Micro Electro Mechanical Systems for mechanical engineering applications

Lecture 1:

Introduction to MEMS: from historical background to current research

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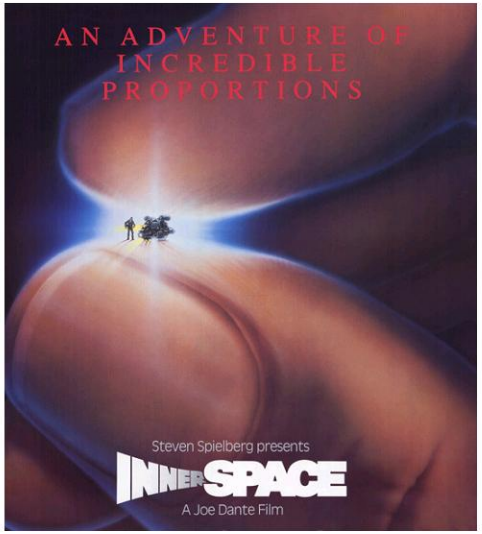
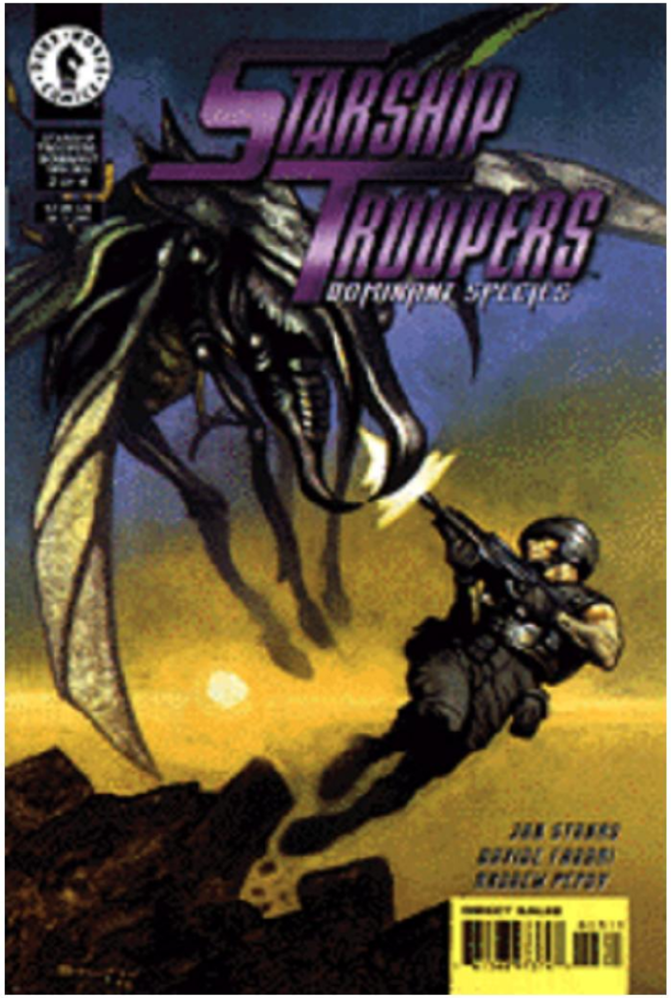
Outline

- Miniaturization
- What are MEMS?
- Why MEMS?
- Scaling concepts
- Examples and applications

Small Scale Worlds



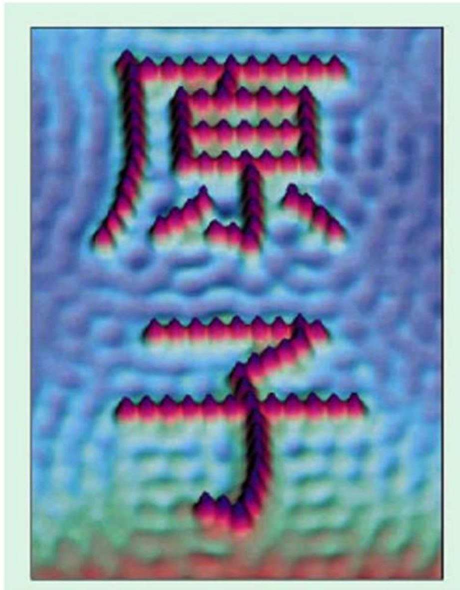


The History of Miniaturization

- **There's Plenty of Room at the Bottom**
  Richard Feynmann (1959)

  "Why cannot we write the entire 24 volumes of the Encyclopedia Britannica on the head of a pin? "

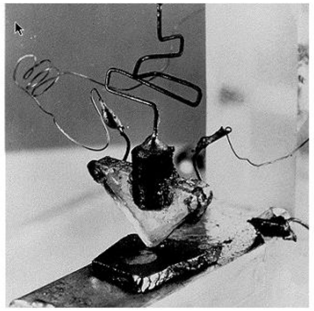
http://www.zyvex.com/nanotech/feynman.html



http://www.jaffebros.com/lee/gulliver/winter/p1.jpeg National Science and Technology Council 1999

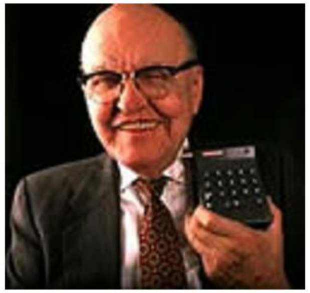
The History of Miniaturization

- 1943
- ENIAC: The first electronic computer (general purpose)
- US Army: US$500,000
- Over 30 tons, 19,000 vacuum tubes, 1,500 relays, 200 KW



- 1947
- The First Transistor: Bell Lab
- Nobel Prize (Bardeen, Brattain, & Shockley)
- Intel Corp. (Shockley)

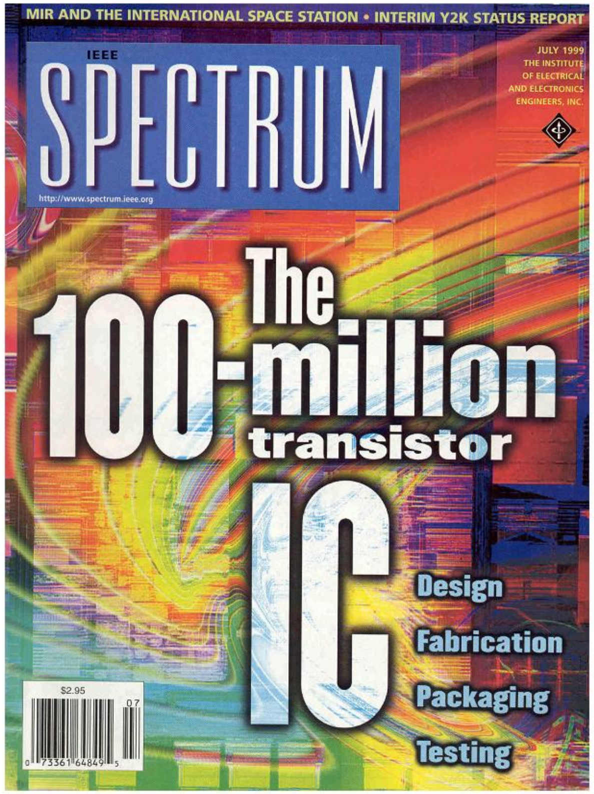
- 1958!

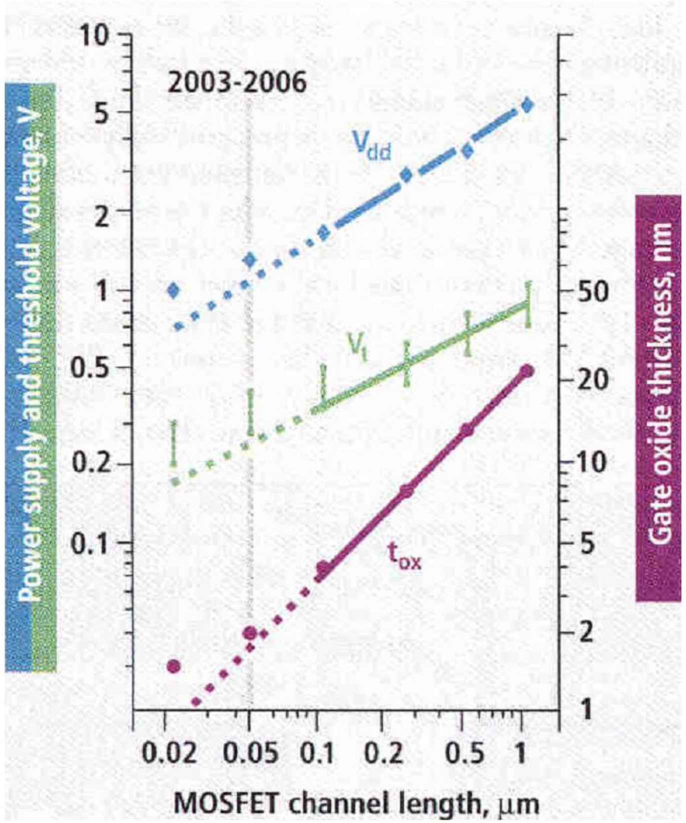


- **The first Integrated circuit**
- Jack Kilby (Texas Instrument)
- Five transistors
- Half an inch long and
- Thinner than a toothpick.

- 1998: Intel Pentium III > 500MHz, 0.2 μ technology, ~ 1 million transistors

Near Future





- Molectronics?
- High Speed, Low Power, Small Size
- Moor's law? – 2 times every 18 months…

Why Miniaturization?

1. Extrinsic Advantages

- Size
- Automation
- Smart systems
- Cost (mass production)

2. Intrinsic Advantages

- Physics law
- Faster response
- Higher sensitivity
- Specificity

Reasons for miniaturization

Miniaturization attributes	Reasons
Low energy and little material consumed	There are limited resources on planet earth
Arrays of sensors	Redundancy, wider dynamic range, and increased selectivity through pattern recognition
Small	Smaller is lower in cost, minimally invasive
Favorable scaling laws (in some cases)	Forces that scale with a low power become more prominent in the micro domain; if these are positive attributes, then miniaturization is favorable, e.g., surface tension becomes more important than gravity in a narrow capillary
Batch and beyond batch techniques	This lowers cost
Disposable	This helps avoid contamination
Breakdown of macro laws in physics ad chemistry	New physics and chemistry might be developed
Increased sensitivity (in some cases)	Nonlinear effects can increase a sensor's sensitivity, e.g., amperometric sensors
Smaller building blocks	The smaller the building blocks, the more sophisticated the system that can be built

What are microelectromechanical systems (MEMS)?

The term MEMS refers to a collection of microsensors and actuators which can sense its environment and have the ability to react to changes in that environment with the use of a microcircuit control. They include, in addition to the conventional microelectronics packaging, integrating antenna structures for command signals into micro electromechanical structures for desired sensing and actuating functions. The system also may need micropower supply, micro relay and microsignal processing units. Microcomponents make the system faster, more reliable, cheaper and capable of incorporating more complex functions.

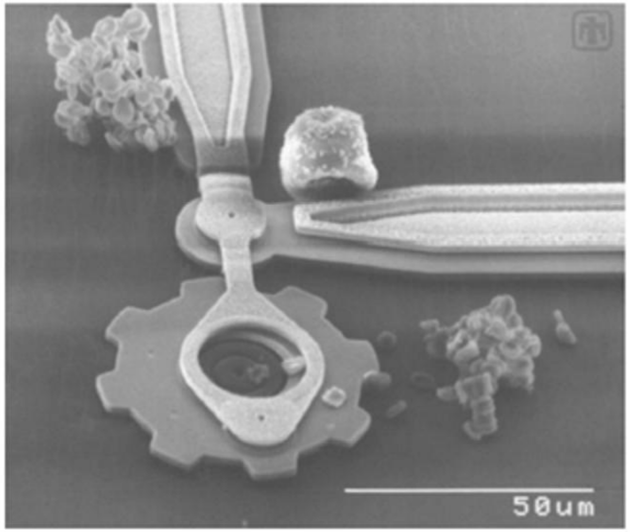
Cf) human body

Ex) RF-MEMS: MEMS for RF integrated circuits
BioMEMS: Biological sensing or actuation
Micro-opto-electromechanical systems (MOEMS)
Micro total analysis systems (μTAS)

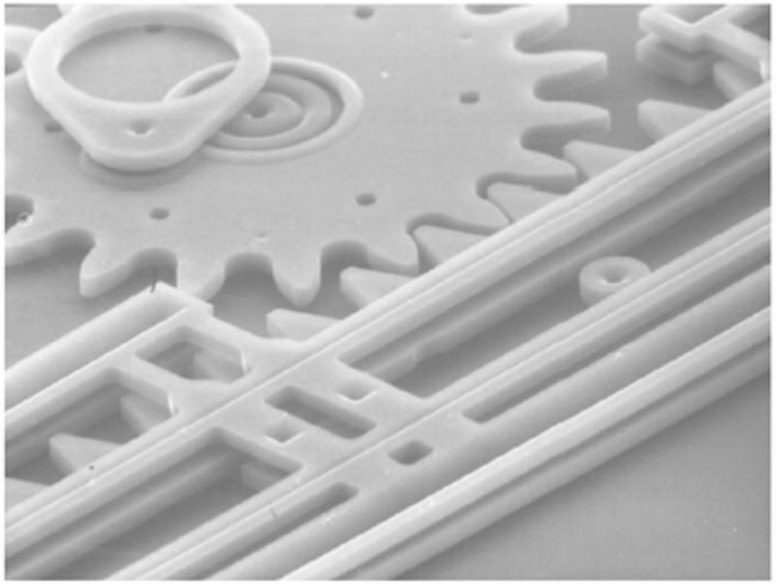
What are MEMS, typically?

Small:

- electro mechanical structures consisting of components measured in micrometers



Sandia National Labs



Sandia National Labs

- can be easily formed into highly complex systems

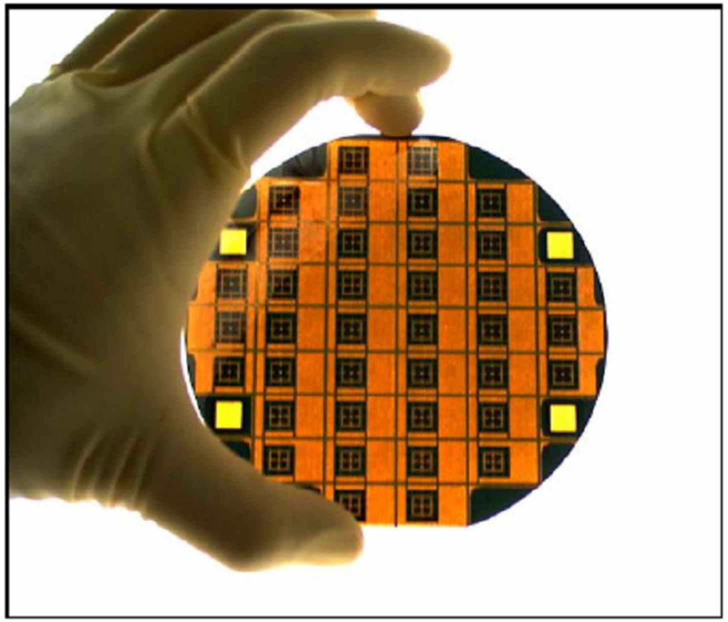
Why MEMS?

Economic benefits:

- Parallel fabrication for mass production
- package-level integration
- system-level integration
- leverages IC fabrication technology

Technical benefits:

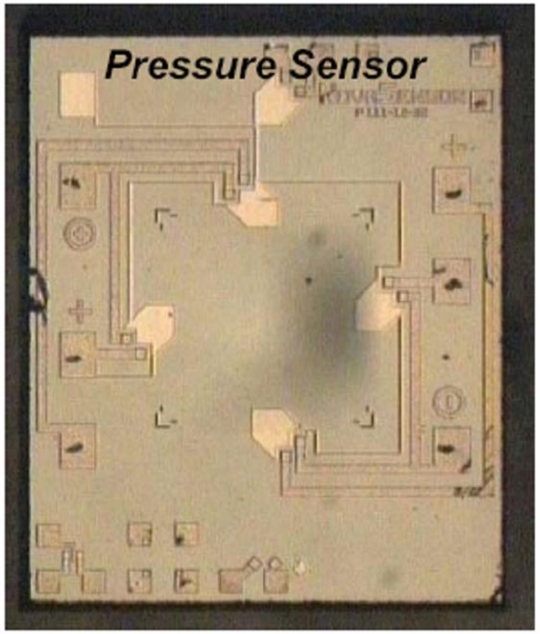
- manufacturing precision
- light weight and small size
- novel capabilities
- materials advantages



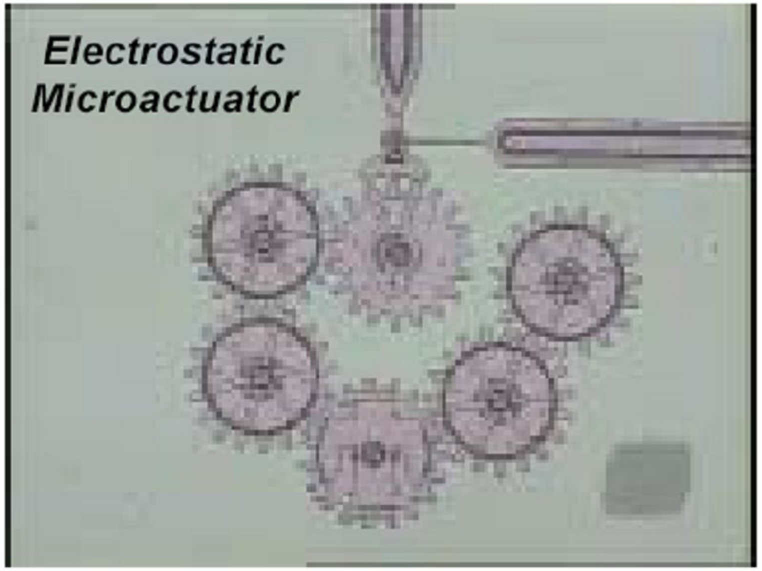
What can MEMS do?

Sense and Act on its Environment!!

- sensing: acceleration, pressure, flow rate, etc...
- actuating: by electric, magnetic, thermal, … forces
- fast: 250,000 RPM go far: >1 mm strong: >1 mN



NovaSensor (TRW)



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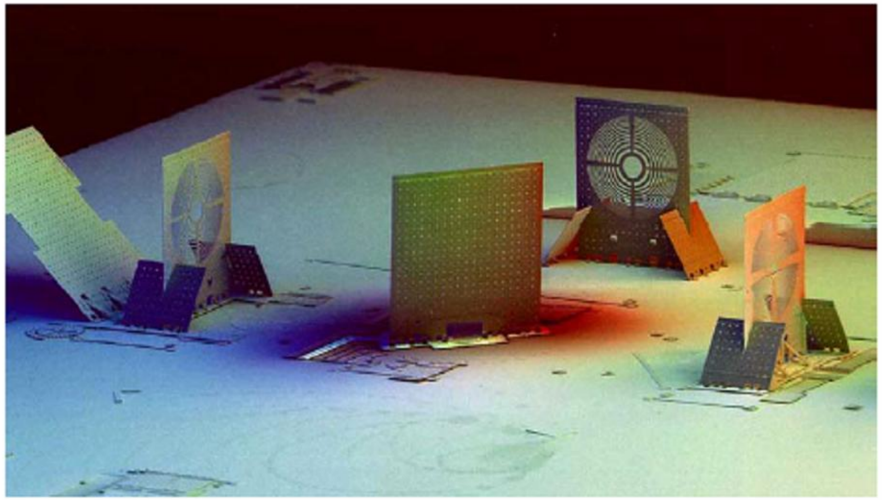
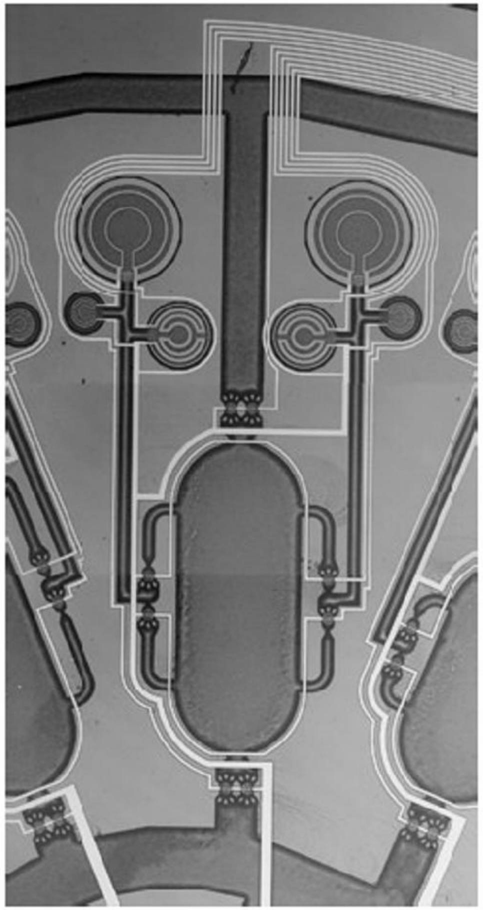
What else can MEMS do?

- Re-direct and process light
- Re-direct and process fluids
- Can be wireless
- Combined with VLSI, MEMS can miniaturize entire systems!

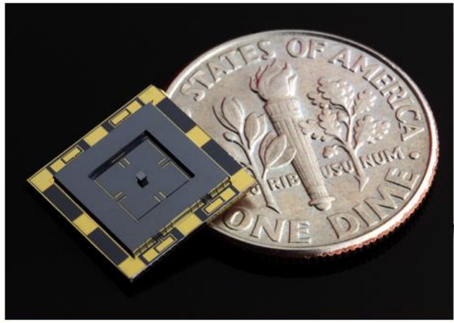


Free-space micro-optical bench (UCLA)



Micro-fluidic mixer
BSAC

Examples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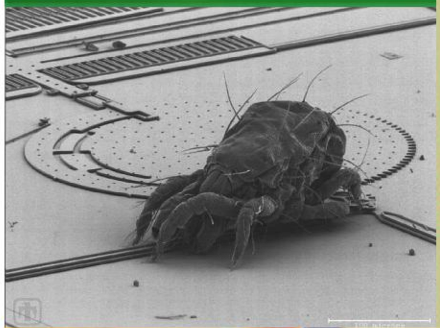

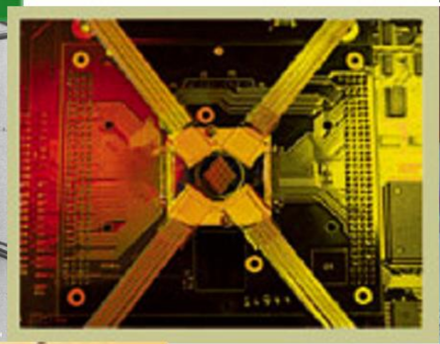

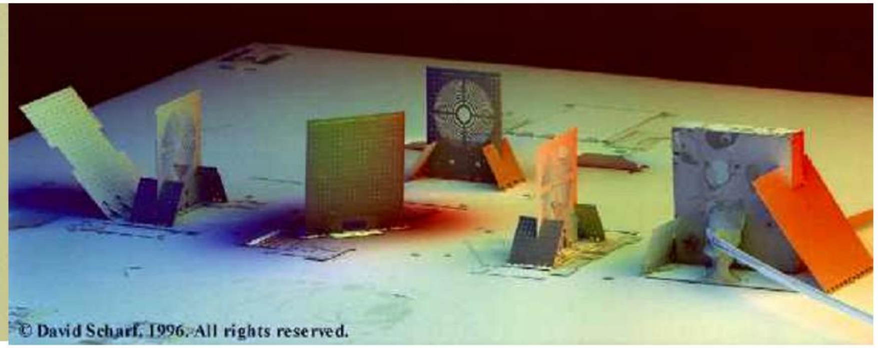
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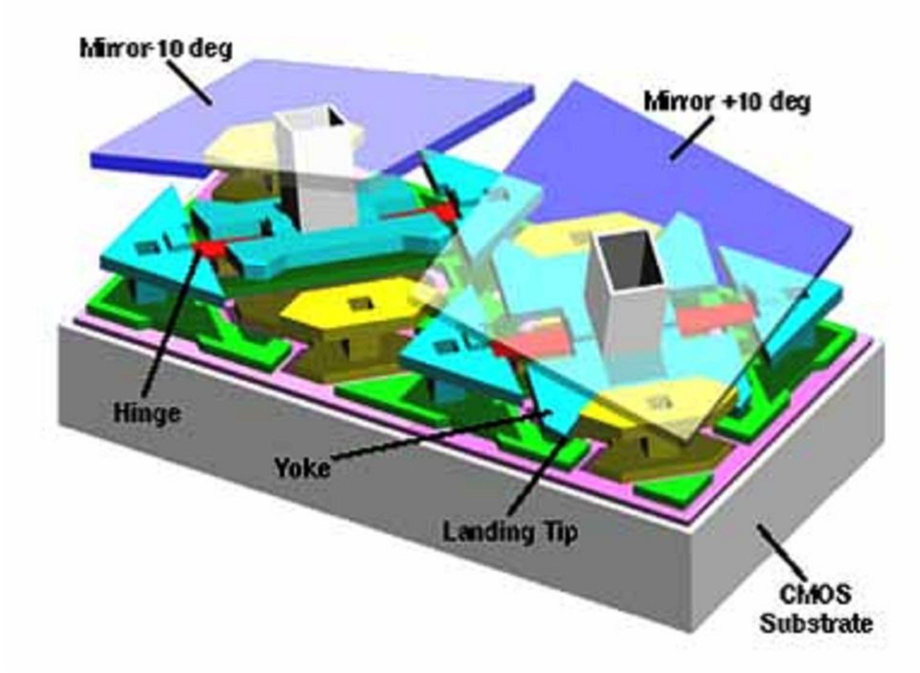
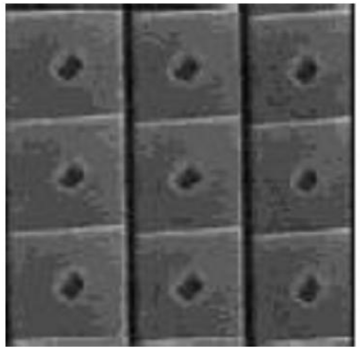
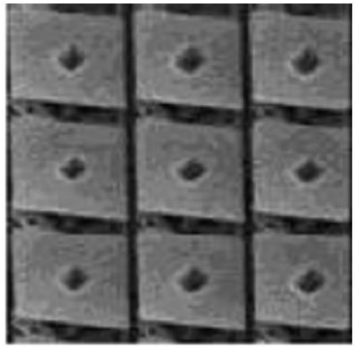
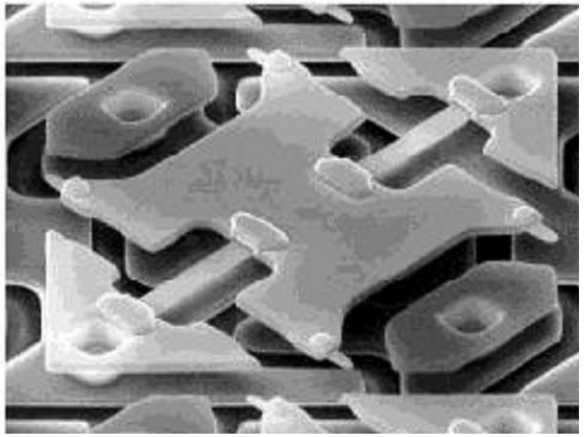
Digital Light Processing™ (TI DMD, 1987)

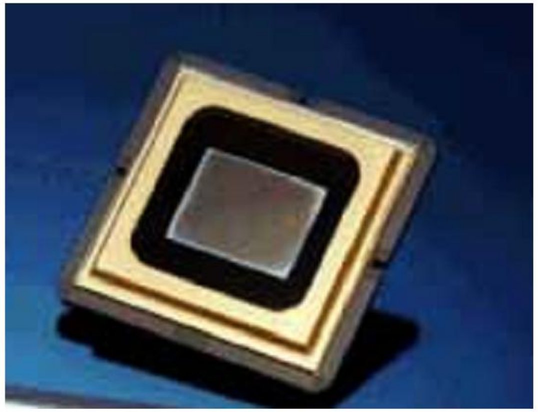


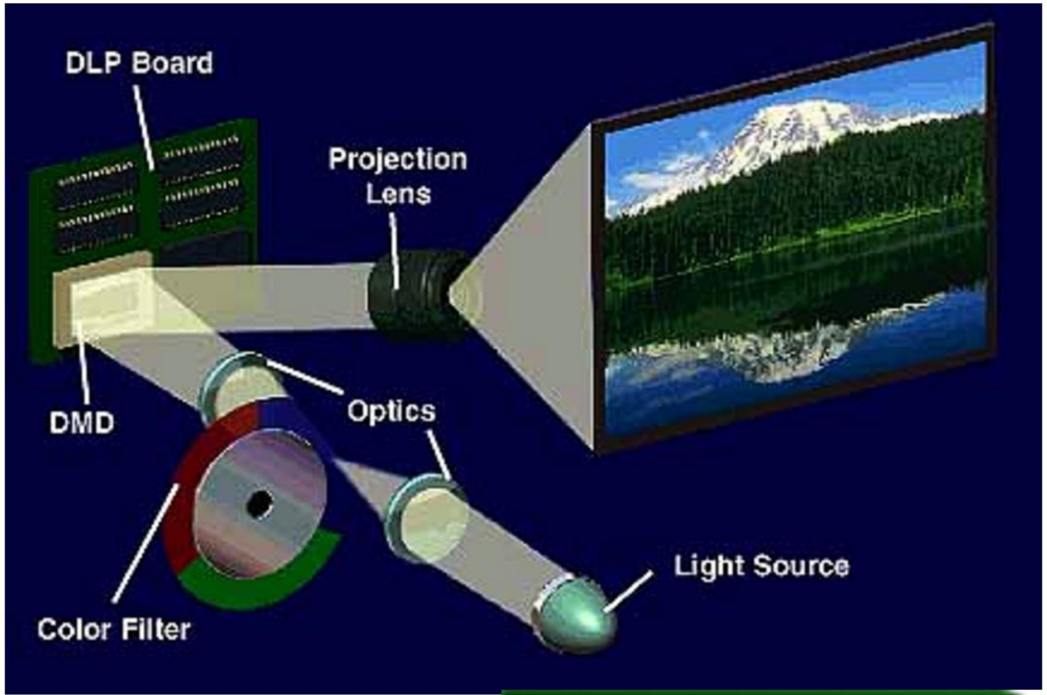






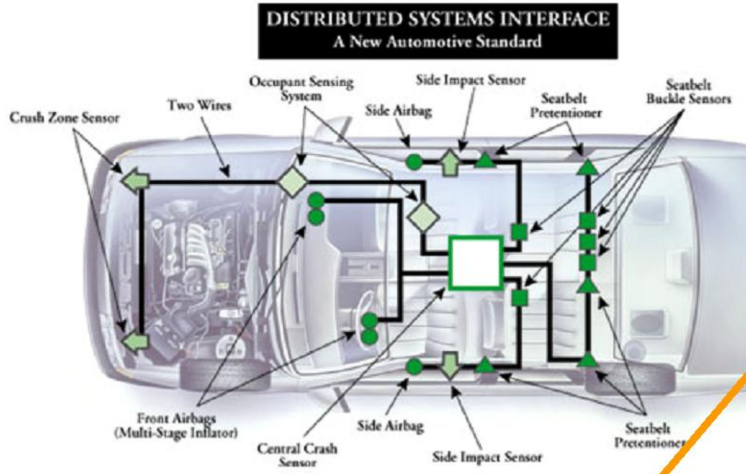
- Microfabricated digital mirror
- High-Brightness (vs. LCD)
- High-Resolution

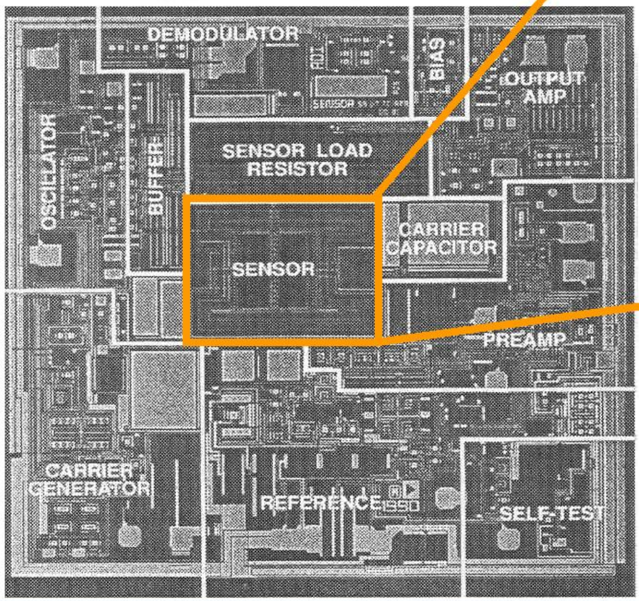


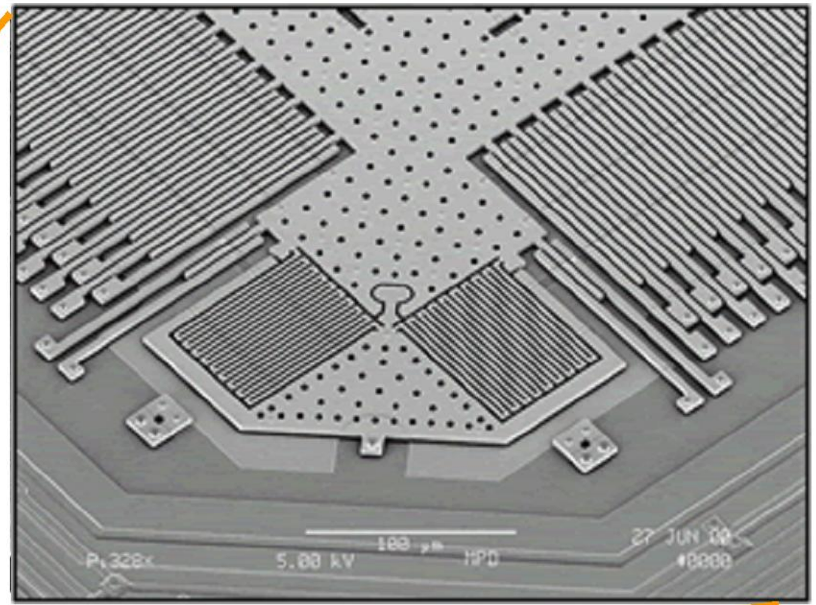


- Electro Mechanical System On Chip
- Compact
- High Performance
- Low cost

ADXL Accelerometer

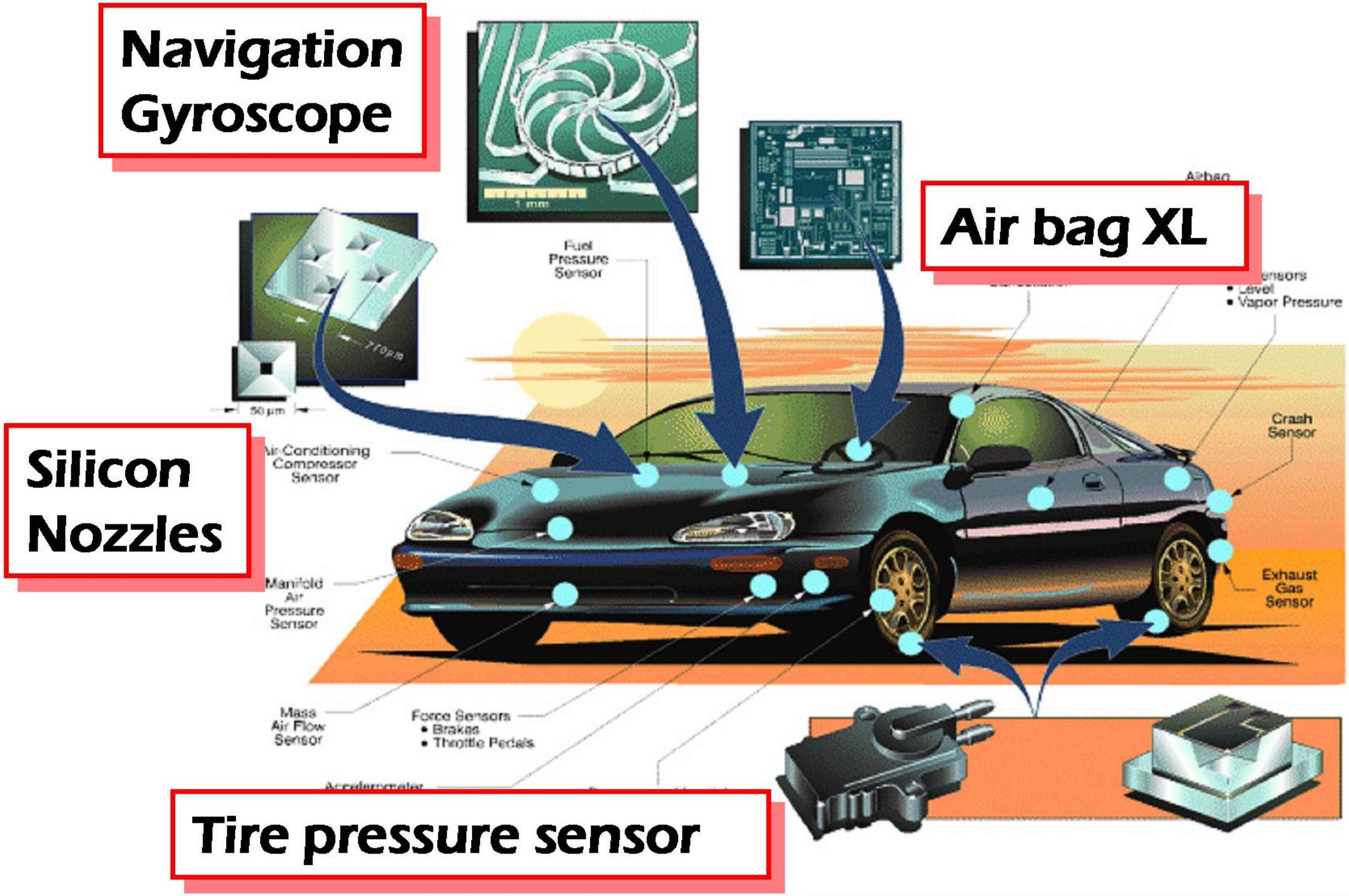






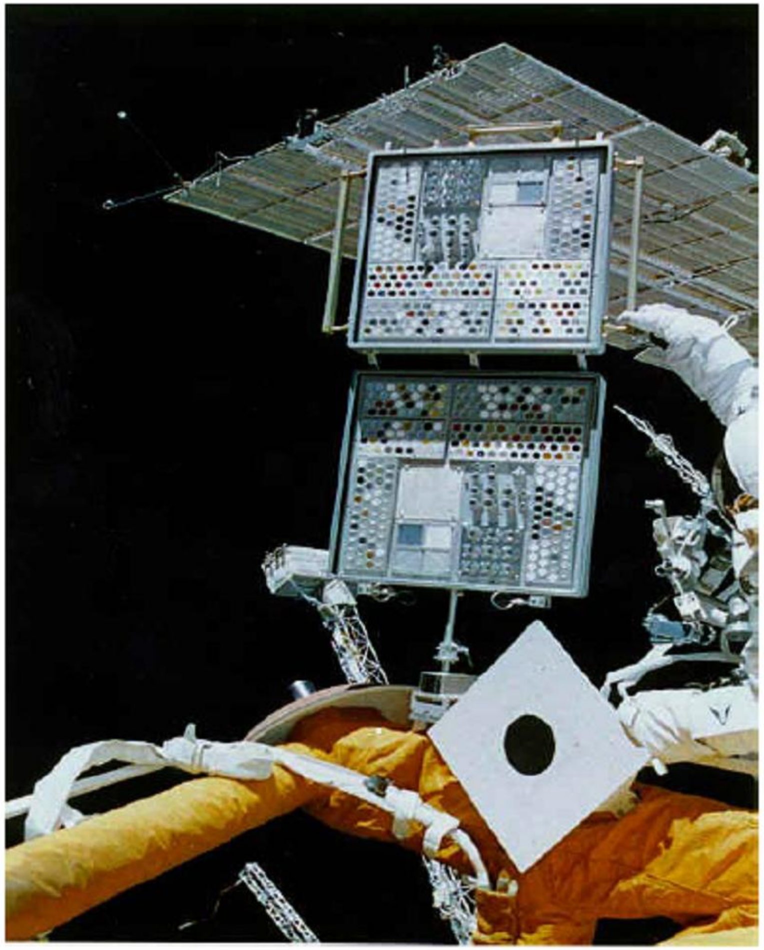
- Electro Mechanical System On Chip
- Compact
- High Performance (linearity, sensitivity)
- Low cost

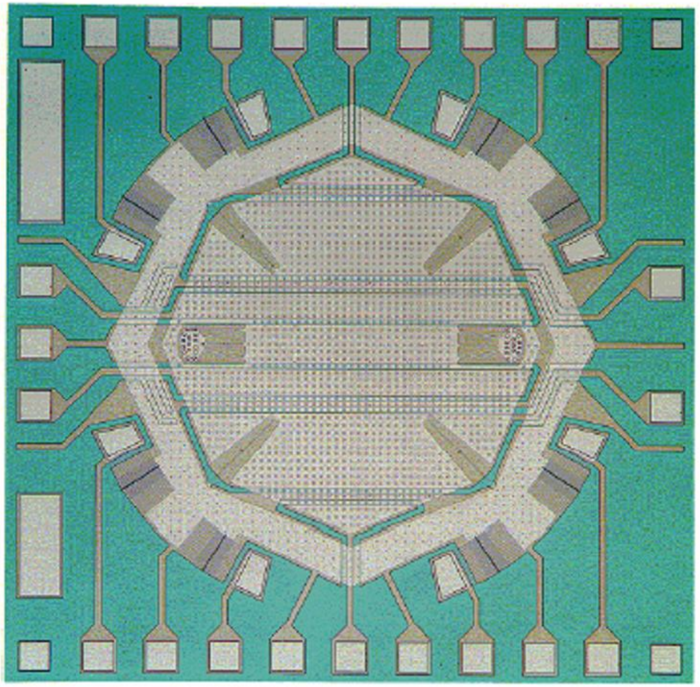
Automotive Applications



Aerospace Applications

- Aircraft, micro-satellites, space exploration …

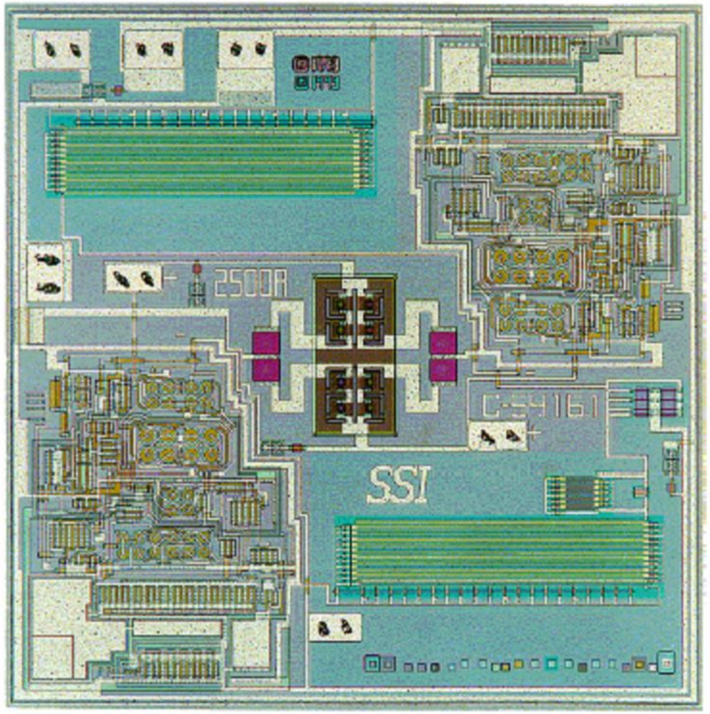




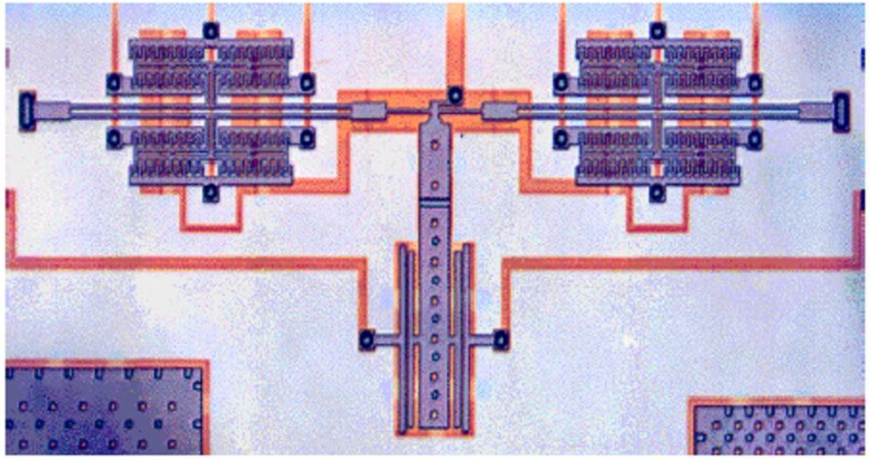
MEMS Gyroscope
(Fabricated at Standard MEMS, Inc.)

Industrial Applications

- Fluid regulation, vibration and strain sensing, environmental monitoring …



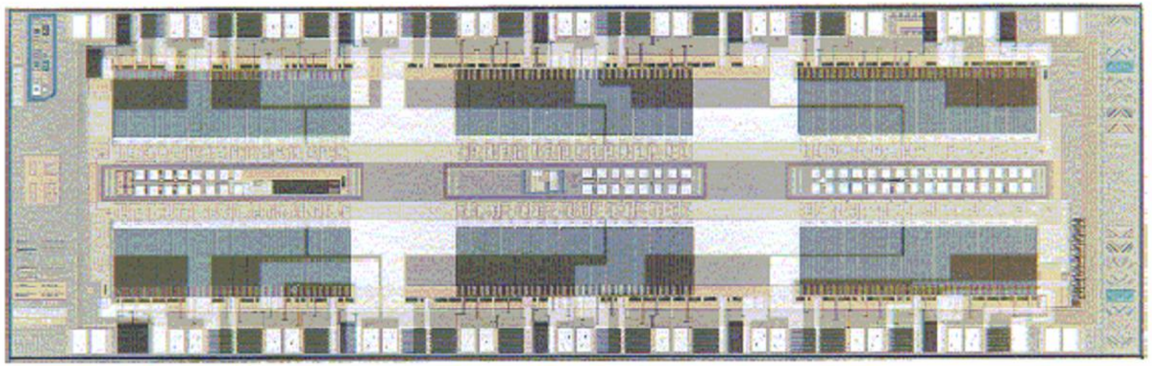
Pressure sensor & Electronics
(Fabricated at Standard MEMS, Inc.)



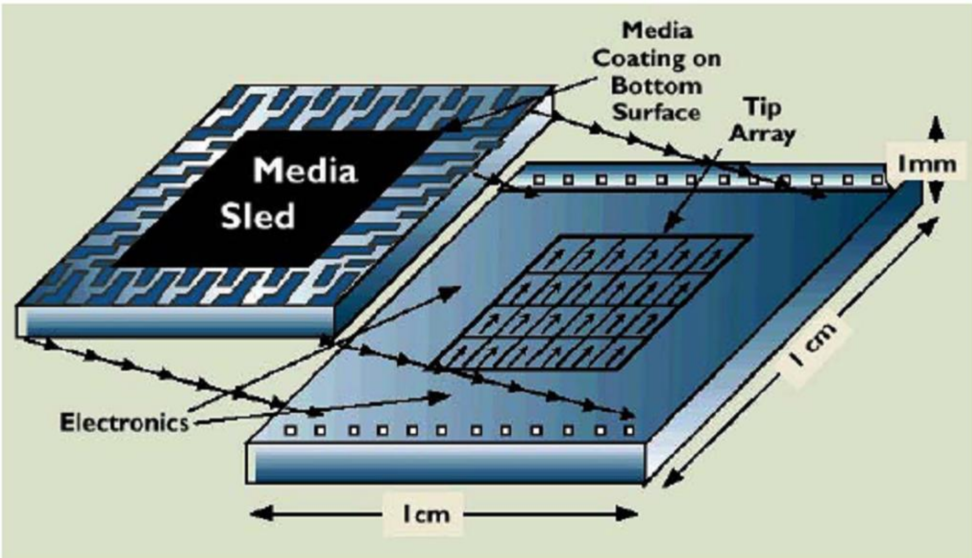
Strain/force sensor
(UC Berkeley, Integrated Micro Instruments)

Customer…

- Computers, data storage, ink jet printers, displays …



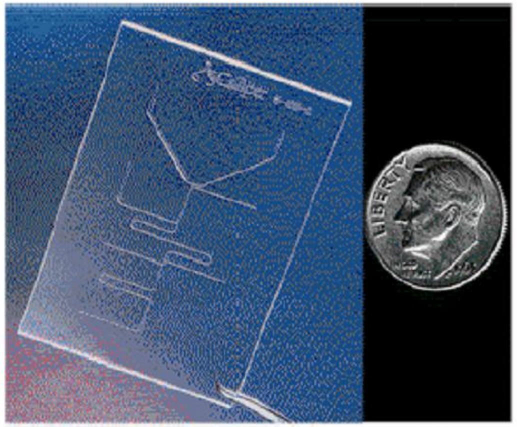
Tri-color ink jet print head (Fabricated at Standard MEMS, Inc.)



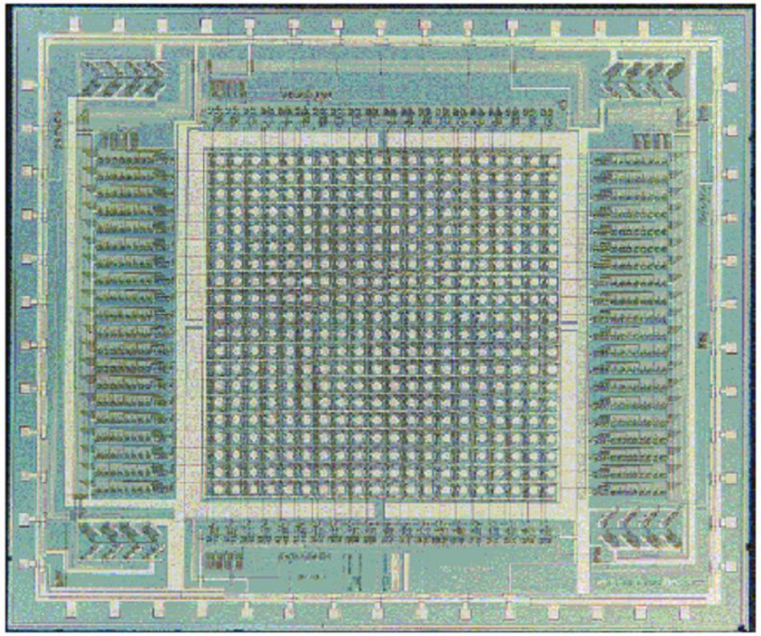
MEMS AFM tip array for data storage (Carnegie Mellon University)

Biomedical…

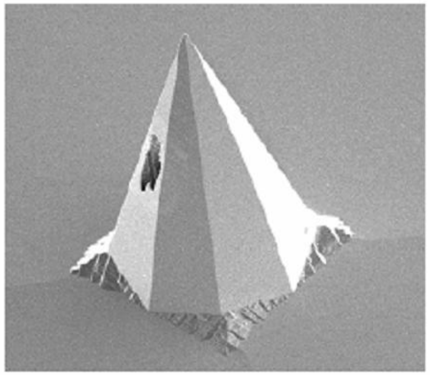
- Biochips, blood pressure sensing, genetic analysis, proteomics, diagnostics, drug delivery …



Disposable lab on a chip
(Caliper Technologies Inc.)

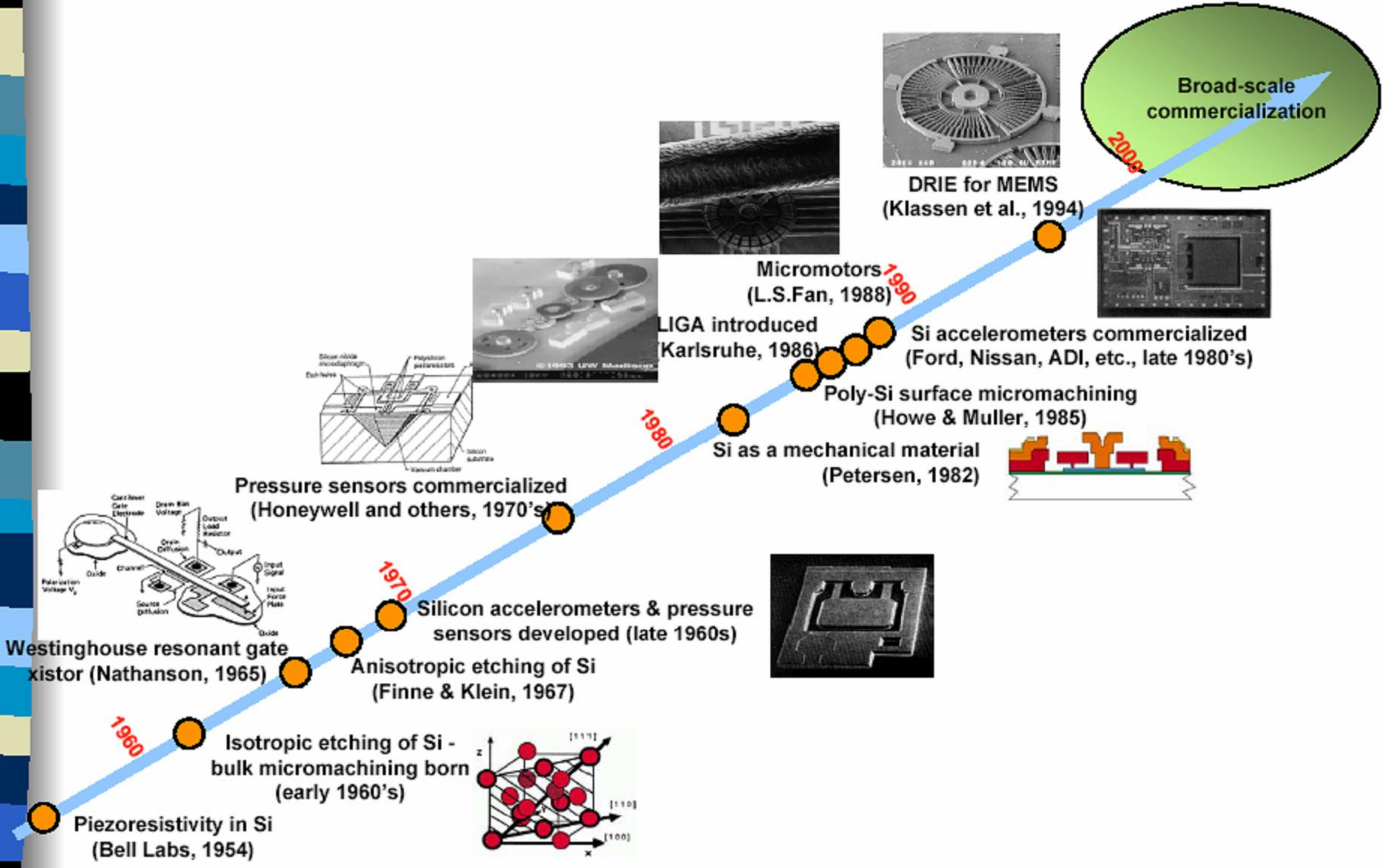


DNA Analysis chip
(Fabricated at Standard MEMS, Inc.)

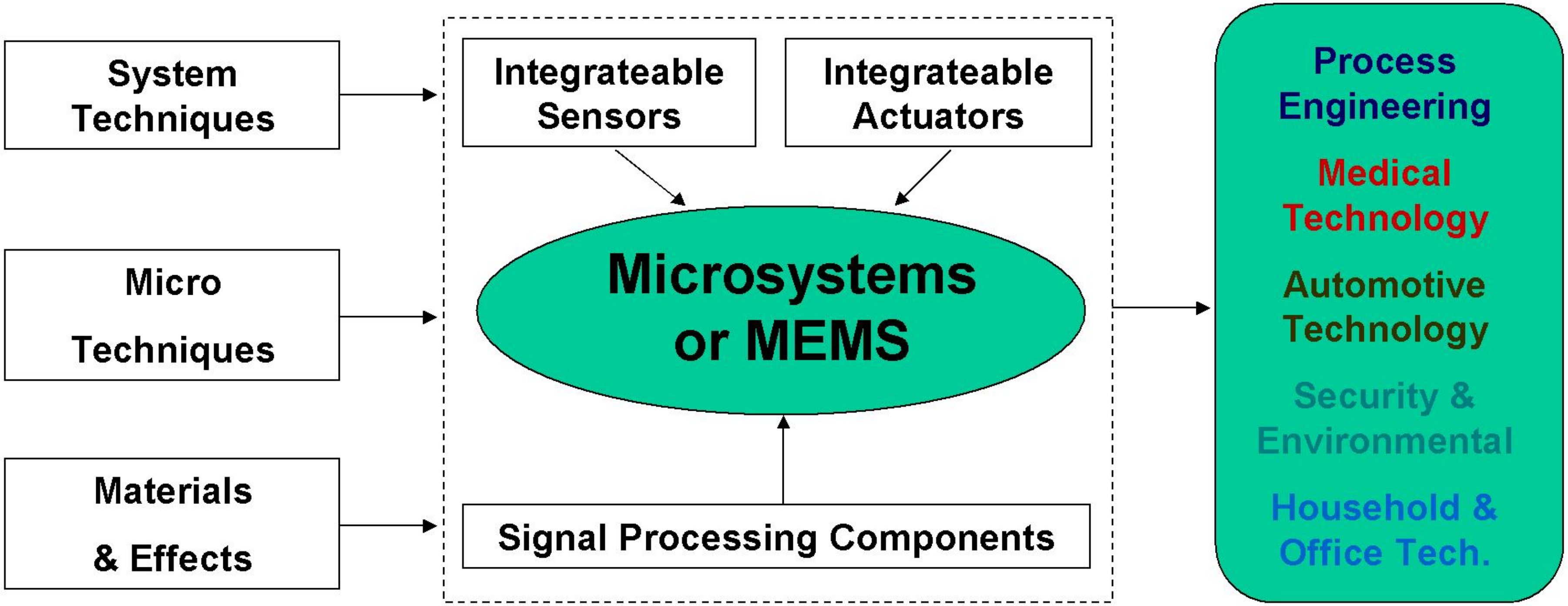


Microneedles
(Fabricated at Standard MEMS, Inc.)

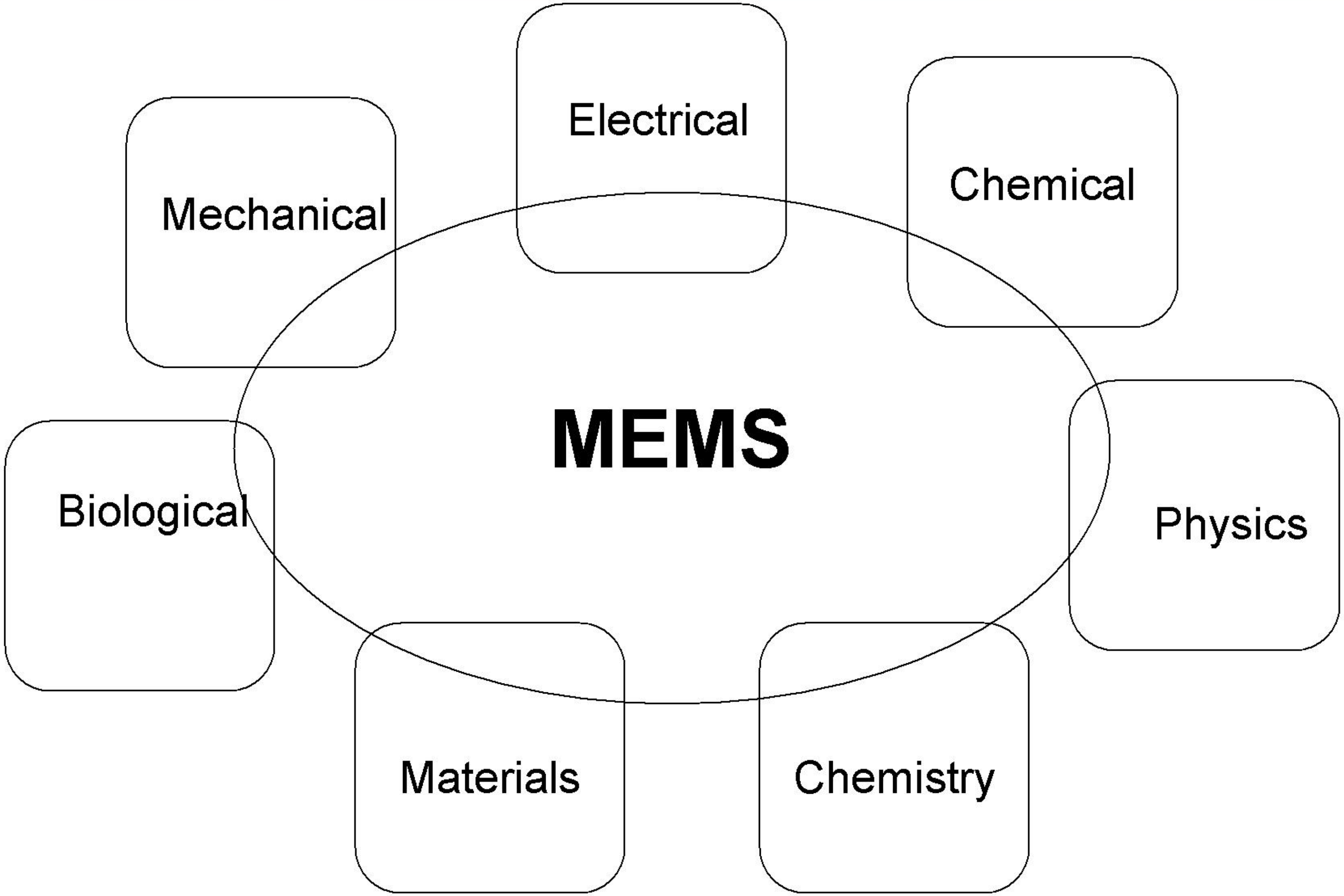
MEMS Technology Timeline



MEMS: Smart Systems



MEMS: Interdisciplinary Systems



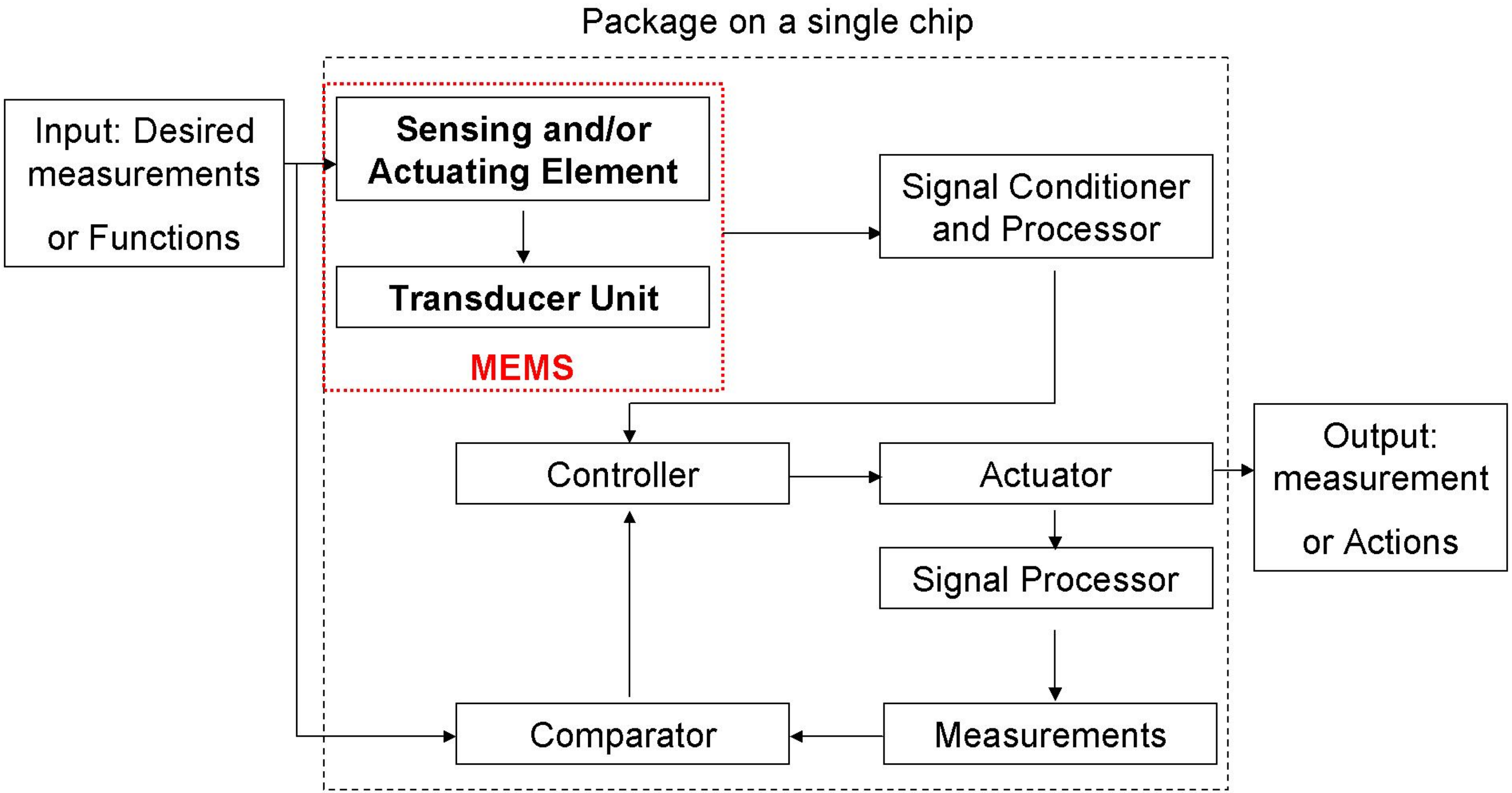
Microelectronics vs. MEMS

Microelectronics	Microsystems (Silicon-based MEMS)
Uses single crystal silicon die, silicon compound, and plastics	Single crystal silicon die, GaAs, quarts, polymers, metals
Transmits electricity for specific electrical functions	Performs biological, chemical, electromechanical functions
Stationary structures	May involve moving components
Primary 2-D structures	Complex 3-D structures
Complex patterns with high density over substrates	Simpler patterns over substrates
Fewer components in assembly	Many components to be assembled
IC die is completely protected from contacting media	Sensor die is interfaced with contacting media
Matured IC design methodology	Lack of engineering design methodology and standards
Large number of electrical feedthroughs and leads	Fewer electrical feedthroughs and leads
Industrial standards available	No industrial standards to follow
Mass productions	Batch production or on customer-needs basis
Fabrication techniques are proved and well documented	Many microelectronics fabrication techniques used
Manufacturing techniques are proved and well documented	District manufacturing techniques
Packaging technology is relatively well established	Packaging technology is at the infant stage

MEMS and related other technologies

		Observation Methods	Parts	Manufacturing Technology
Milli-machine	10 mm – 1 mm	Visible	Miniaturized parts	Precision manufacturing
Micro-machine	1 mm – 1 μm	Optical microscope	Micro parts	Silicon process LIGA-process
Nano-machine	1 μm – 1 nm	Scanning electron microscope Scanning probe microscope	Molecular parts	Protein engineering

MEMS components



Scaling Laws in Miniaturization (1)

- Two scaling law:
  - Scaling of geometry governed by the law of physics: dynamics, electrostatics, electromagnetic forces

- Scaling of Geometry: Volume and Surface
  - Volume: Mass & weight related to both mechanical and thermal inertia (heat capacity)
  - Surface: pressure & buoyant force in fluid mechanics, heat absorption/dissipation
  - $S/V = l^{-1}$: a reduction of size of 10 times ($l = 0.1$) means a $10^3 = 1000$ times reduction in volume, but only $10^2 = 100$ times reduction in surface area

Scaling Laws in Miniaturization (2)

- Scaling in Mechanics
  - Variables of engineering mechanics: Power, Force, Inertia Momentum (speed, controllability), Time
  - In miniaturizing MEMS components, one need to understand the effect of reduction in the size on the *power P, force F, and pressure p, and the time t required to deliver the motion*.

- Scaling in Dynamic Forces
  - Distance s ~ *l (linear scale), velocity* $v = s/t \sim (l)/t$
  - $S = v_o t + 1/2at^2$, v_o *: initial velocity, a: acceleration*

  by setting $v_o=0$, $a=2s/t^2$

  Newton's second law, dynamic force, $F = Ma = M2s/t^2 \sim (l)(l^3)\ t^{-2}$

Scaling Laws in Miniaturization (3)

- Trimmer Force Scaling Vector
  - Force scaling vector, F
  - $F = [l^F] = \begin{pmatrix} l^1 \\ l^2 \\ l^3 \\ l^4 \end{pmatrix} \quad a = [l^F][l^3]^{-1} = [l^F][l^{-3}] = \begin{pmatrix} l^1 \\ l^2 \\ l^3 \\ l^4 \end{pmatrix} [l^{-3}] = \begin{pmatrix} l^{-2} \\ l^{-1} \\ l^0 \\ l^1 \end{pmatrix}$
  - $t = (2sM/F)^{1/2} \sim ([l^1][l^3][l^{-F}])^{1/2} = [l^2][l^F])^{-1/2} = \begin{pmatrix} l^{1.5} \\ l^1 \\ l^{0.5} \\ l^0 \end{pmatrix}$
  - Power Density, P/V_o

$$P/V_o = W/t\,V_o = Fs/tV_o = \begin{pmatrix} l^{-2.5} \\ l^{-1} \\ l^{0.5} \\ l^2 \end{pmatrix}$$

Scaling Laws in Miniaturization (4)

- Estimate the associated change in the acceleration a and the time t and the power supply to actuate a MEMS component if its weight is reduced by a factor of 10. (Density = M/V)

-> Since the weight of a solid is equal to the mass times gravitational acceleration, and the mass is proportional to the cubic power of the linear scale, we will have the weight $W \sim l^3$, which means an order of 3 in scaling law.

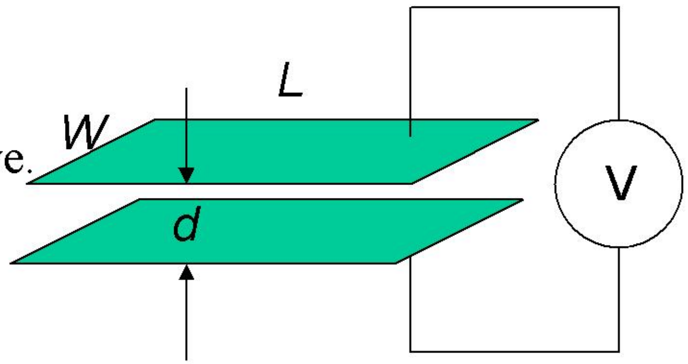
- No reduction in the acceleration – l^o
- There will be an $(l^{0.5}) = (2.15^{0.5}) = 1.47$ reduction in the time to complete the motion
- There will be an $(l^{0.5}) = (2.15^{0.5}) = 1.47$ times reduction in power density (P/V_o). Also the power may be reduced by a factor of $(2.15^{3.5}) = 14.57\ 0$

Scaling Laws in Miniaturization (5)

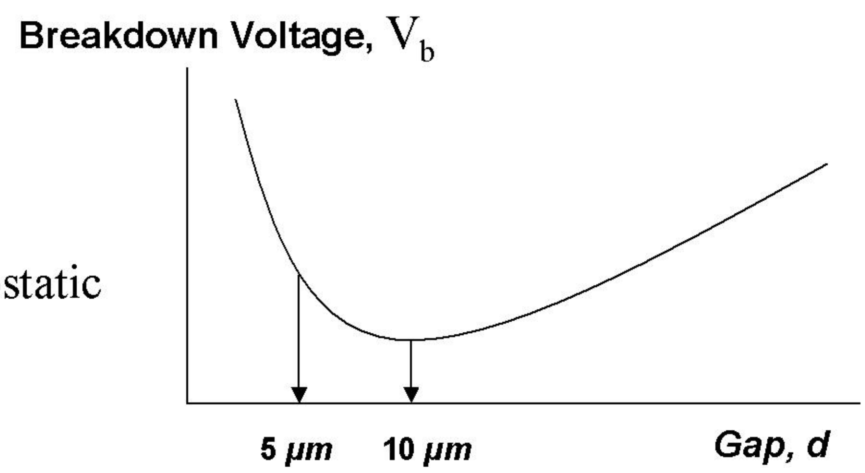
- Scaling in Electrostatic Forces
  - Maximum electric potential induced in the parallel plates is

    $U = -\frac{1}{2} C \cdot V_b^2 = -\frac{1}{2} (e_o \cdot e_r \cdot WL/d) \cdot V_b^2$

  - When the applied voltage is a breakdown voltage of air gap, *d*, following the Paschen curve.



    We can see that the breakdown voltage V_b drops drastically with the increase of the gap for $d < 5\ \mu m$. The trend, however, is slowed down significantly after the gap widens from $d > 5\ \mu m$. Variation of the voltage reverses at $d = 10\ \mu m$.



  - We can express the scaling of the electrostatic potential energy as follows:

    $U \sim [(l^o) (l^o) (l^1) (l^1) (l^1)^2 / (l^1)] = (l^3)$

Scaling Laws in Miniaturization (6)

Scaling in Electricity

- Domains: electrostatic actuation, piezoresistive, piezoelectric, thermal resistance heating, etc.
- Electric resistance, $R = \rho L/A \sim (l)^{-1}$
- Resistive Power loss, $P = V^2/R \sim (l)^1$, where V is applied voltage $\sim (l)^0$
- Electrostatic energy density, $U = \frac{1}{2}\epsilon \bullet E^2 \sim (l)^{-2}$, where ϵ is the permittivity of dielectric $\sim (l)^0$, E (= V/d) is electric field strength $\sim (l)^{-1}$
- Scaling of electric power supply for miniaturization, for example, electrostatic actuation circuit,

  the available power is directly related to the system's volume, $E_{AV} \sim (l)^3$

  The ratio of power loss to available energy or power for performing the designed functions can be expressed as:

$$P/E_{AV} = (l)^1/(l)^3 = (l)^{-2}$$

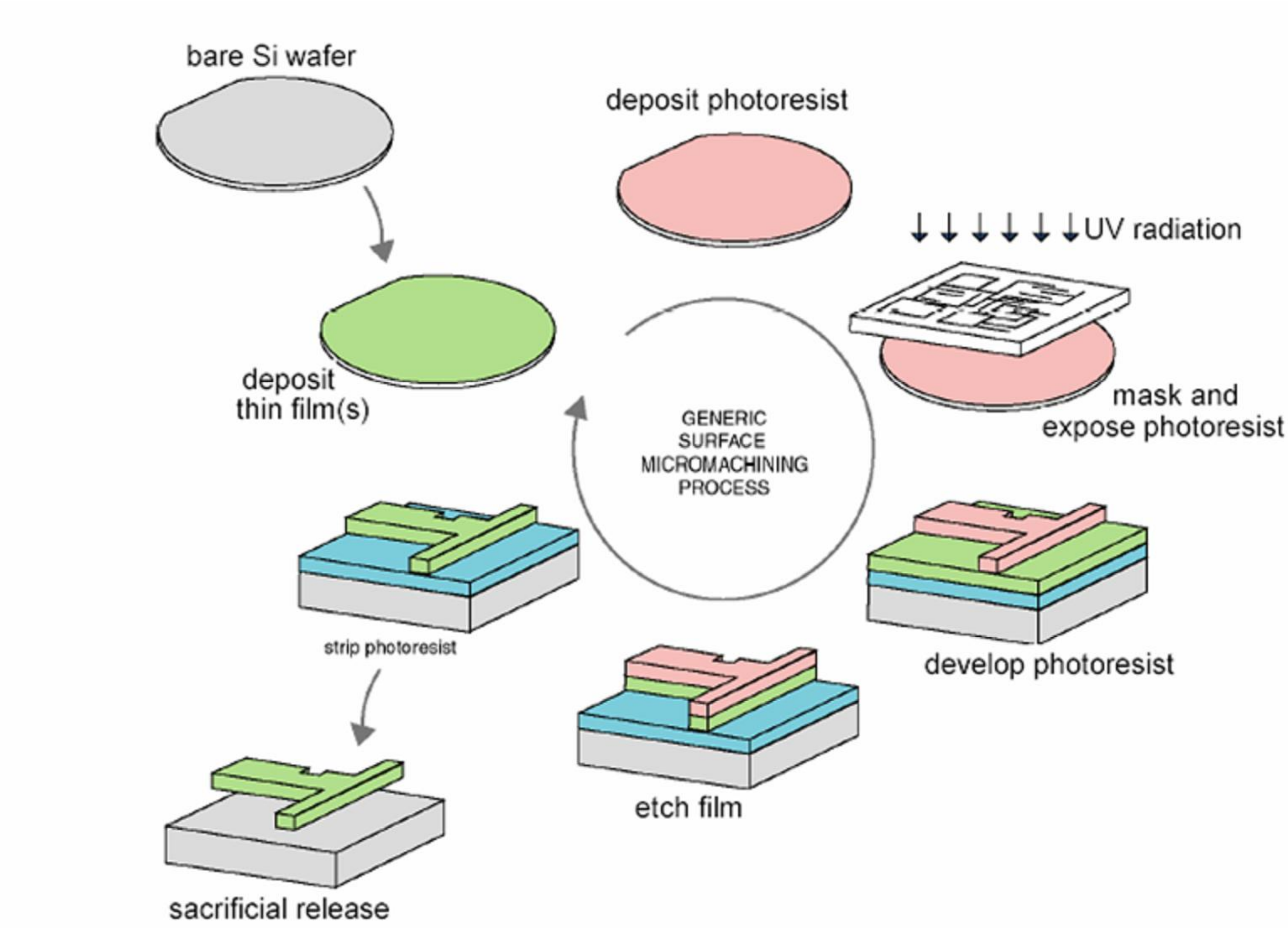
Scaling Laws Example

- Surface tension
  - Weight scales as l^3 whereas surface tension force as l^1
  - More difficult to empty liquids from a capillary than to spill coffee from a cup
  - Ex) Water strider

    10 mg mosquito ~ 1 mm foot area, 60 kg man ~ 8000 m foot area

- Animals in Nature
  - African elephant of 3.80 m on land vs. a whale of 20 m long in sea
  - Foxes in cold or warm regions
  - No warm-blooded animal smaller than a shrew or a hummingbird
  - A smaller creature finds weight less troublesome

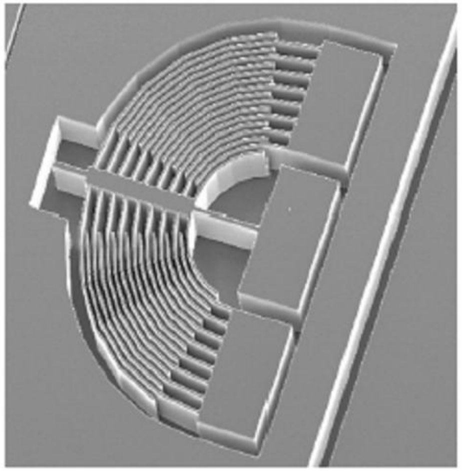
MEMS: Lithography and Sacrificial Etching



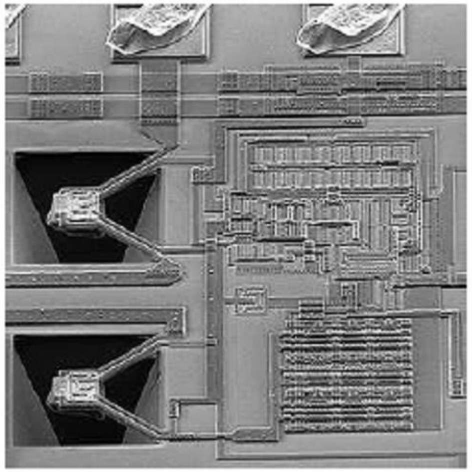
Si Micromachining Methods

- Bulk micromachining (1960s)
  - Chemical etching of bulk silicon wafers
- Surface micromachining (1983)
  - Sequential deposition/etching of thin films (0.1-2.5um) on silicon surface
  - Selective etching of a sacrificial thin film
- LIGA & derivitives (1985)
  - X-ray lithography for high aspect-ratio molds in PMMA
  - Electroplating of metal structures in molds
  - Repeated plastic injection molding
- SOI/SFB + DRIE (1990s)
  - High aspect ratio etching of multiple silicon layers

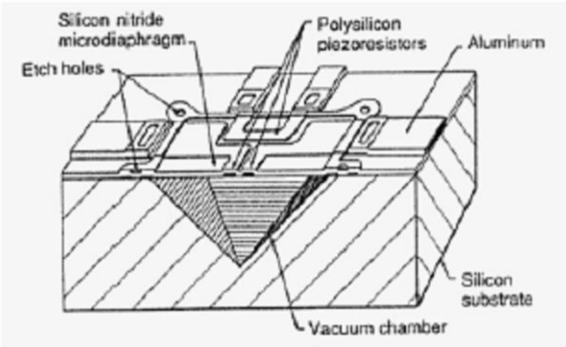
Bulk Micromachining



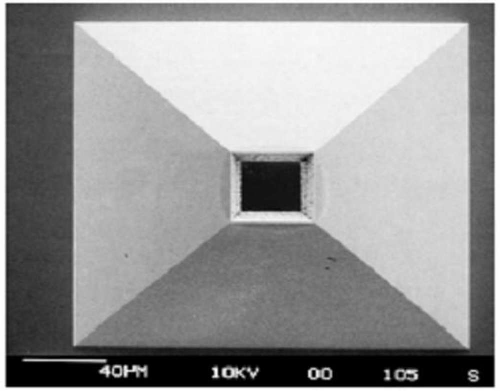
High aspect ratios



Thermal isolation



Enclosed cavities



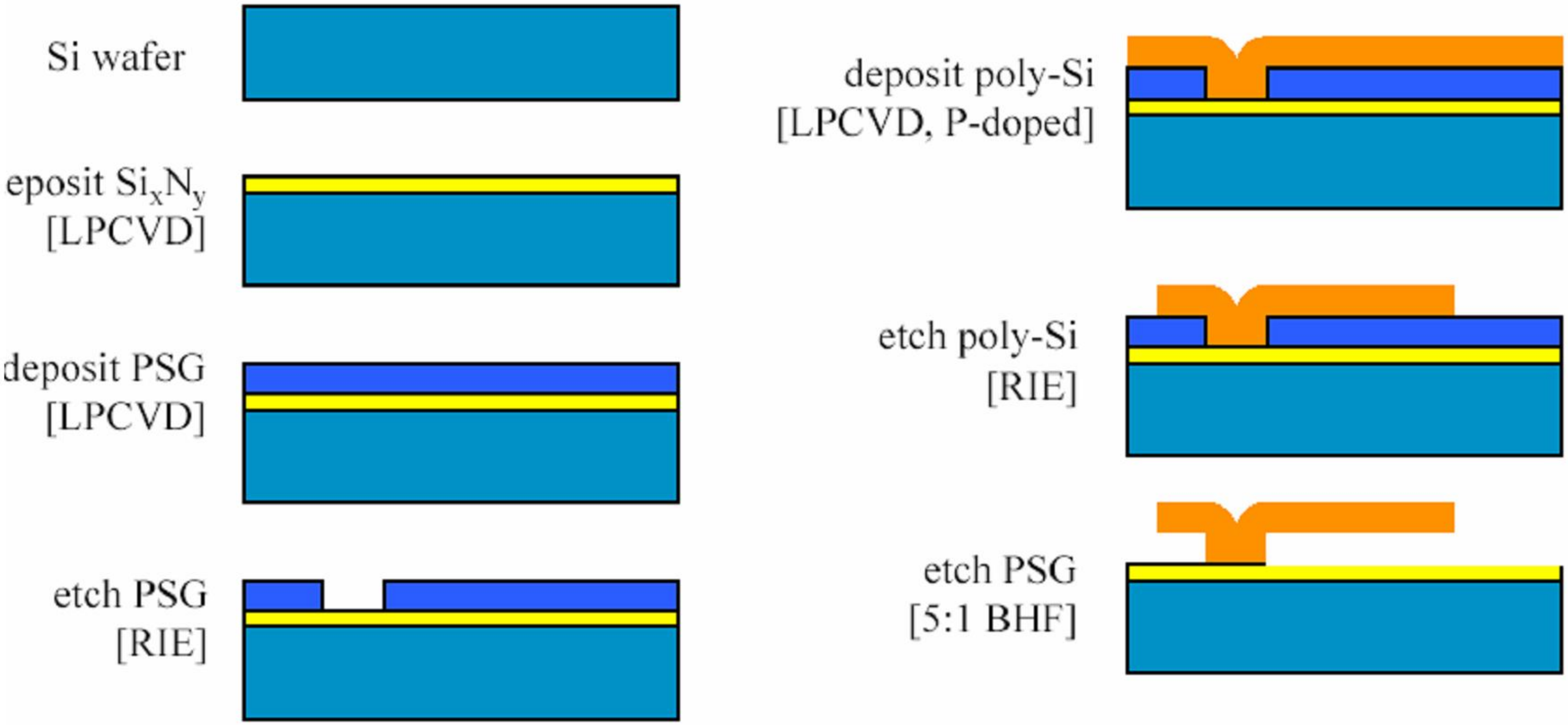
Through-wafer vias

Benefits of Si bulk micromachining

- intrinsic mechanical stability
- minimal intrinsic stresses
- integrated electronics feasibility
- fabrication equipment availability
- useful (although limited) geometry range
- inexpensive “garage” fabrication

Polysilicon surface micromachining

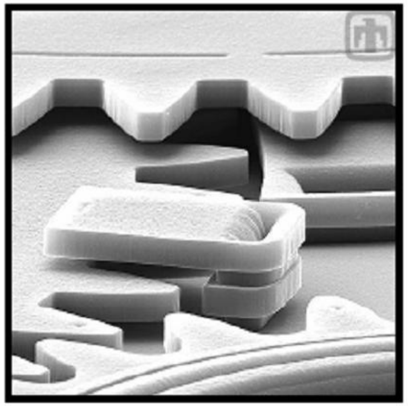
- Invented by R. Howe & R. Muller (1982)
- Basic 1-layer poly-Si process:



- Commercial processes range from 2.5-layer poly process to 4.5-layer process:
  - Sandia Labs 4.5-layer, CMOS (SUMMiT)
  - MCNC 2.5-layer (MUMPs)
  - Analog Devices 2.5-layer, 3μm BiCMOS (iMEMS)
  - SMSC 2.5-layer, 2μm CMOS
  - MOSIS 1.5-layer IC-MEMS, 0.35μm CMOS

- Extra 1/2-layer used for ground plane - depending on the process, ground plane may be the same as used for CMOS gate definition in integrated MEMS/VLSI fabrication

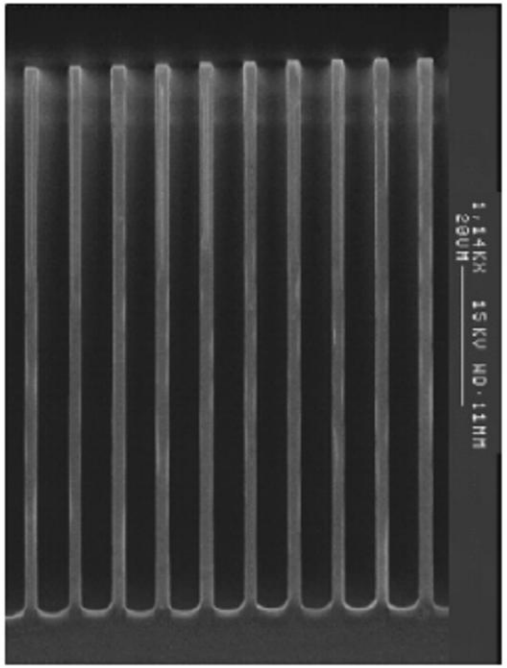
Gear-and-clip system used in micro-scale speed reduction unit, fabricated in Sandia National Labs 4.5-layer poly-Si process:



Deep reactive ion etching (DRIE)

Cryogenic process:
- ICP for high density plasma
- aperture for uniformity
- SF_6/O_2 sidewall passivation
- F-based chemistry for high etch rate
- low-temp (-110°C) to reduce sidewall passivation etch

Bosch Process:
- segregate sidewall passivation and bottom etch - "time multiplexed etching"
- CF_4 for passivation
- SF_6 for etching
- room temperature etching - no LN cooling

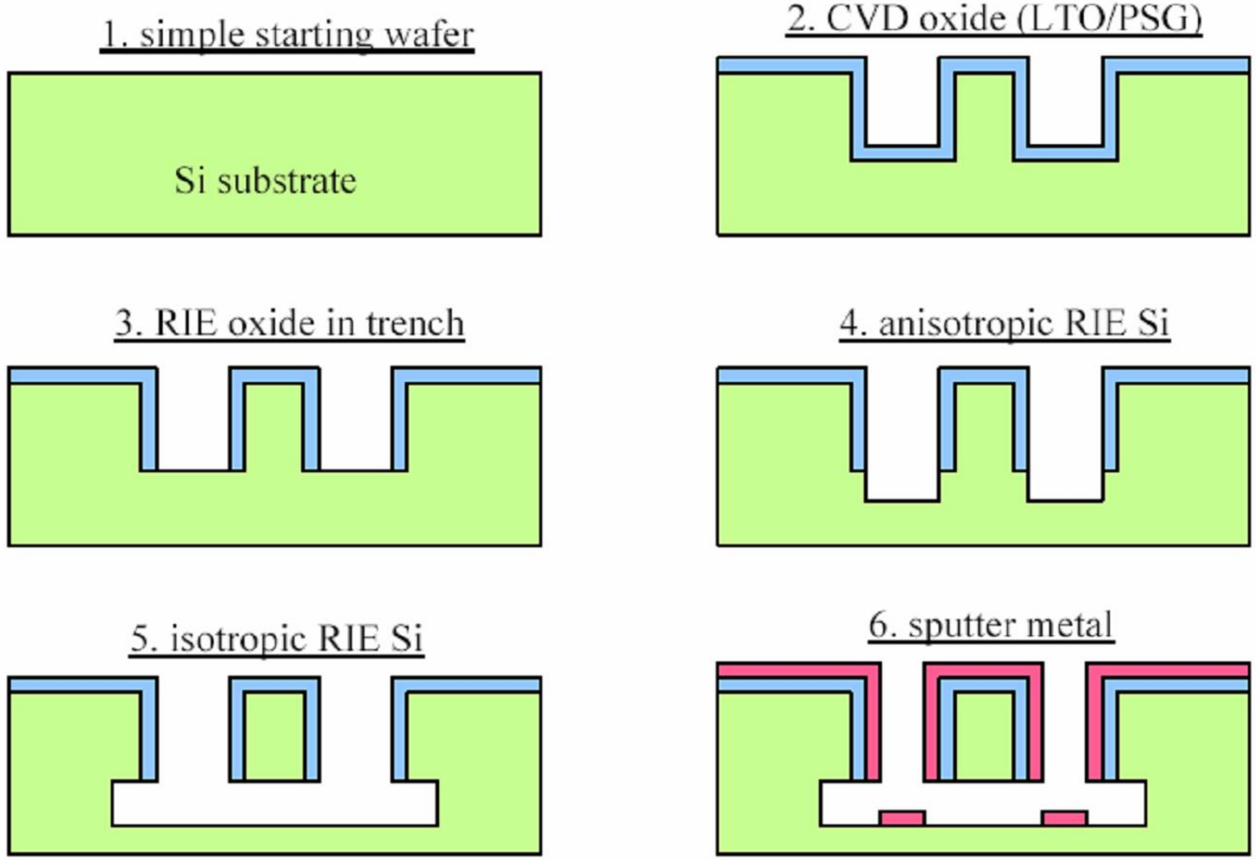


• etch rate	> 3 μm/min
• selectivity to Resist	> 75:1
• selectivity to SiO_2	> 150:1
• aspect ratios	> 40:1

SCREAM

SCREAM = single crystal reactive-ion etching and metallization
(N. MacDonald, Cornell)

10:1 aspect ratios possible

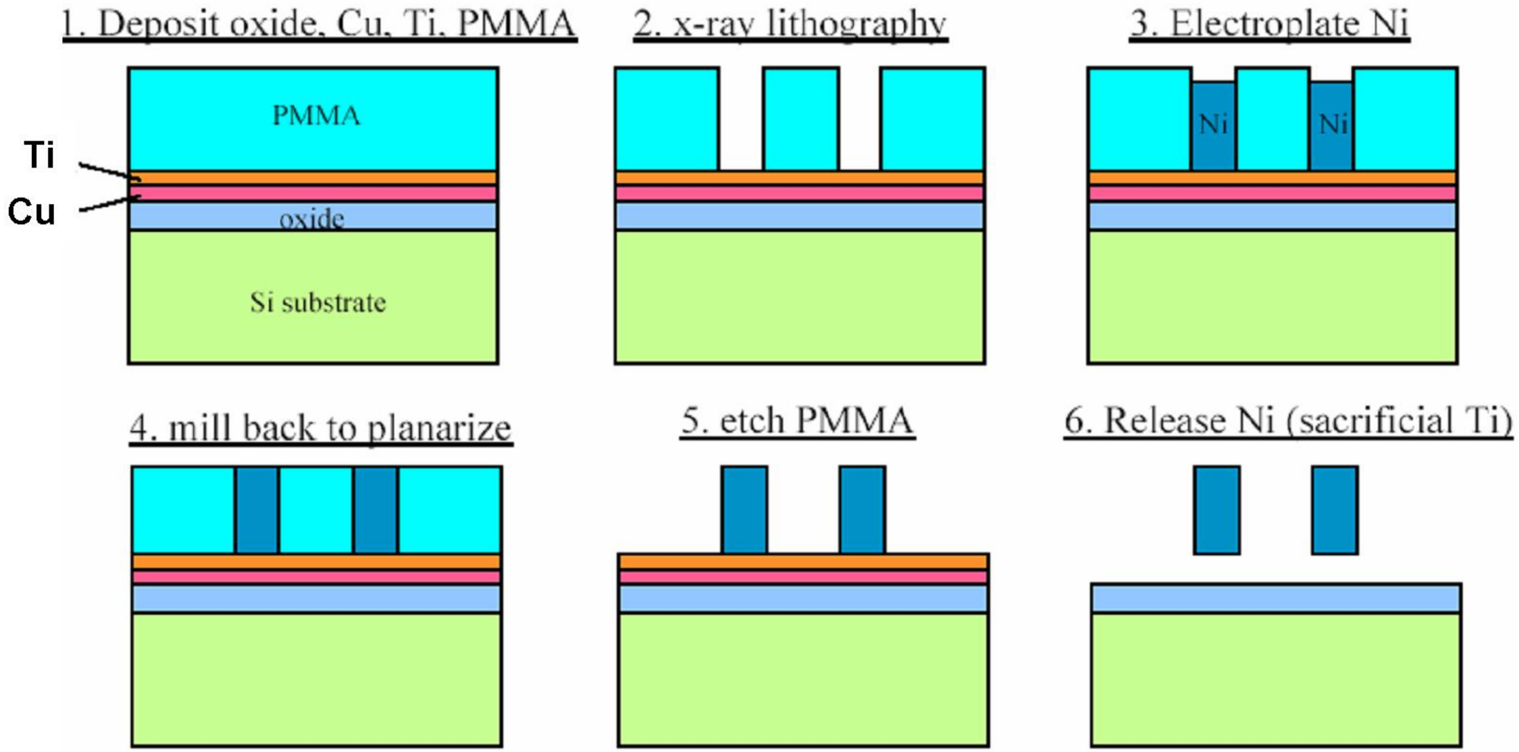


LIGA

LIGA = lithography, galvanoformung/electroplating, abformung/plastic molding – (Ehrfeld et al., Karlsruhe Center, Germany)

Lines/spaces: 5μm

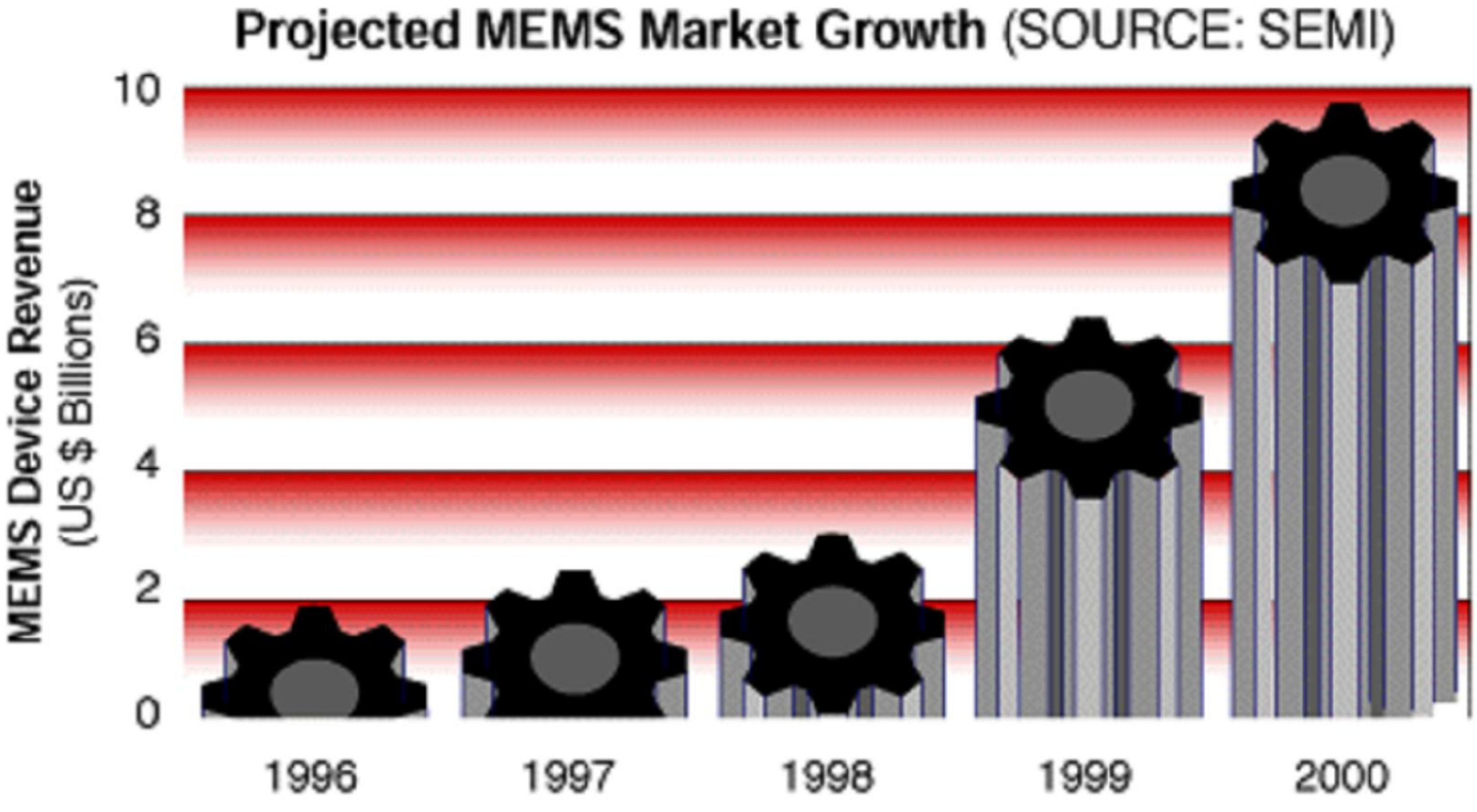
Aspect ratios of 10:1 to 20:1



World Market for Emerging MST-Products

Products	1996 Units (millions)	1996 $ (millions)	2002 Units (millions)	2002 $ (millions)
drug delivery systems	1	10	100	1 000
optical switches	1	50	40	1 000
lab on chip (DNA, HPLC, ...)	0	0	100	1 000
magneto optical heads	0.01	1	100	500
projection valves	0.1	10	1	300
coil on chips	20	10	600	100
micro relays	-	0.1	50	100
micromotors	0.1	5	2	80
inclinometers	1	10	20	70
injection nozzles	10	10	30	30
anti-collision sensors	0.01	0.5	2	20
electronic noses	0.001	0.1	0.05	5

NEXUS (The Network of Excellence in Multifunctional Microsystems)
1998 Task Force Market Analysis MST report on microsystems technology

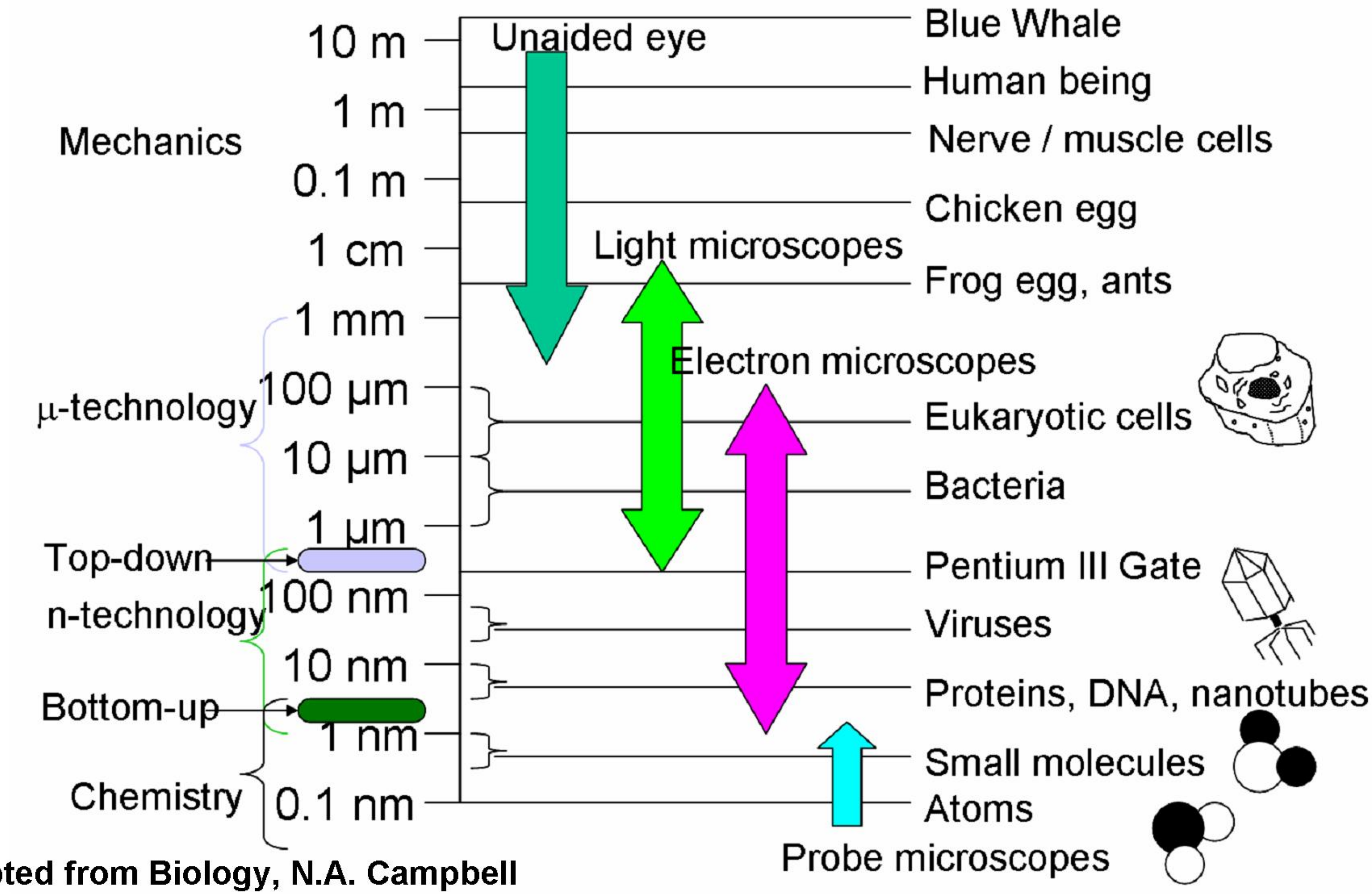


Semiconductor Equipment and Materials International (SEMI)

Standard Decimal Prefixes

Multiplier	Prefix	Abbreviation	Size examples (in meter)
10^{12}	tera	T	?
10^{9}	giga	G	Sun
10^{6}	mega	M	Earth
10^{3}	kilo	k	
			Animals
10^{-1}	deci	d	
10^{-2}	centi	c	Ant
10^{-3}	milli	m	frog egg
			paramecium
			eukaryotic cells
			bacteria
10^{-6}	micro	μ	CMOS
			nanotubes, proteins
10^{-9}	nano	n	molecules
10^{-12}	pico	p	?
10^{-15}	femto	f	
10^{-18}	atto	a	
10^{-21}	zepto	z	

What size are we talking about?



Adapted from Biology, N.A. Campbell