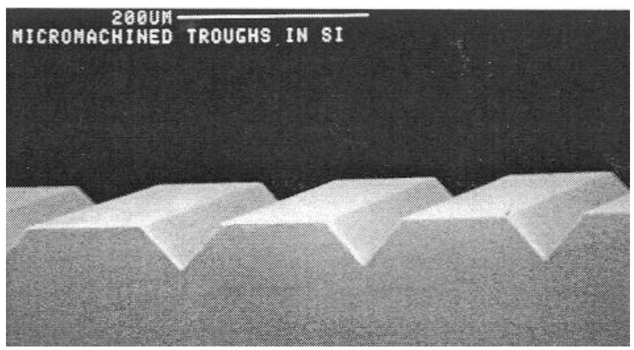
Anisotropic etching of silicon

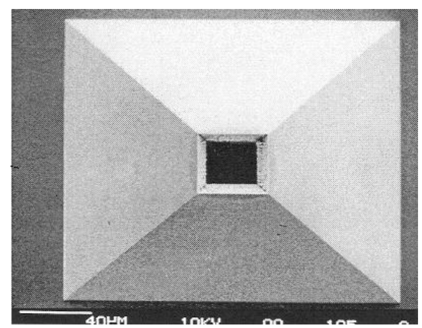
Etchant	$\frac{r_{etch}\langle 100\rangle}{r_{etch}\langle 111\rangle}$	Selectivity to p^+- Si	Disadvantages
Potassium Hydroxide (KOH)	100	Yes	-Highly corrosive -Not CMOS compatible
Tetramethyl ammonium hydroxide (TMAH)	30-50	yes	-formation of pyramidal hillocks at bottom of cavity
Ethylenediamine pyrochatechol (EDP)	35	Yes	-carcinogenic vapors

Bulk micromachining

Anisotropic etch of {100} Si

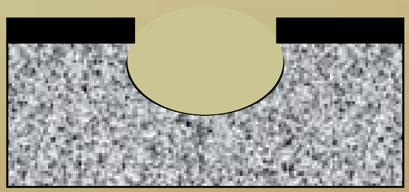




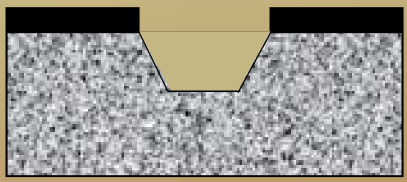


Bulk Micromachine: Wet Etchit- Isotropic and anisotropic Etching

Depending on the chemical/structure combinations, etching can be…

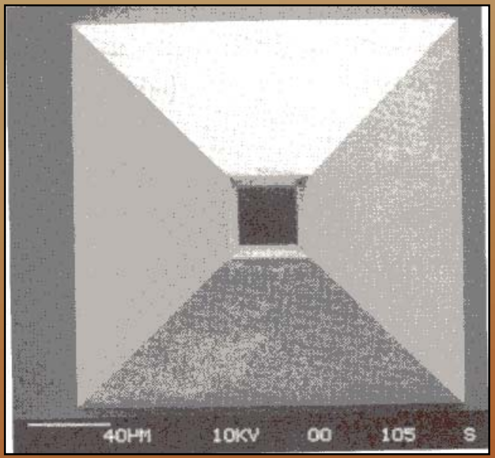


isotropic

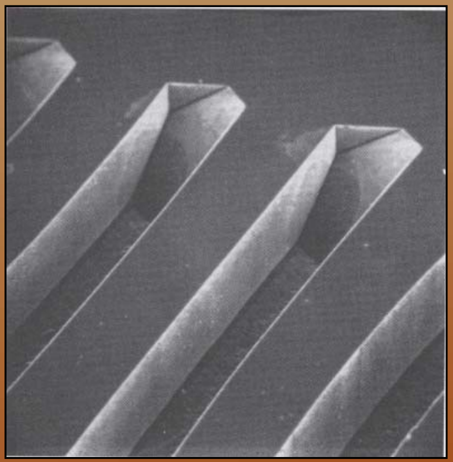


or anisotropic

Anisotropic etches



001 silicon wafer

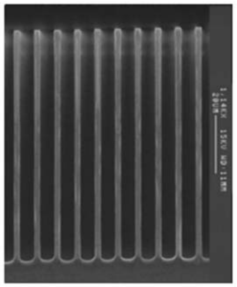


011 silicon wafer

Dry Etching

High Aspect Ratio Fabrication (Silicon):

- Deep reactive ion etching (DRIE)
- Enables very high aspect ratio etches to be performed into silicon substrates
- Sidewalls of the etched holes are nearly vertical
- Depth of the etch can be hundreds or even thousands of microns into the silicon substrate.



cross section of a silicon wafer demonstrating trenches that can be fabricated using DRIE tech

https://www.memsnet.org/mems/fabrication.html

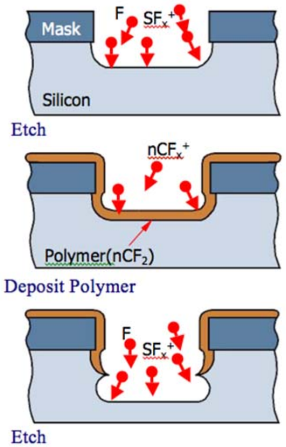
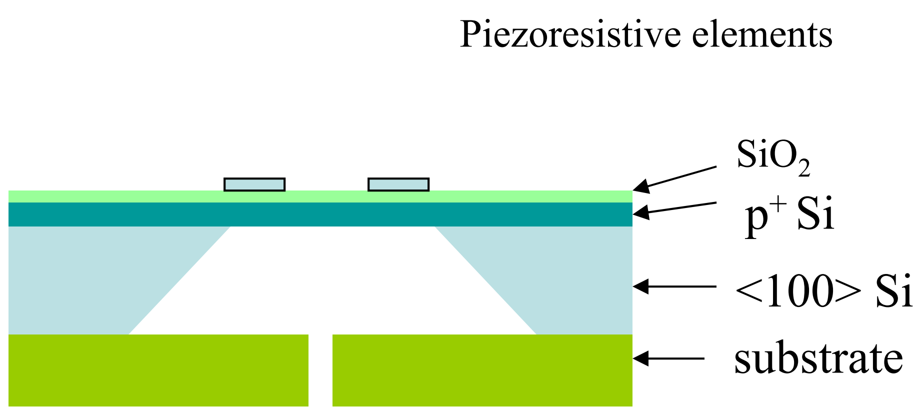


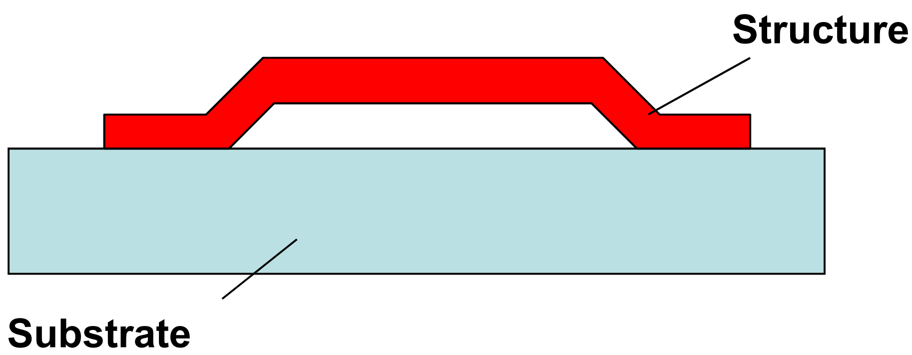
Figure 7: Illustration of how deep reactive ion etching works.

Example of Bulk micromachining: Pressure sensors



Surface Micromachining

Mechanical structures formed on the surface of a substrate. Formed from materials deposited on the substrate. Most common method of surface micromachining is known as **Sacrificial Layer Technology.** Additive process growing / depositing layers of materials, patterning and selectively removing them



Surface Micromachining (Concept)

The Si wafer functions like the big green flat plate.

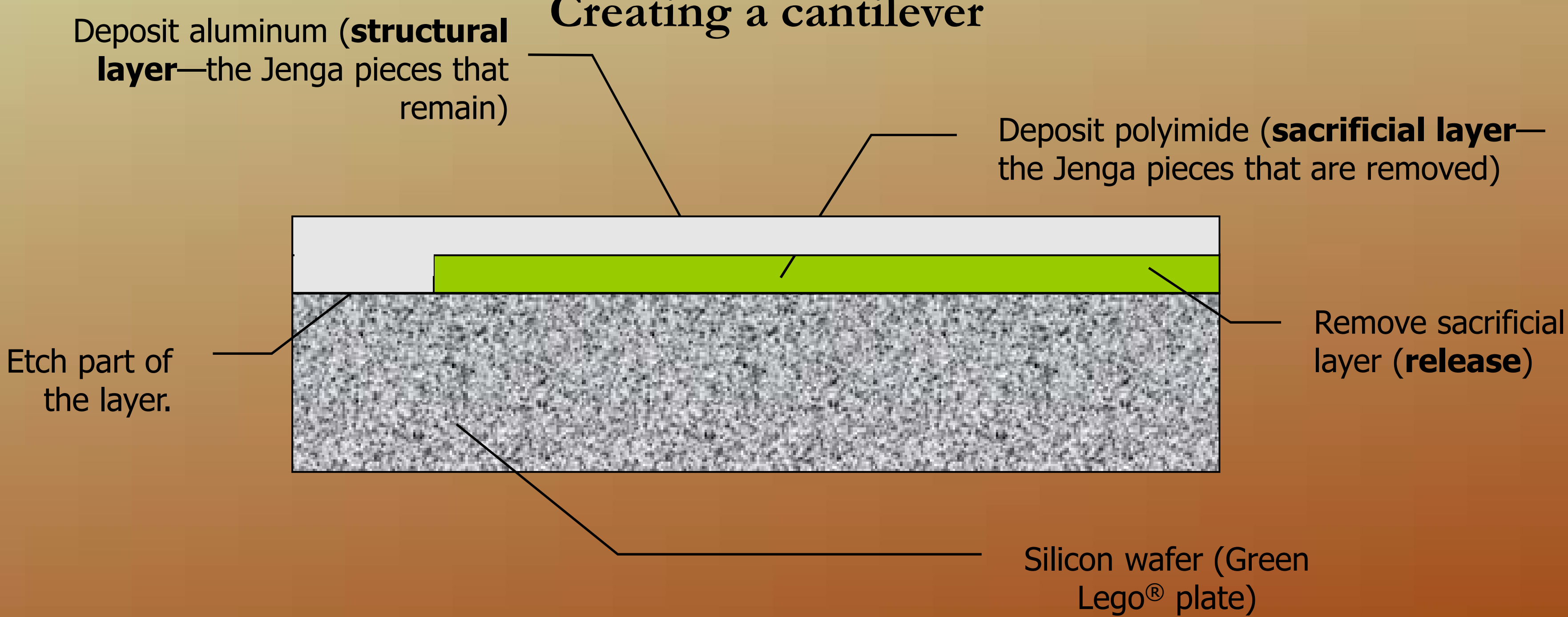
Some Jenga pieces are removed. The ones that remain form the MEMS structure.

+

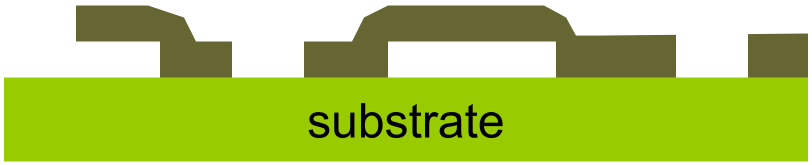
= Surface micromachining

Surface Micromachining

Surface micromachining example – Creating a cantilever



Surface Micromachining



Important issues:

- selectivity of structural, sacrificial and substrate materials
- stress of structural material
- stiction

Surface Micromachining

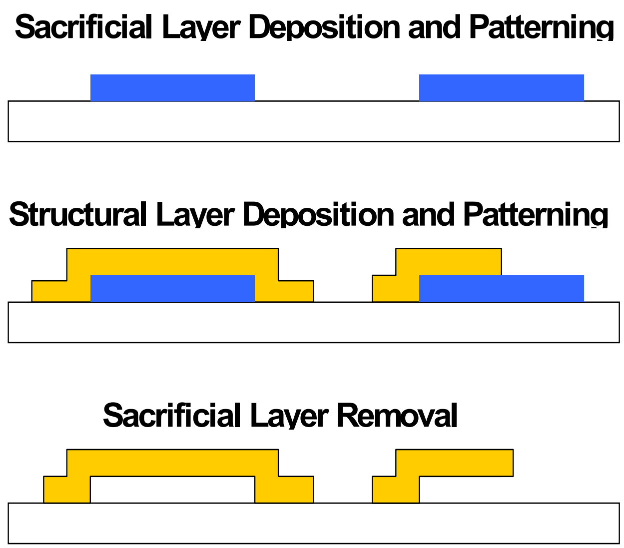
Most commonly used materials for surface micromachining:

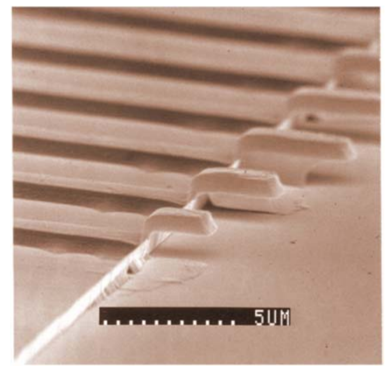
- substrate: silicon
- sacrificial material: SiO_2 or phosphosilicate glass (PSG)
- structural material: polysilicon

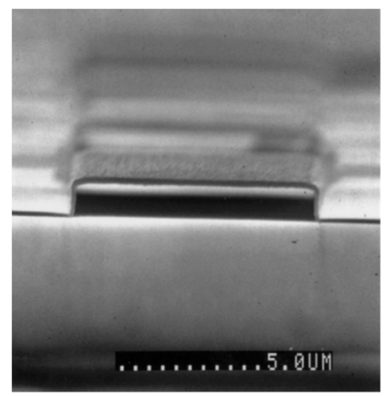
Alternative materials

Substrates	**Sacrificial**	**Structural**
Glass	Polymer	Thin film silicon (a-Si:H, µc-Si)
Plastic	Metals	silicon nitrides
metals	silicon nitride	Silicon carbide
		Metals
		polymers
		bilayer composites

Surface micromachining on glass







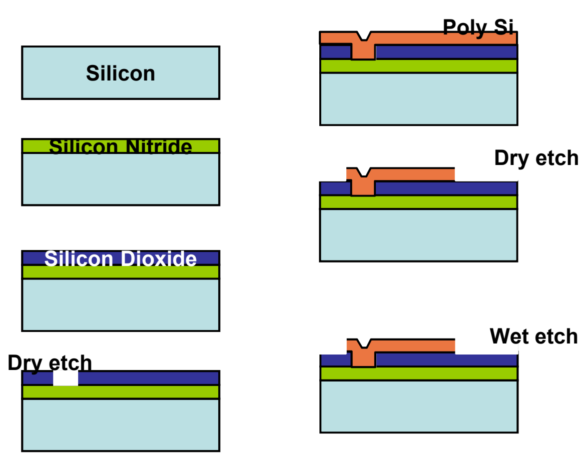
d=1 μm; h=500 nm; b=10 μm

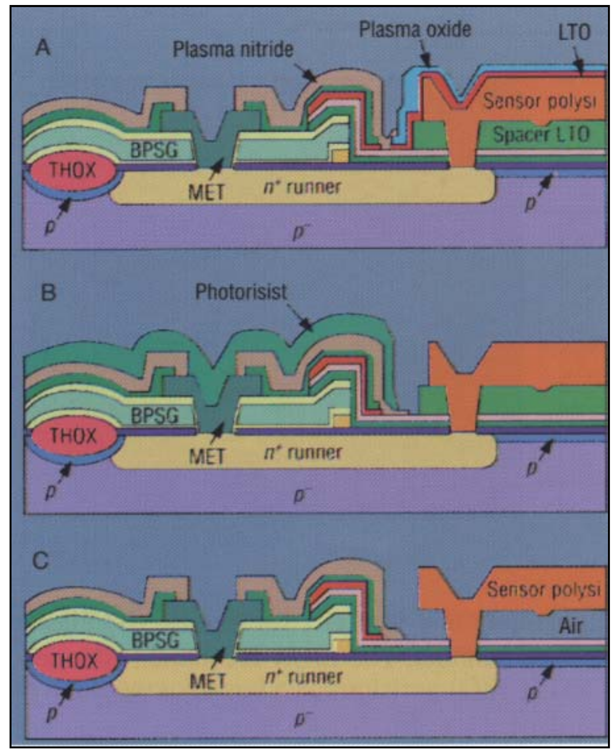
L_{max}(bridge) ~ 60 μm ; L_{max}(cantilever) ~ 30 μm

Surface Micromachining (Multilayer structure)

Complicated structures can be made by combining these techniques and repeating

Example on silicon:

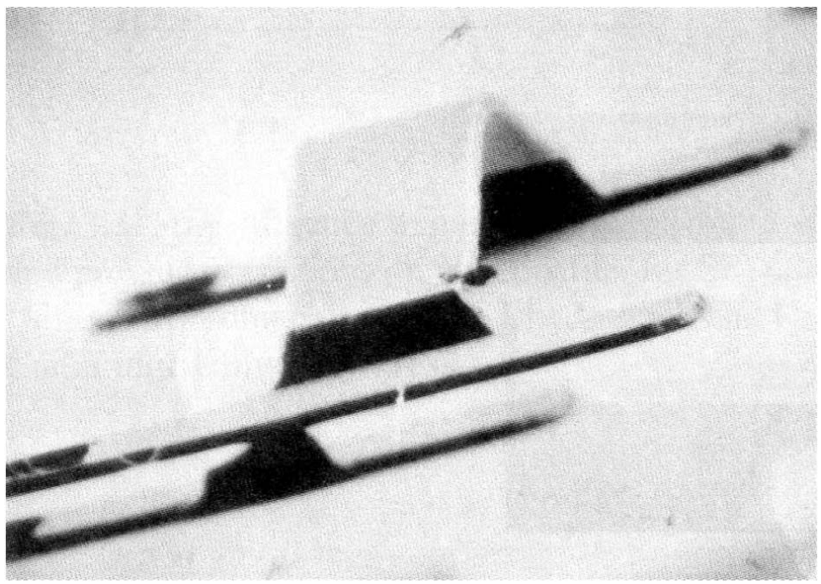




Surface Micromachining

Residual Stress

- Polysilicon deposited by LPCVD (T~600 ºC) usually has large stress
- High T anneal (600-1000 ºC) for more than 2 hours relaxes the strain



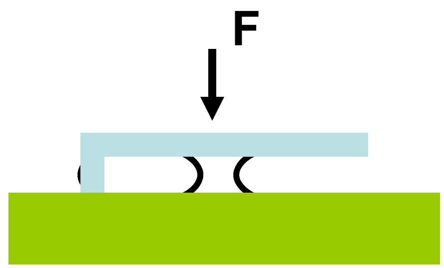
➡ Low temperature, thin film materials has much less intrinsic stress

Photo from R.T. Howe, Univ. of Calif, Berkeley, 1988

Surface Micromachining

Stiction

Surface tension of liquid during evaporation results in capillary forces that causes the structures to stick to the substrate if the structures are not stiff enough.



To avoid this problem

- make the structures stiffer (ie, shorter, thicker or higher Young's modulus)
- use super-critical drying in CO_2 (liquid $\rightarrow$ supercritical fluid $\rightarrow$ gas)
- roughen substrate to reduce contact area with structure
- coat structures with a hydrophobic passivation layer

Thin-film MEMS

Thin films allows:

- Low-temperature processing
- Large area, low cost, flexible or biocompatible substrates
- Possibility to integrate with a CMOS or thin film electronics based back plane
- Control of structural material film properties (mechanical, electronic, optical and surface)

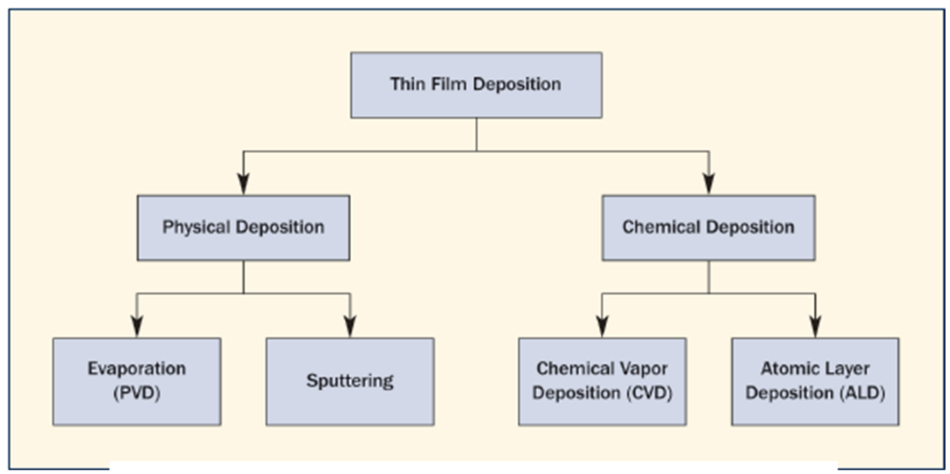
Fabrication Processes: Deposition

Deposition:

- deposit thin film of material (mask) anywhere between a few nm to 100 micrometers onto substrate
- **physical:** material placed onto substrate, techniques include sputtering and evaporation
- **chemical:** stream of source gas reacts on substrate to grow product, techniques include chemical vapor deposition and atomic layer deposition

- **substrates:** silicon, glass, quartz

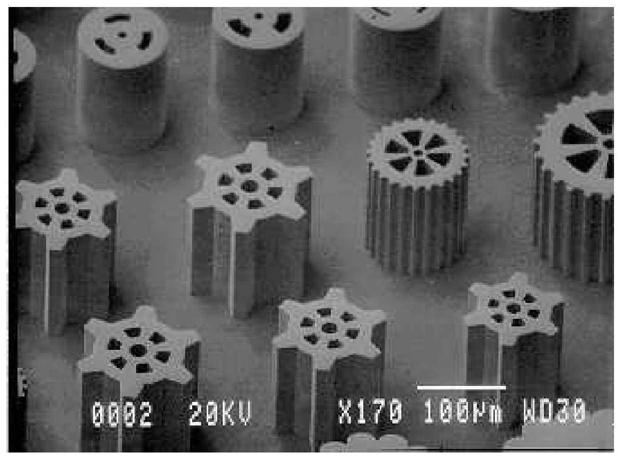
- **thin films:** polysilicon, silicon dioxide, silicon nitride, metals, polymers



http://www.empf.org/empfasis/2010/December10/images/fig3-1.gif

LIGA

German acronym for Lithographie, Galvanoformung, Abformung (**Lithography**, Electroplating, and Molding) that describes a fabrication technology used to create high-aspect-ratio microstructures.



Photos from MCNC – MEMS group

LIGA – X-ray Lithography, Electroplating (Galvanoformung), Molding (Abformung)

Remove mold
Immerse in chemical bath and electroplate the metal
Expose and develop photoresist
Deposit photoresist
Deposit plating base

Need a X ray proof mask!!!!!

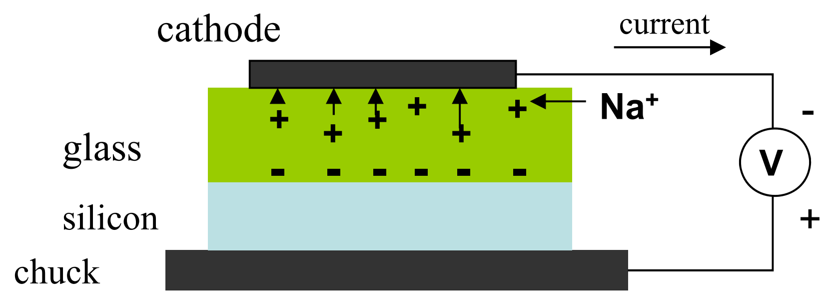
Wafer Bonding

Method that involves joining two or more wafers together to create a wafer stack

Three types of wafer bonding: direct bonding, anodic bonding, and intermediate layer bonding

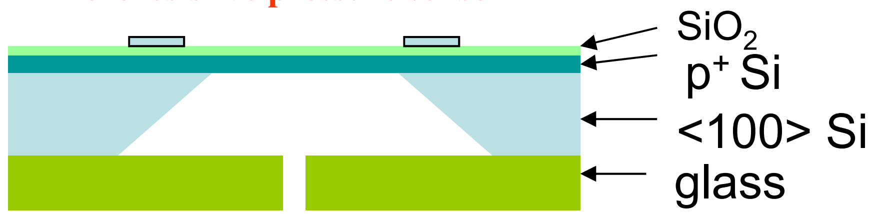
All require substrates that are flat, smooth, and clean in order to be efficient and successful

Wafer bonding- Anodic



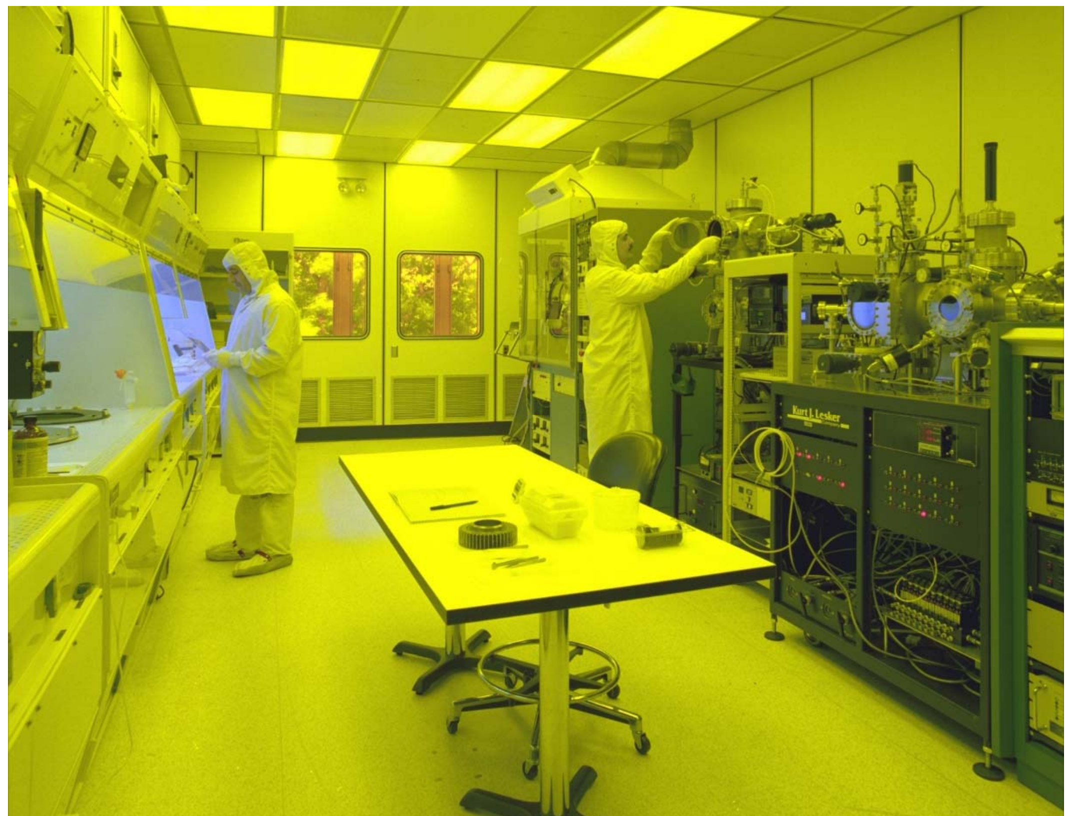
• bring sodium contating glass (Pyrex) and silicon together
• heat to high temperature (200-500 ºC) in vacuum, air or inert ambient
• apply high electric field between the 2 materials (V~1000V) causing mobile + ions to migrate to the cathode leaving behind fixed negative charge at glass/silicon interface
• bonding is complete when current vanishes
• glass and silicon held together by electrostatic attraction between – charge in glass and + charges in silicon

Piezoresistive pressure sensor

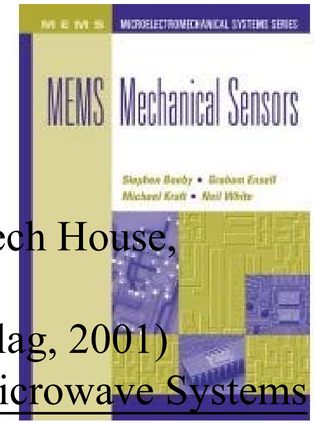


Microfabrication Facility

- Cleanliness is the key to successful fabrication!
- Class 100- 10,000 environment



MEMS Resources



Reference Books

• Nadim Maluf, An Introduction to Microelectromechanical Engineering (Artech House, Boston,2000)

• M. Elewenspoek and R. Wiegerink, Mechanical Microsensors (Springer-Verlag, 2001)

• Héctor J. De Los Santos, Introduction to Microelectromechanical (MEM) Microwave Systems (Artech House, Boston, 1999)

• MEMS Mechanical Sensors by Steve P. Beeby, Graham Ensell, Michael Kraft and Neil White

Websites

• Sandia National Lab: http://mems.sandia.gov

• Berkeley Sensors and Actuators Center: http://www-bsac.eecs.berkeley.edu

• MEMS Clearinghouse: http://www.memsnet.org/

Some companies with MEMS products

• Accelerometers – Analog Devices: http://www.analog.com/technology/mems/index.html

• Digital Light Processing Projector- Texas Instruments: http://www.dlp.com

• Micro-electrophoresis chip – Caliper Technologies: http://www.calipertech.com

NTHU iNEMS Program

Institute of NanoEngineering & MicroSystems

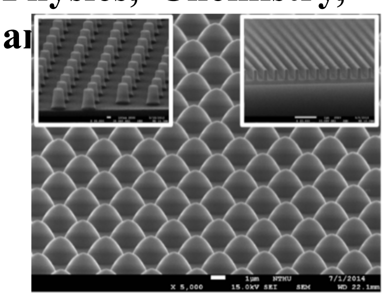
www.nems.nthu.edu.tw/en

***Brings together the MEMS/NEMS-related education, researches and related resources to facilitate the integration effort in the multidisciplinary themes behind science and technology of "miniaturization".**

***Research fields:(1) Physical MEMS Sensors and Actuators, (2) Biomedical MEMS, (3) RF MEMS, (4) Optical MEMS, (5) Nano-sensors and Nanotechnology.**

***14 faculty members , 51 M.S. and 45 Ph.D. students.**

***The students are from different backgrounds, such as Physics, Chemistry, Material Eng., Mech. Eng., Electrical Eng., Applied Math., ar**



***Ranked #1 in Micro/Nano research fields in Taiwan.**

***More than 90% courses are offered in English.**

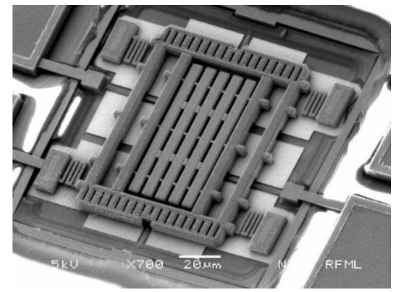
iNEMS NTHU Taiwan

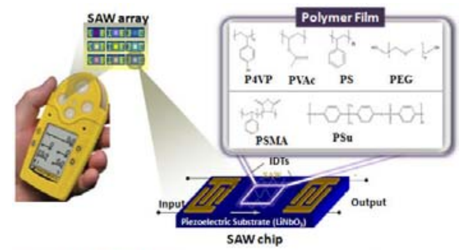
Institute of NanoEngineering & MicroSystems

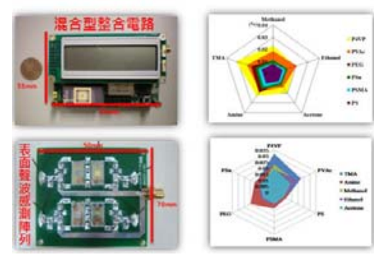
iNEMS Research Labs

Biomedical MicroSystems Lab (Prof. C.-C. Chen)
Integrated Control MicroSystems Lab (R.-S. Chen)
Cellular & Molecular BioMEMS Lab (Prof. L.-S. Fan)
Advanced LIGA Lab (Prof. C.-C. Fu)
MicroDevice Lab (Prof. W.-L. Fang)
Microfluidic Biochips Lab (Prof. G.-B. Lee)

RF MicroSystems Lab (Prof. S.-S. LiProf. C.-Y. Lo)
Bioelectronics and Nanosystems Lab (Prof. Y.-L. Wang)
Micro Technology Laboratory (Prof. W.-C. Wang)
Bio-Medical Thermo-Fluidic Lab (Prof. D.-J. Yao)
Quantum Microsystems Lab (Prof. J)
Flexible Printronics Lab (. A. Yeh)







Market Research

Microelectromechanical System (MEMS) Market Segments

- Sensors
  - Inertial Sensors
  - Pressure Sensors
  - Optical Sensors
  - Environment Sensors
  - Ultrasonic Sensors
- Actuators
  - Optical MEMS
  - Microfluidics
  - RF MEMS
  - Others (e.g. Microspeakers, Ultrasonic Finger Prints)

Commercialization of Selected MEMS devices

Product	Discovery	Evolution	Cost Reduction/ Application Expansion	Full Commercialisation
Pressure sensors	1954-1960	1960-1975	1975-1990	1990-present
Accelerometers	1974-1985	1985-1990	1990-1998	1998
Gas sensors	1986-1994	1994-1998	1998-2005	2005
Valves	1980-1988	1988-1996	1996-2002	2002
Nozzles	1972-1984	1984-1990	1990-1998	1998
Photonics/displays	1980-1986	1986-1998	1998-2004	2004
Bio/Chemical sensors	1980-1994	1994-1999	1999-2004	2004
RF switches	1994-1998	1998-2001	2001-2005	2005
Rate (rotation) sensors	1982-1990	1990-1996	1996-2002	2002
Micro relays	1977-1982	1993-1998	1998-2006	2006

Global MEMS market 2005-2010 (Silicon based devices, update 2006)

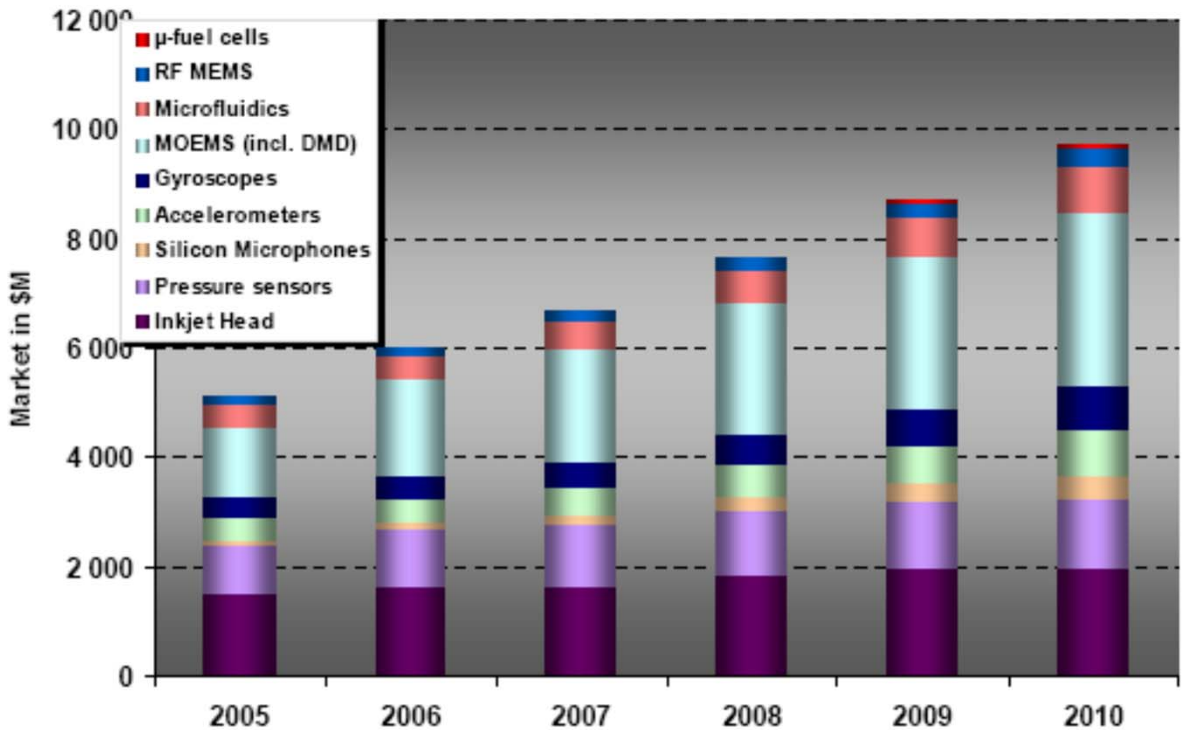
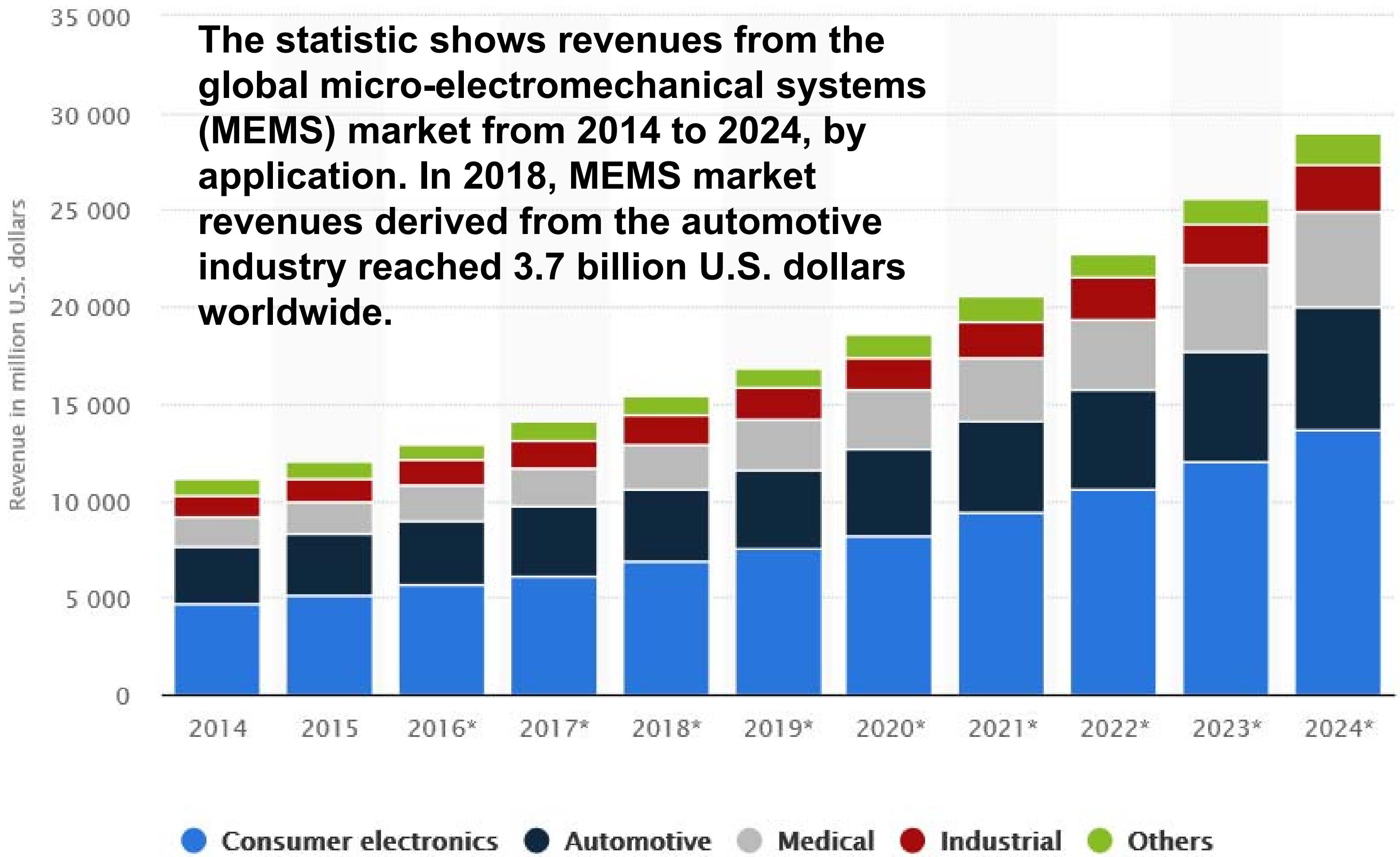


Fig.1. MEMS markets 2005-2010.

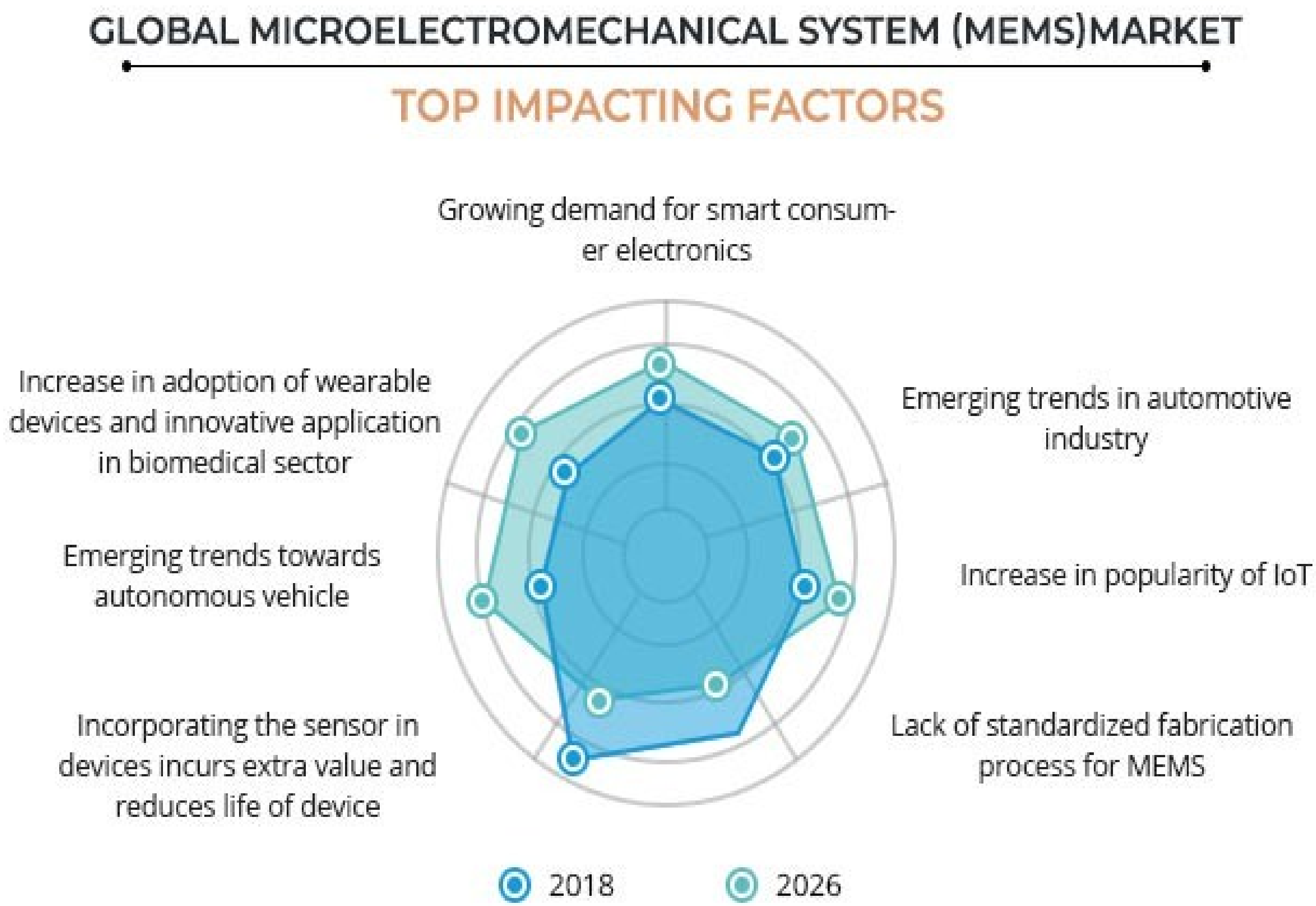
Sensors & Transducers Magazine (S&T e-Digest), Vol.66, Issue 4, April ***2006***, *pp.521-525*

Micro-electromechanical systems (MEMS) Market Revenues Worldwide

The statistic shows revenues from the global micro-electromechanical systems (MEMS) market from 2014 to 2024, by application. In 2018, MEMS market revenues derived from the automotive industry reached 3.7 billion U.S. dollars worldwide.




Global
Microelectromechanical
System (MEMS)
Market
OPPORTUNITIES AND FORECASTS,
2018-2026
Global Microelectromechanical system (MEMS) Market is expected to reach $122.8 Million by 2026.
Growing at a CAGR of 11.3% (2019-2026)
compound annual growth rate
©Allied Market Research


GLOBAL MICROELECTROMECHANICAL SYSTEM (MEMS)MARKET
TOP IMPACTING FACTORS
Growing demand for smart consum-er electronics
Emerging trends in automotive industry
Increase in popularity of IoT
Lack of standardized fabrication process for MEMS
Incorporating the sensor in devices incurs extra value and reduces life of device
Emerging trends towards autonomous vehicle
Increase in adoption of wearable devices and innovative application in biomedical sector
2018
2026

Key MEMS Market Leaders

- Panasonic Corporation, Robert Bosch GmbH, STMicroelectronics N.V., Texas Instruments, Analog Devices Inc., Broadcom, Denso Corporation, HP Inc., NXP Semiconductors, and Knowles Corporation.
- Local MEMS foundries: TSMC, Asia Pacific Microsystems, Inc., UMC etc.