Module 6: Intelligent Devices based on Smart Materials

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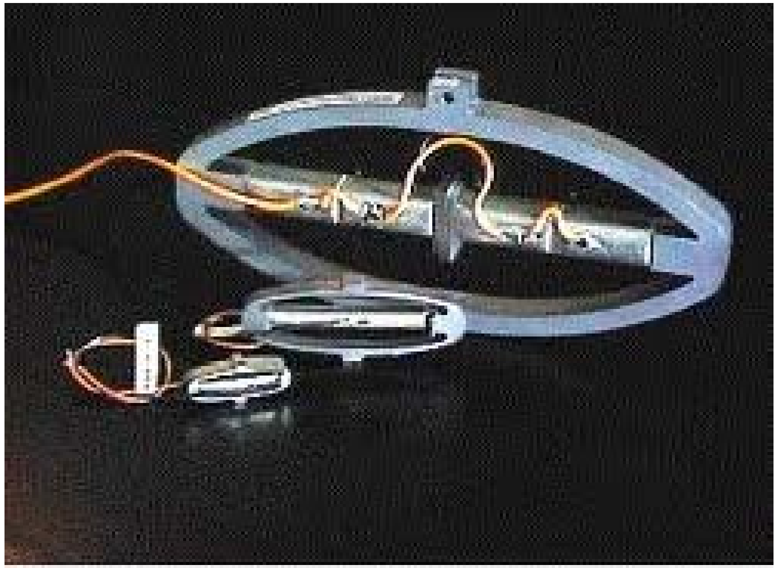

APA230L, APA150M, APA100S

Lecture 40: MEMS based Actuators

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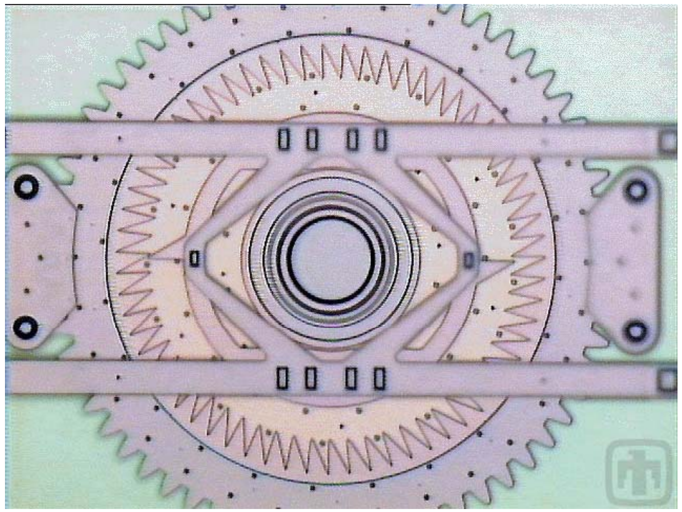


Topics Covered in the Last Lecture

- Piezoelectric Inchworm Devices
- Inchworm devices for Actuation
- Rainbow and Thunder Actuation
- Active Elasto-dynamic Motion

This lecture will cover

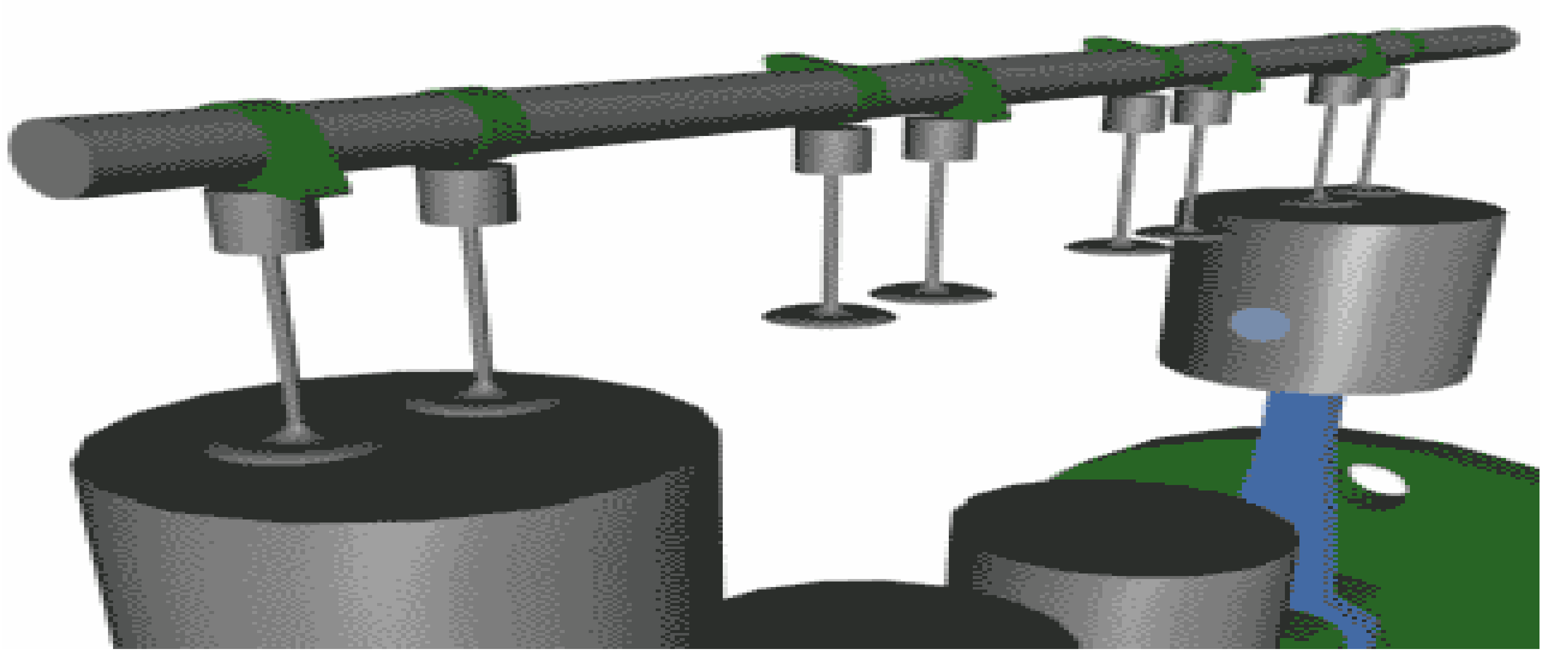
- A Case history of Sensor Application
- Introduction to MEMS Devices
- MEMS based Accelerometers
- How to develop MEMS?

A case history: Automobile

- Till 1960 Radio was the only electronics system – Engine systems were controlled mechanically

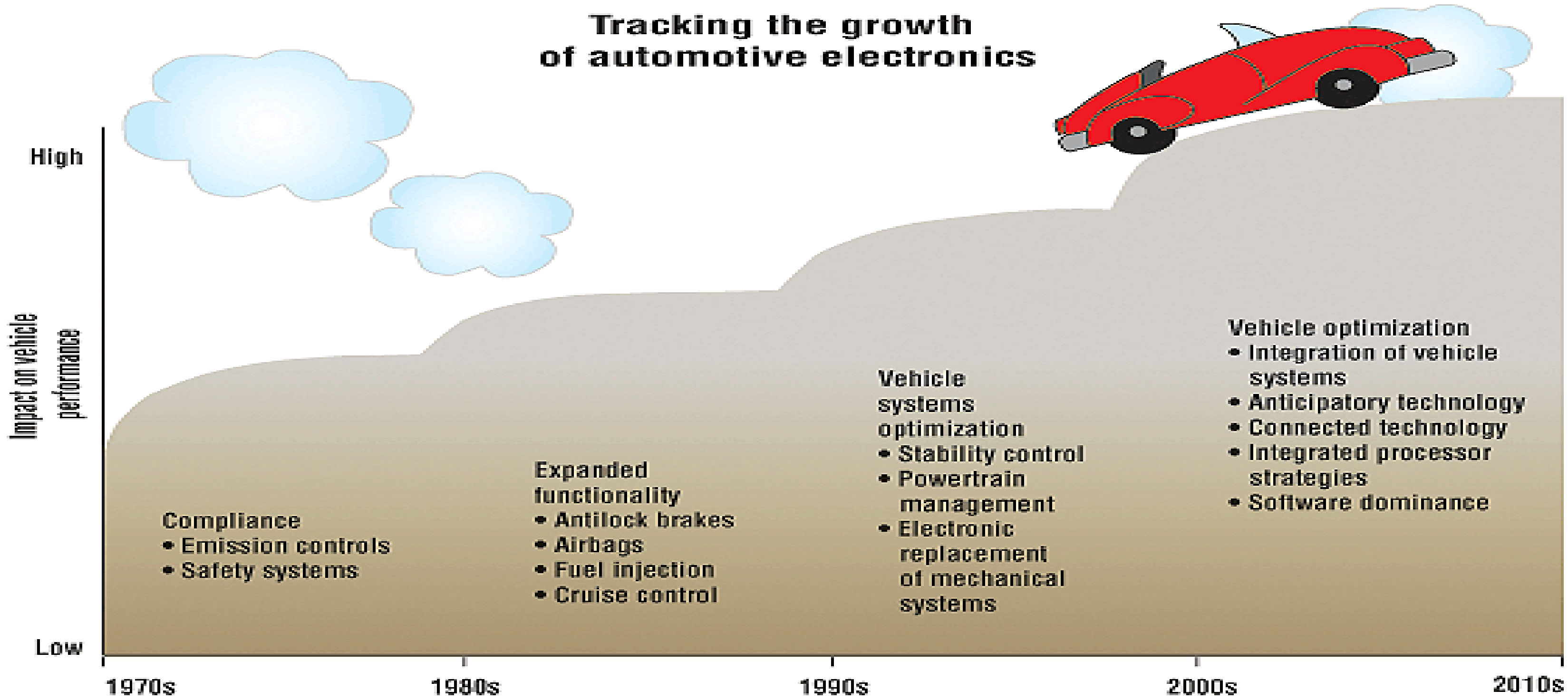
A case history: Automobile

- conventional mechanically actuated ignition and fuel systems weren't precise enough to control exhaust emissions
- 1960-70: Electronic ignition system was introduced requiring
  - **Crankshaft position sensor**
  - **Camshaft position sensor**
  - **Airflow rate sensor**
  - **Gas sensor at the exhaust**
  - **Throttle position sensor**
  - **Microcontroller to control ignition**
  - http://auto.howstuffworks.com/engine3.htm



Automobile

- Late 1970: ABS (Antilock Brake Device)
  - Sense locking of wheels and modulate hydraulic pressure to minimize sliding
- Mid 1990: TCS(Traction Control System)
  - Sense slippage during acceleration and modulate power to prevent slipping
- More advances like VDS (Vehicle Dynamics Control), Millimeter wave Radar Technology with GPS based traffic updating etc.



Tracking the growth
of automotive electronics
High
Low
Impact on vehicle performance
Compliance
• Emission controls
• Safety systems
Expanded functionality
• Antilock brakes
• Airbags
• Fuel injection
• Cruise control
Vehicle systems optimization
• Stability control
• Powertrain management
• Electronic replacement of mechanical systems
Vehicle optimization
• Integration of vehicle systems
• Anticipatory technology
• Connected technology
• Integrated processor strategies
• Software dominance
1970s
1980s
1990s
2000s
2010s

Sensors & Actuators

- Sensors – Exposure to a specific Physical/Chemical/Biological Phenomenon would produce a significant output signal (electrical/mechanical/optical/acoustic etc.)
- Actuators – Accept a Control Command (mostly in the form of an electric signal) and produce a change in the physical system by generating force, motion, heat, flow etc.

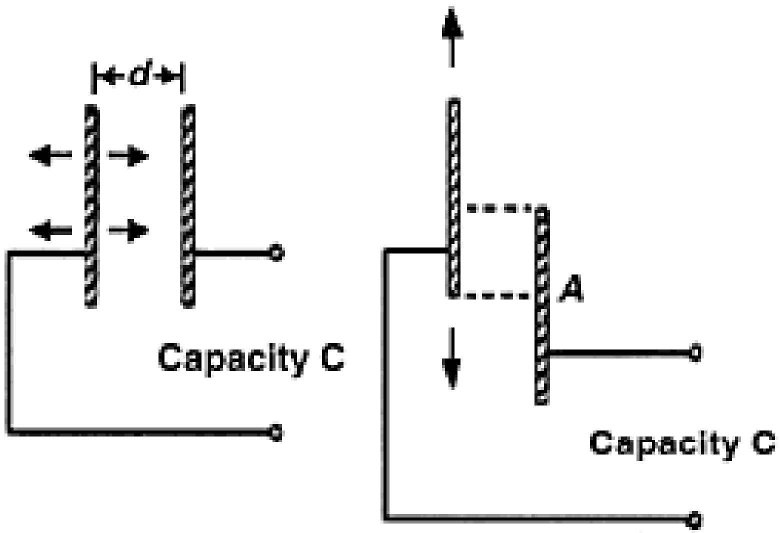
Why MEMS based Systems?

- MEMS as the name suggests refers to micro-scaled electro-mechanical systems.
- The advantage of MEMS systems over macro systems are:
  - low power consumption,
  - high sensitivity, easy to integrate/communicate
  - low noise, high machine precision
  - decreased cost (due to removal of manual assembly and substitution by batch fabrication)

Earliest MEMS products: MEMS Accelerometer & ..

- Accelerometers based on Capacitive Sensing, Piezoresistivity, Piezoelectricity, Optical Interferometry, thermal expansion
- First micro-machined accelerometers are developed at Stanford in 1979!
- Gyroscopes like Inertial Measurement Units (IMUs)
- Digital Micro Mirrors (DMMs)

MEMS Accelerometers: Fact Sheet



$$C = \varepsilon_0 \varepsilon_r A / d$$

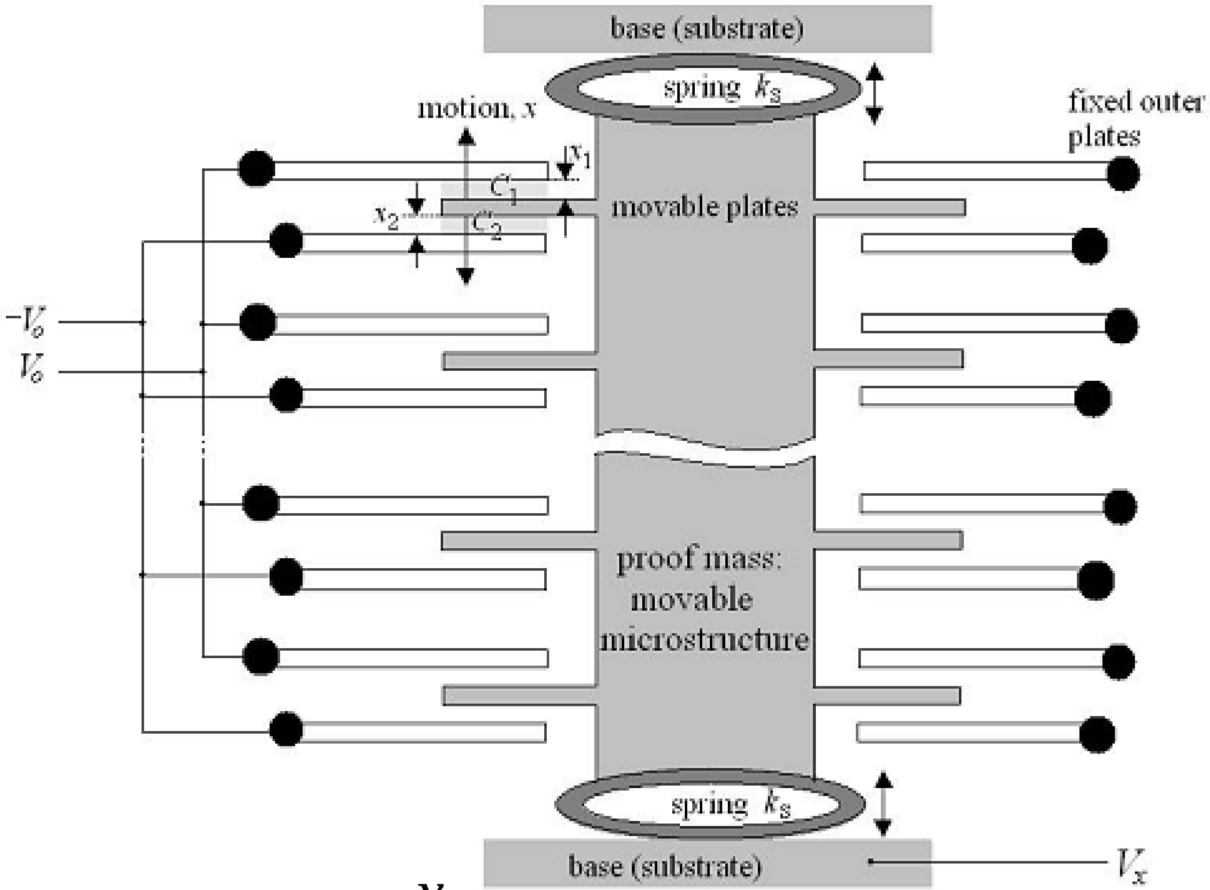
Consider two parallel steel plates with a gap between them. When a voltage is applied to one of the plates, the difference between the charges stored on the surfaces of the plates will cause an electric field to exist between them.

- ε_0 = absolute permittivity of free space (8.85×10^{-12})
- ε_r = relative permittivity (dielectric constant) of medium in gap between plates
- A = plate common surface area
- d = plate separation (displacement)

- There are three ways to change the capacitance of the parallel-plate system:

  – Variation of the distance between the plates (d)
  – Variation of the shared area of the plates (A)
  – Variation of the dielectric constant (r)

MEMS Accelerometers: based on capacitance Change

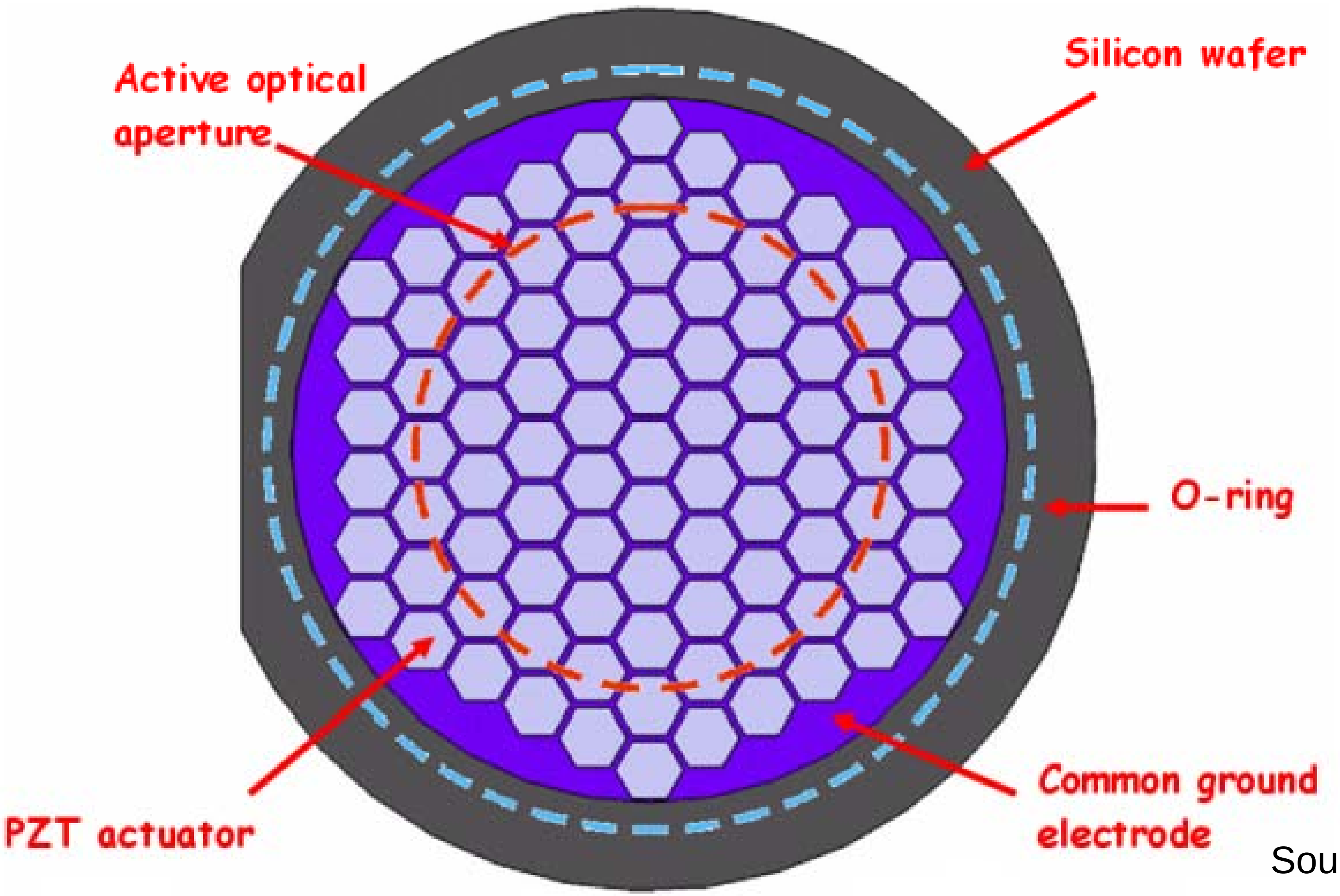


$$C_2 - C_1 = 2\Delta C = 2\varepsilon \frac{x}{d^2 - x_2}$$

Ref: Matej Andrejašič

University of Ljubljana
Faculty for mathematics and physics
Department of physics

Vibration & Shape Control of Optical Mirror



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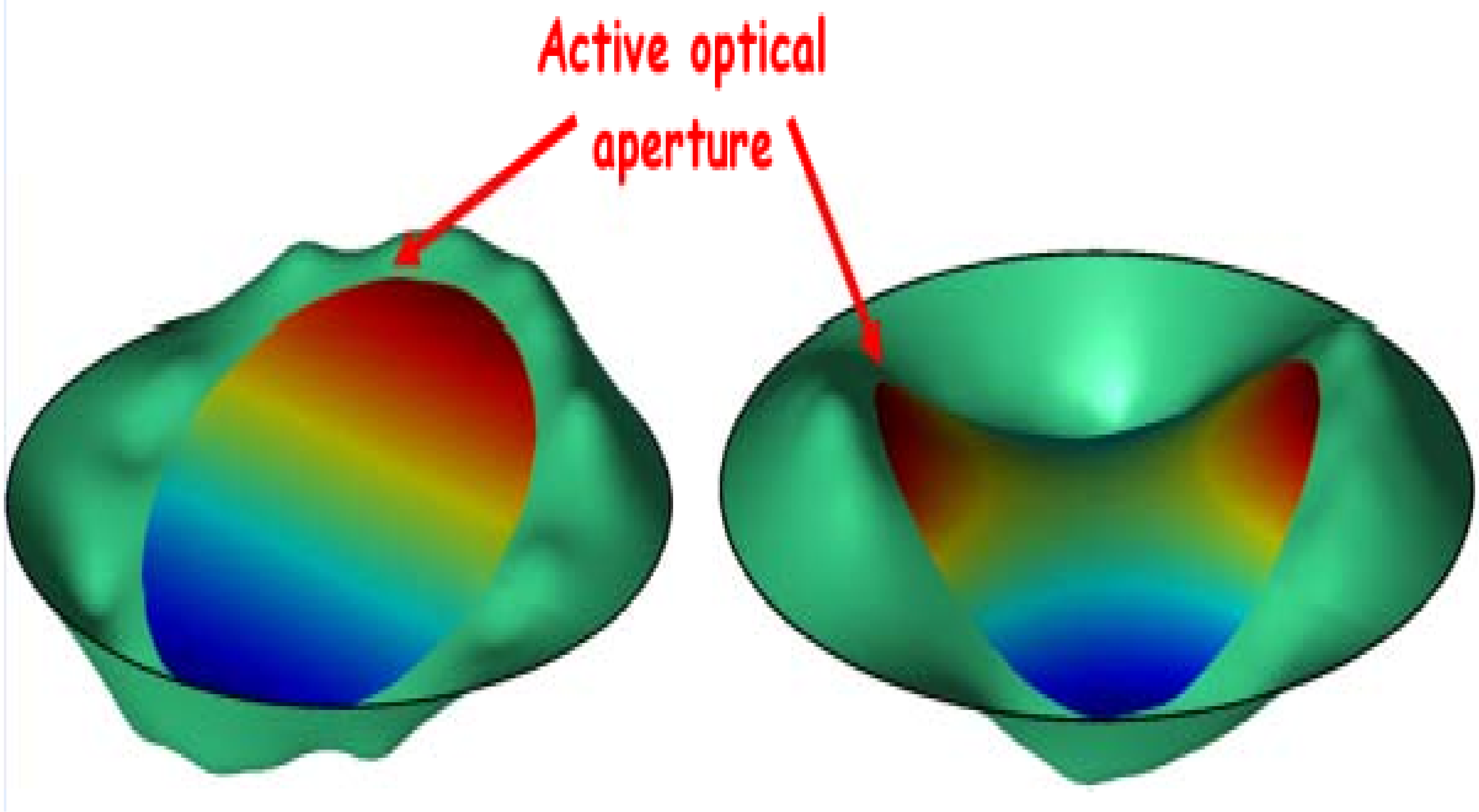
Active Control of Optical Aperture



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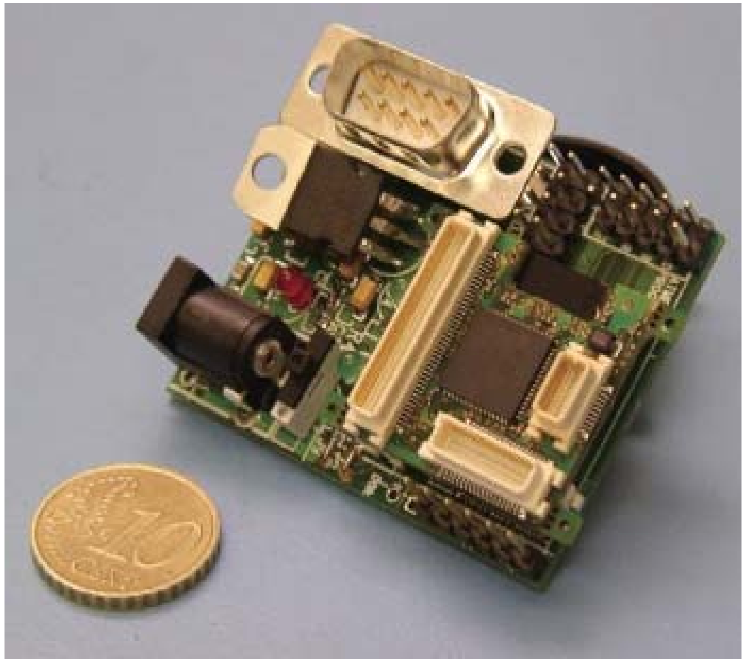
MEMS based Actuators

- MEMS as the name suggests refers to micro-scaled electro-mechanical systems.
- Automotive Sector Applications:
  - Airbag System
  - Automatic Door Locking
  - Active Suspension
- Consumer Sector Applications:
  - Computer Peripheral Devices
  - Subwoofers
  - Sports Training Devices

Applications of MEMS

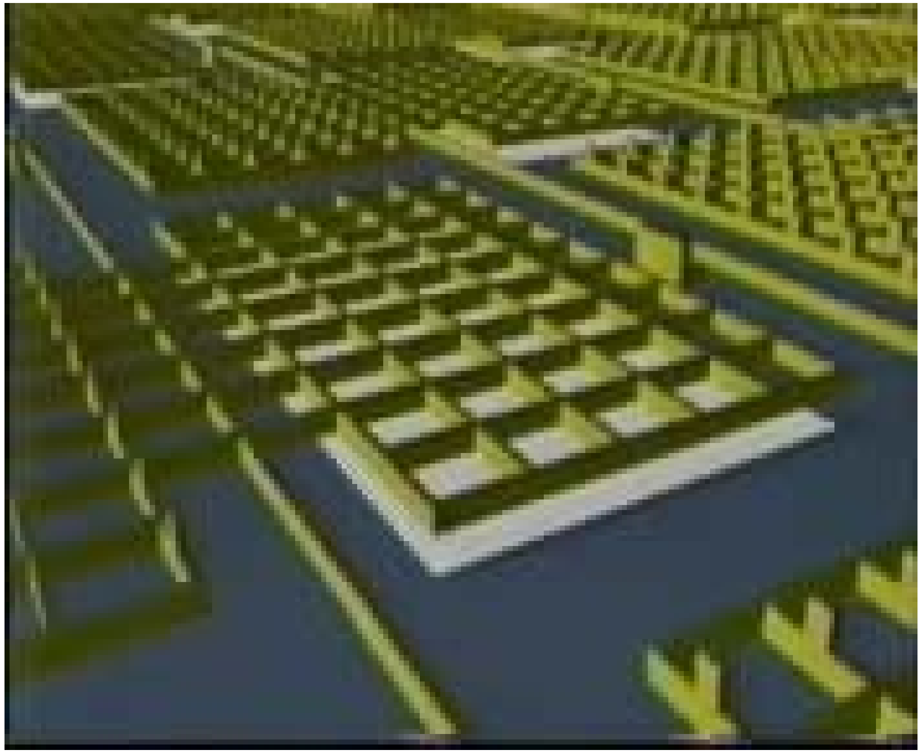
- There are many other applications of MEMS:
- General Industrial Applications:
  - Condition and Health Monitoring Devices
  - Earthquake Detection
  - Shock and Tilt Detection
- Military Applications
  - Explosive Detection
  - High precision Accelerometers
  - Navigation System

Intelligent Mote for Exercise Control



The ‘mote’ has embedded piezoelectric sensors which sense the level of stresses applied on the limb during exercise.
It is connected via a microprocessor to a visual warning system that indicates over-exercise. Not only that, there are continuous health monitoring and compliance control system which can control the grip of the cast around the limb.

MEMS in motion?



Acknowledgement: Donald Lab at Duke University

Application of AC between the electrode and silicon develops electrostatic force and create oscillation.

MEMS Development

There are broadly three issues related to MEMS development. These are

(a) System Level Development including signal processing, networking, packaging, design and simulation

(b) Micro-engineering including Layering, Micromechanics, Micro-electronics, Photonics and Micro-molding

(c) Materials and effects including smart materials

Foundation Materials for MEMS

- **Inorganic**
  - Silicon, Silica, Quartz, Glass
  - Gallium Arsenide
  - Ploydimethylsiloxane (PDMS)
- **Metallic**
  - Gold
  - Aluminum
  - Platinum and Palladium
- **Organic**
  - Polymides, PMMA

Why Silicon as the first choice?

- Excellent Mechanical Property. Three times Young's Modulus of Steel bout 700 GPa, but as light as Aluminium 2500 Kg/m^3

- It is mechanically stable and can be easily developed by using micro-fabrication

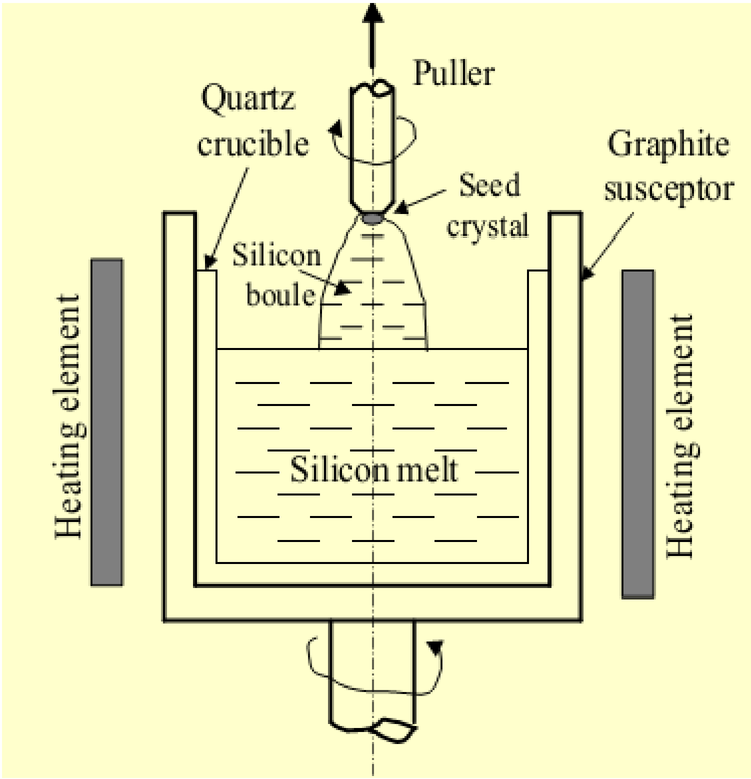
  technology.
- For signal transductions, 'p' or 'n' type semiconductors can be readily integrated with the Si subsrtate.

Silicon as the best choice

- Melting point around 1400 degree centigrade – makes it thermally stable
- Very low thermal expansion coefficient – 10 times smaller than Aluminium
- No mechanical hysteresis
- Very Flat for coating

Single Crystal Silicon

- **Czocharlski** Method – Raw Silica (Quatzite) is molten in a chamber. The crystal formation process is initiated with a seed crystal which is gradually pulled to get the complete bigger crystal.



Crystal Structure

- Silicon Crystal Structure is basically FCC in nature.
- An FCC structure has 8+6=14 atoms
- However, Si has four extra atoms inside, making it of18 atoms and partly anisotropic in nature. The weakest being the 100 plane and the strongest the 111 plane.

Property Sets

	σ_y (10^9 N/m^2)	E (10^{11} N/m^2)	ρ (g/cm^3)	C (J/g-^{o}C)	k (W/cm-^{o}C)	α ($10^{-6}/^o$C)	T_M (^{o}C)
Si	7.00	1.90	2.30	0.70	1.57	2.33	1400
SiC	21.00	7.00	3.20	0.67	3.50	3.30	2300
Si_3N_4	14.00	3.85	3.10	0.69	0.19	0.80	1930
SiO_2	8.40	0.73	2.27	1.00	0.014	0.50	1700
Aluminum	0.17	0.70	2.70	0.942	2.36	25	660
Stainless Steel	2.10	2.00	7.90	0.47	0.329	17.30	1500
Copper	0.07	0.11	8.9	0.386	3.93	16.56	1080
GaAs	2.70	0.75	5.30	0.35	0.50	6.86	1238
Ge		1.03	5.32	0.31	0.60	5.80	937
Quartz	0.5-0.7	0.76-0.97	2.66	0.82-1.20	0.067-0.12	7.10	1710

Three common techniques used for MEMS fabrications

- Bulk Micromachining – removal of materials from Bulk substrates – either by isotropic or anisotropic wet etching
- Dry etching – by corrosive gases
- Wafer bonding - using precisely aligned wafers
- Surface micromachining by thin film fabrication

Special reference for this lecture

- Micro-mechatronics by Uchino & Giniewicz, Marcel, Dekker
- Microsensors MEMS and Smart Devices, Gardener, Varadan and Awadelkarim
- Donald Lab at Duke University
- Fundamentals of Microfabrication, Marc Madou, CRC Press, 2007.

Thank you