

Introduction to Microelectromechanical Systems (MEMS) Materials, Fabrication Processes and Failure Analysis

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Purpose

- Familiarize everyone with different materials and fabrication technologies for **Microelectromechanical Systems (MEMS)**
- Provide examples of **MEMS** materials and fabrication technologies
 - Discuss different actuation mechanisms
 - Electrostatic
 - Electrothermal
- Present applications associated with each fabrication technology
- Discuss **MEMS** failure analysis

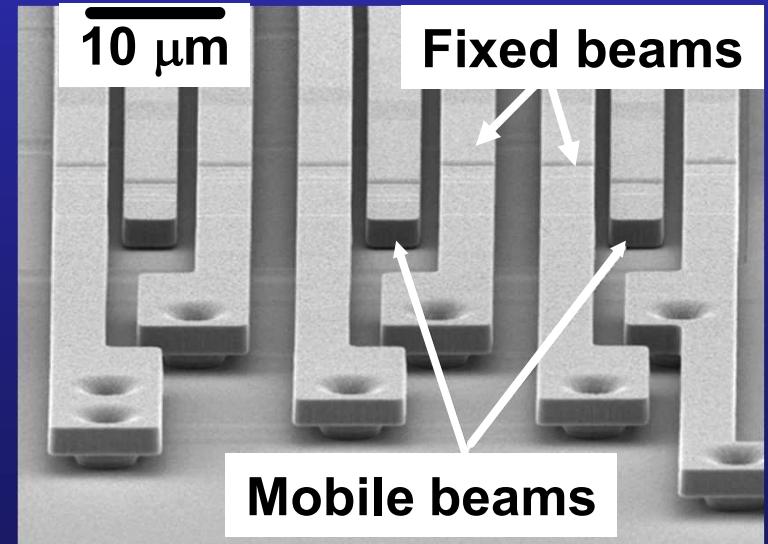
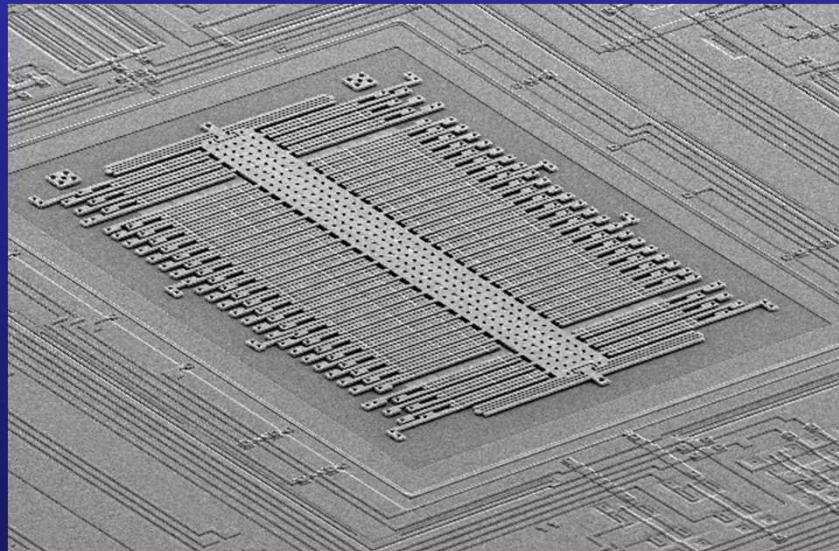
Outline

- **What are MEMS?**
- **Motivation for using MEMS**
- **MEMS materials**
 - Discuss materials and fabrication processes
 - Applications associated with each material and fabrication technology
 - Pros and cons
- **MEMS failure analysis**
- **Actuation mechanisms**
- **Conclusions**

What are MEMS?

- **Microscopic devices used to sense, transport, direct, or produce a change in an environment**
 - An external mechanical, electrical, or chemical stimulus can be detected and measured then produce a response to the stimulus

ADXL accelerometer



ADXL accelerometer images courtesy of Analog Devices

Motivation for using MEMS

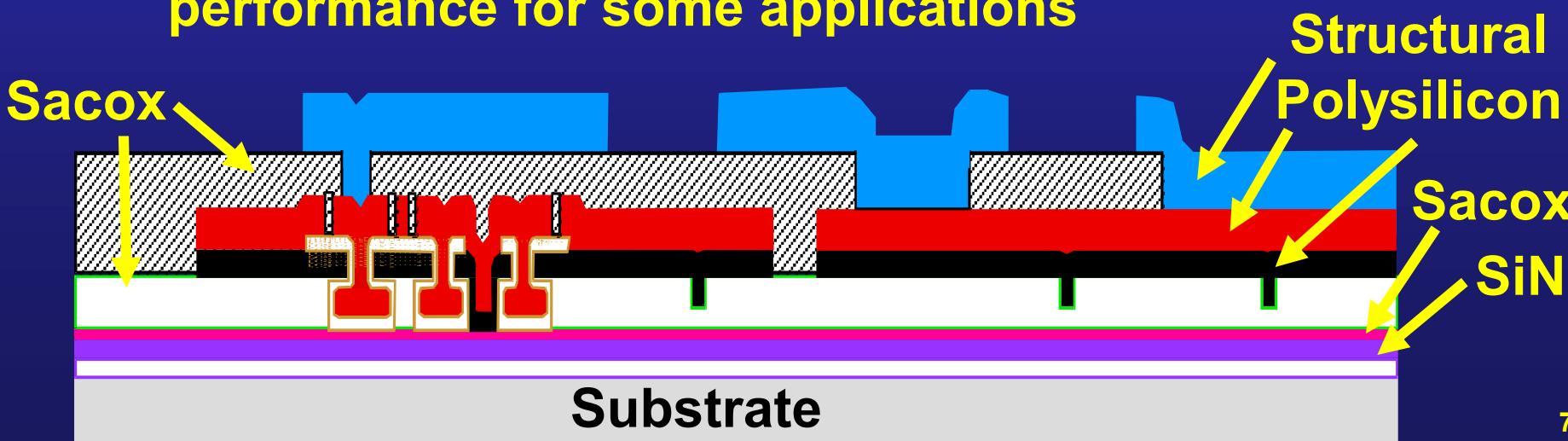
- Take advantage of batch fabrication processes
 - Reduced manufacturing costs
- Small, light weight
 - Consume less power
 - Replace larger, more expensive components
- Performance
 - Comparable or improved performance over bulk counterparts
 - Implement redundancy
 - Multiple components can be fabricated or assembled in arrays to improve system performance and functionality

MEMS materials

- Some materials systems used to fabricate MEMS include:
 - Polysilicon surface micromachining
 - Bulk silicon micromachining
 - Metal surface micromachining
 - GaAs processes - Polyimide/SiON
 - LIGA
 - Silicon carbide
 - Diamond and diamond-like carbon
 - Polymers

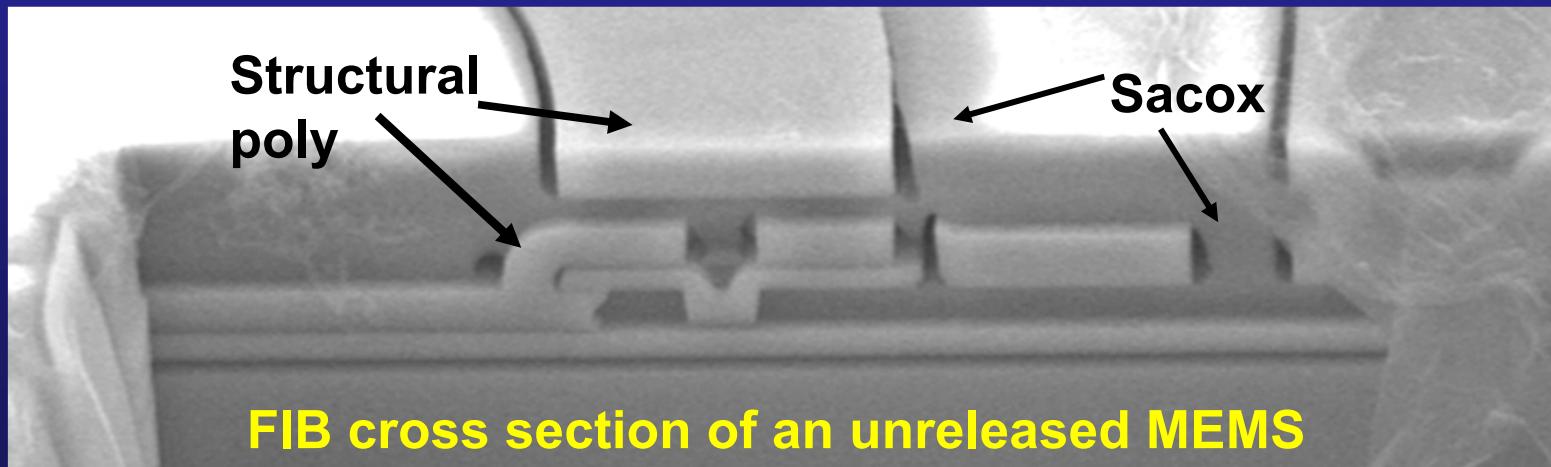
Polysilicon surface micromachining

- Polysilicon (poly) is used to as the structural material to fabricate moving components
 - Structural material is encased in sacrificial silicon oxide (sacox)
- Multiple layers are deposited and etched to fabricate 3-dimensional structures
 - Metal deposited on top layers may improve device performance for some applications



Examples: polysilicon surface micromachining

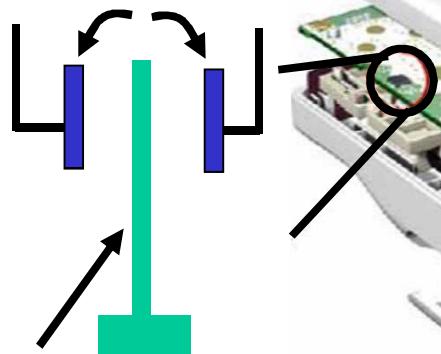
- Deposition of oxide, SiN, poly, and sacrificial oxide
 - SiO_2 and SiN insulate structural material from the substrate
- High temp. anneals needed to relieve stress in poly
 - Internal stress is reduced to prevent thin film warping
- Sacrificial oxide is removed using super critical CO_2 drying to prevent a liquid/vapor interface
- Released structural poly is free to move
 - Metal can be deposited on the top poly level



Polysilicon micromachined devices in consumer electronics

Wii hand-held controller

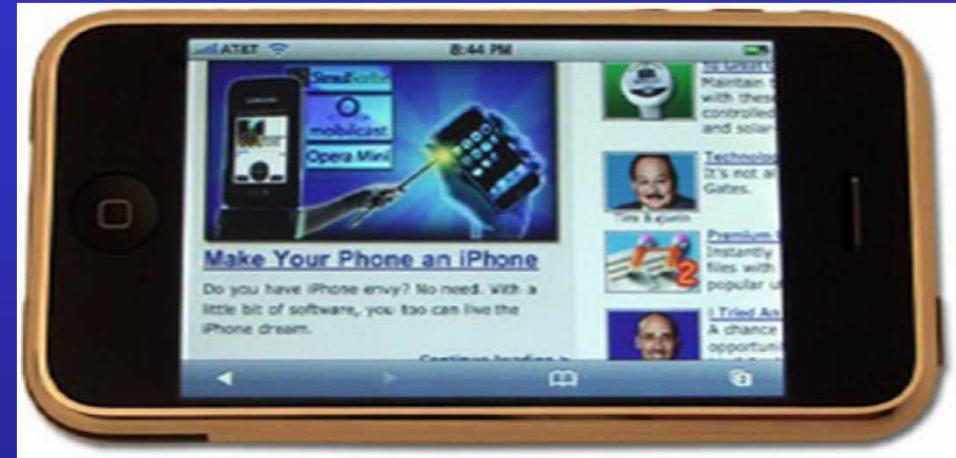
Acceleration



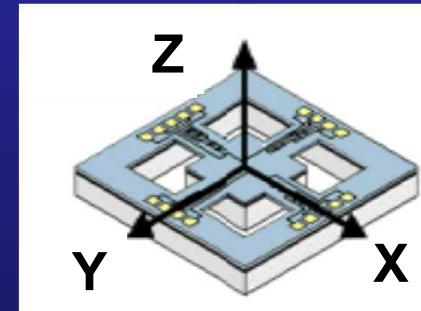
Polysilicon
MEMS beam

- Anchored silicon evenly spaced in an electric field between 2 capacitor plates
 - Si beam bends with acceleration
- Acceleration changes the electric field which translates into motion on the screen

*iPhone and iPod Touch products



Tri-axial accelerometer

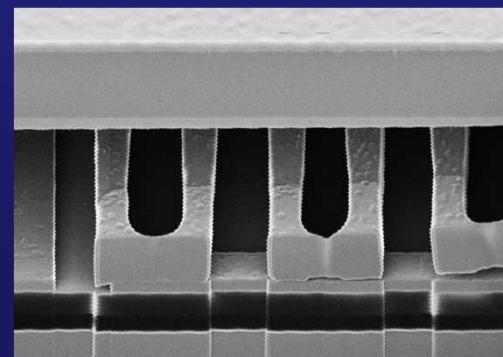
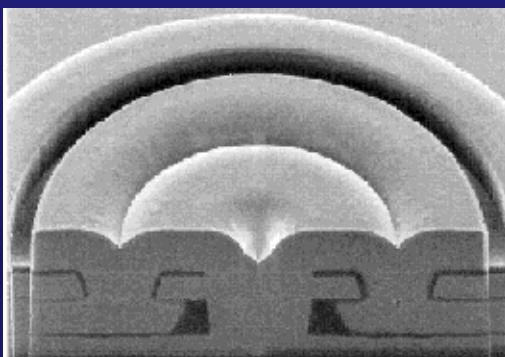


*over 15 different MEMS devices used

Polysilicon micromachining: pros and cons

- Pros
 - Fabrication equipment & infrastructure is readily available
 - Use same tools and wafers used in the IC industry
 - IC compatible process
 - Fabricate MEMS & ICs on same chip
- Cons
 - High temperature fabrication processes
 - Anneal temps can reach 1100°C
 - Release and dicing require care
 - Device release is done at wafer level then die are sawed and packaged

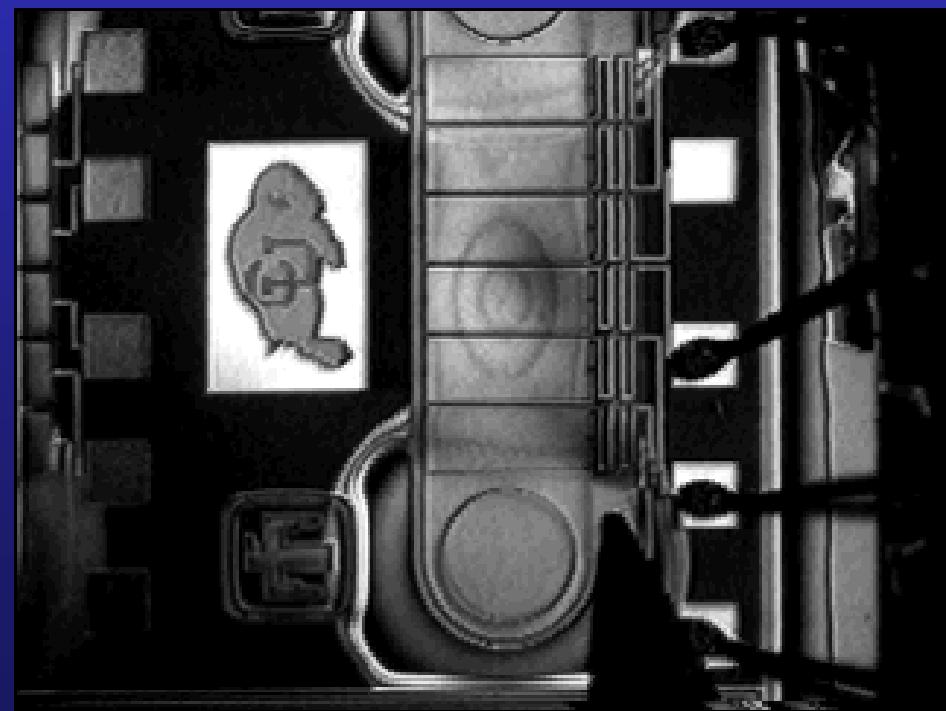
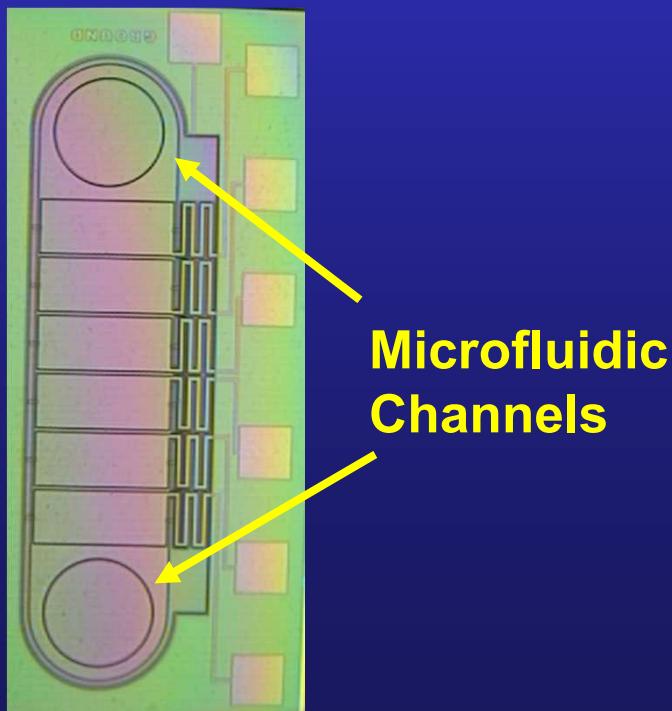
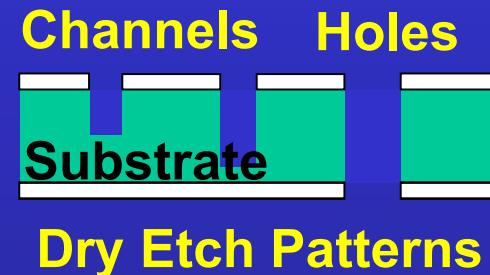
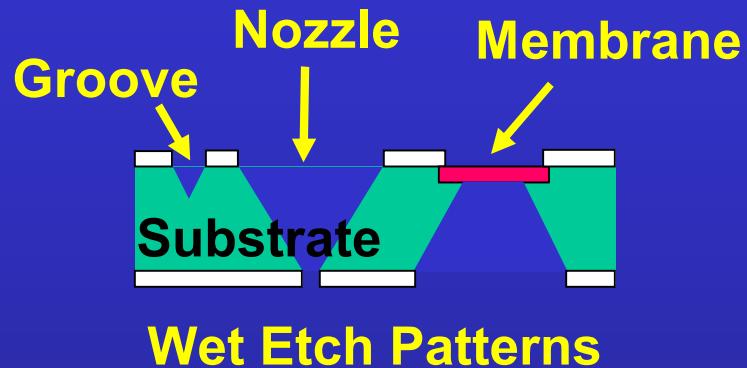
FIB cross-section of released devices



Bulk silicon micromachining

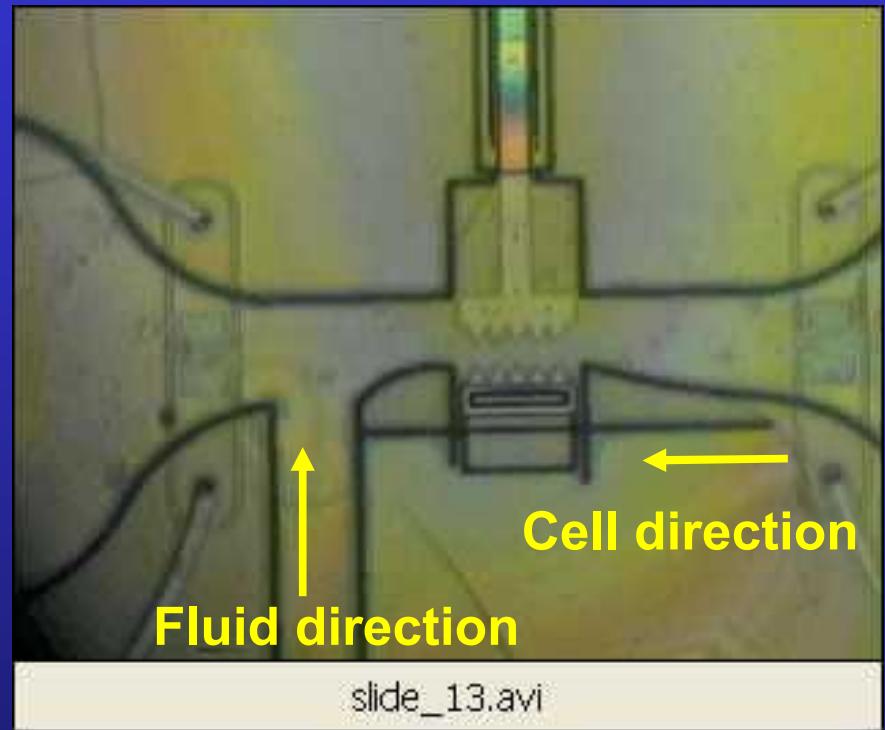
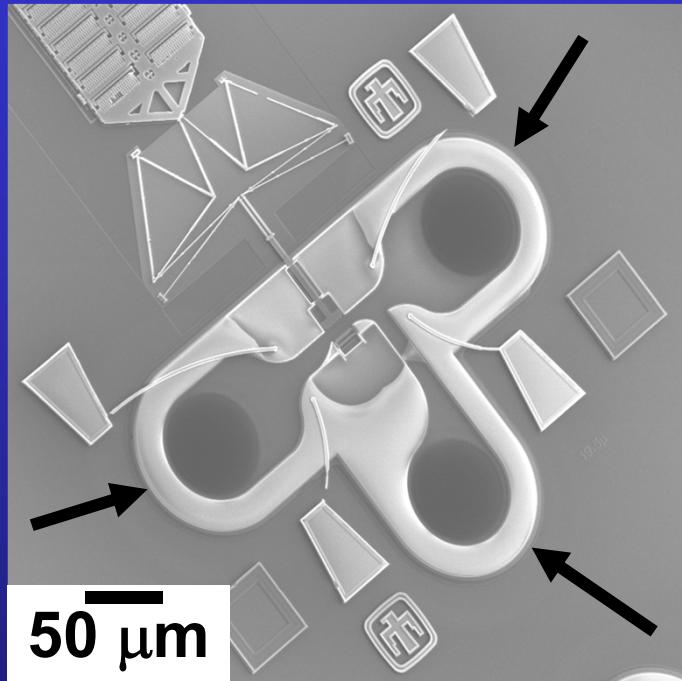
- Bulk silicon substrates are used as the structural material
 - Channels or holes fabricated in the substrate use wet or dry silicon etch processes
 - Wet etch process
 - Requires potassium hydroxide and etches along $<111>$ planes more quickly creating a hole or channel
 - Requires etch stops or timed etch to prevent overetch
 - Dry etch process
 - Deep Reactive Ion Etch (DRIE) or Bosch etch
 - Iterative polymer deposition and ion etch process
 - Higher selectivity creates higher aspect ratios (30:1 – 1000:1)

Example: bulk micromachining



Example: bulk micromachining

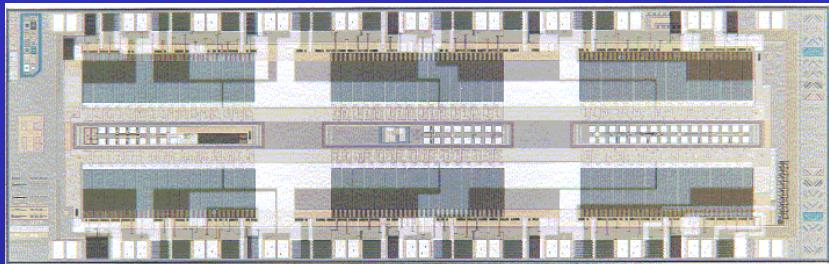
Micro biological cell manipulator



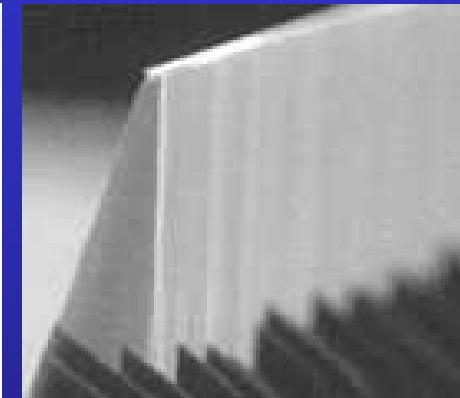
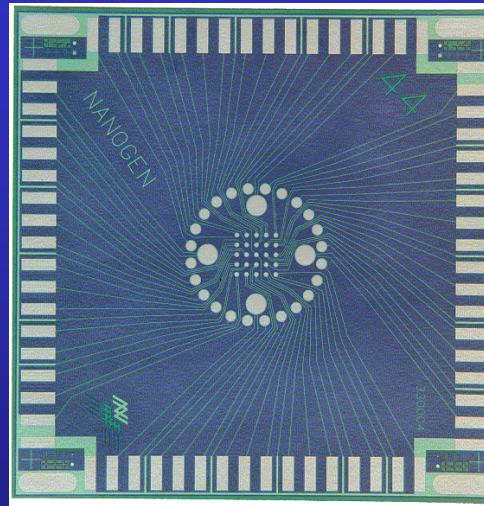
- **Bosch etch holes act as channels for fluid flow**
 - Each hole serves as a channel for medicinal interaction, insertion, and retrieval
 - Channels and holes allow for fluid flow and interaction of fluids and gases

Bulk micromachined devices in today's products

Ink Jet Print Head



DNA Chip & Silicon Blade



- **Bulk micromachined nozzle with integrated CMOS**
 - Ink is resistively flash heated and ejected through nozzles

- **Bulk micromachined DNA analysis on a chip**
- **Silicon etched blades for microsurgery**

Bulk silicon: pros and cons

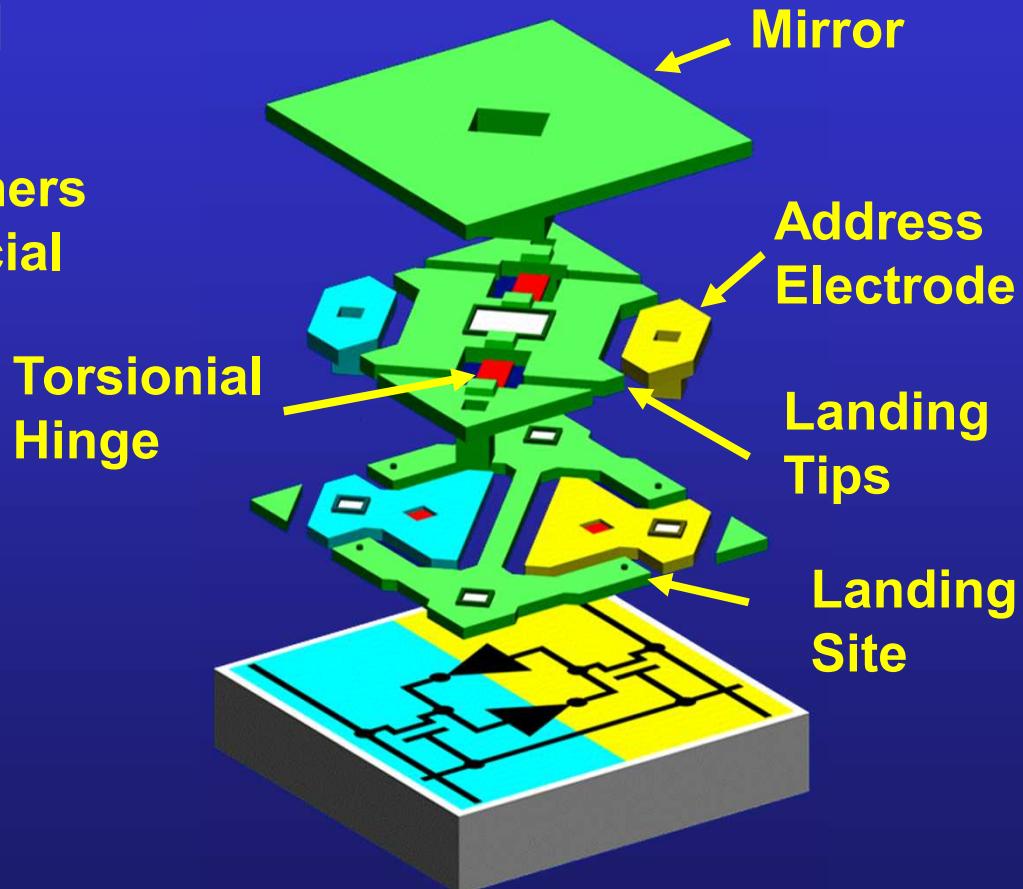
- Pros
 - Fabrication equipment and infrastructure is readily available
 - Use same tools and wafers developed for the IC industry
 - Bulk processes can be combined with surface micromachining
 - Fabricate moveable structures with channels and holes
 - IC compatible process
 - Fabricate MEMS & ICs on same chip
- Cons
 - Requires wet or dry etching through the substrate
 - Creates holes with limited placement accuracy
 - Wet etch leads to large holes on the backside of the substrate

Metal surface micromachining

- Metal (gold, aluminum) are used as the structural material to fabricate moving components
 - Structural material is encased in sacrificial material (photoresist)
 - Like IC fabrication, multiple layers of metal and sacrificial material are deposited and etched to fabricated 3-D structures
- Metal processes are also compatible with GaAs and RF applications
 - Metal MEMS technology is readily suited and compatible with MMIC processing and integration

Example: metal surface micromachining

- **Deposition of metals and sacrificial material**
 - Photoresist or other polymers can be used as the sacrificial material
- **Stress relief can be performed with low temperature thermal anneals**
 - Internal stress is reduced to prevent the mirror from warping

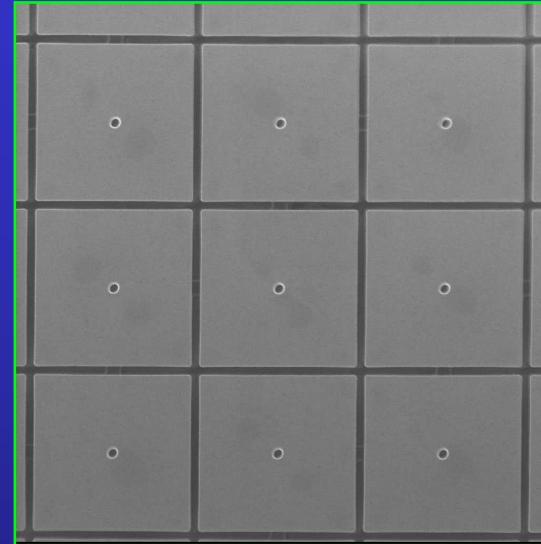


DMD structure, Image courtesy of TI

Example: metal surface micromachining



Image courtesy of Lucent Technologies

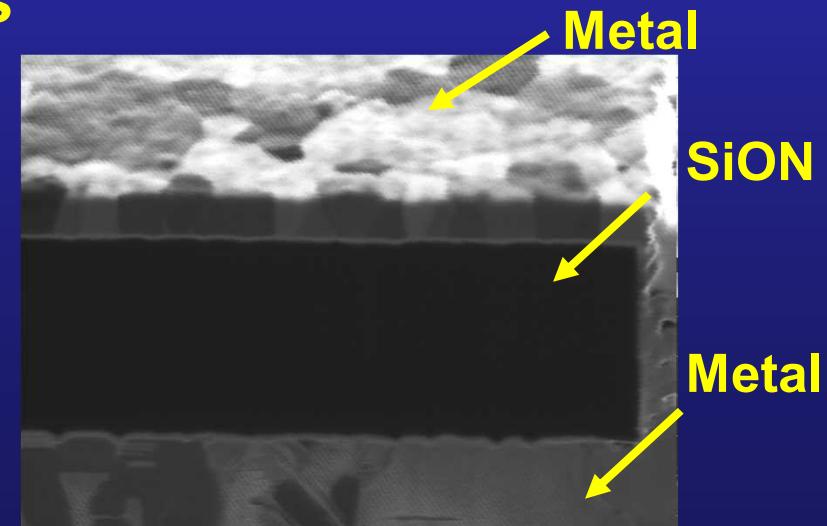
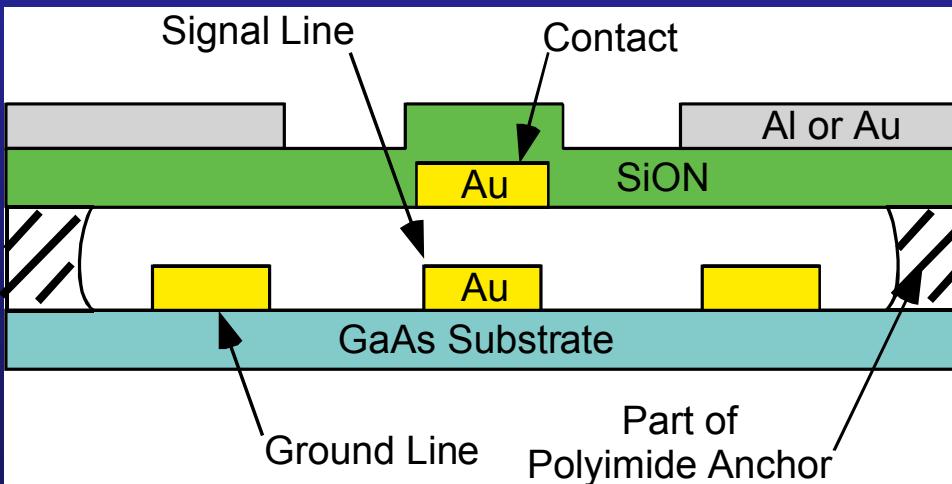


Images courtesy of TI

Thin metal layers are used to create the Lambda Router™ and Digital Micromirror Display (DMD™) optical switches

Example: metal surface micromachining

- RF MEMS can be realized using SiON, polyimide, gold and/or aluminum on GaAs or alumina substrates
- Polyimide acts as the sacrificial material
- SiON is the structural material with either gold or aluminum deposited to form an electrode
- RIE etches are used to remove the polyimide and free up the metallized SiON structures



Gold and SiON used as the structural material for GaAs MEMS

Metal: pros and cons

- Pros
 - Fabrication equipment and infrastructure is readily available
 - Materials are readily compatible with IC materials
 - Fabricate MEMS & ICs on same chip
 - Metal MEMS are typically low temp. processes
- Cons
 - Thin film stress management
 - Reduced stress is needed to prevent thin film warping
 - Metal components are more susceptible to fatigue and creep than polysilicon

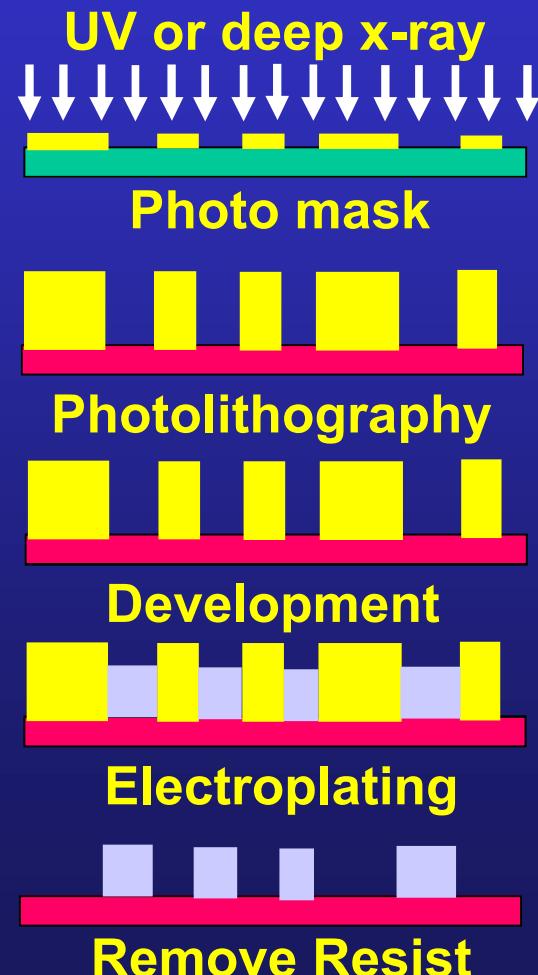
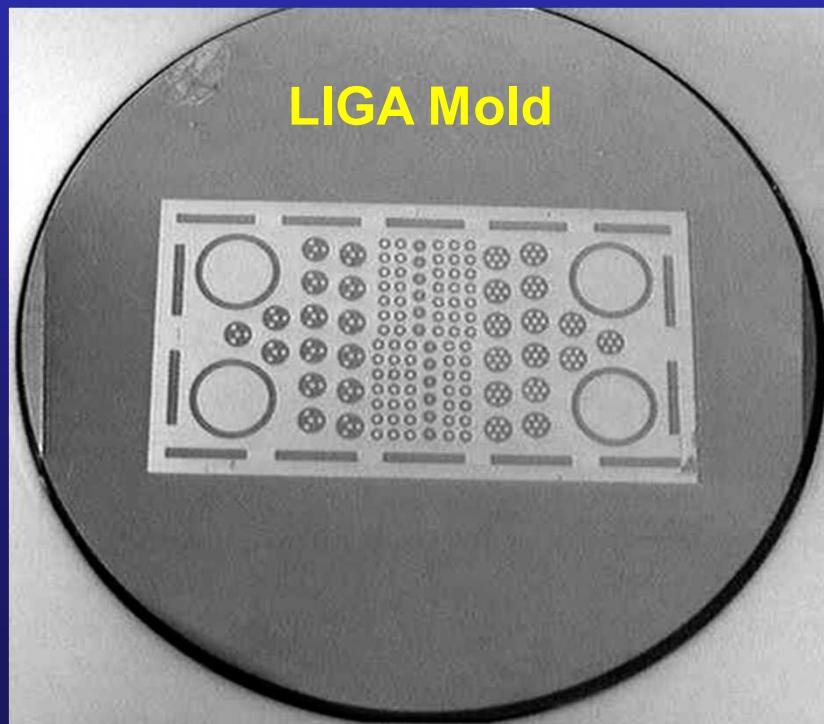
LIGA micromachining

- *Lithographie Galvanoformung Abformung*
 - Lithography, electroplating and molding process used to fabricate small metal parts
 - Typical LIGA materials include gold, nickel, copper, iron, nickel iron, permalloy, etc.
- **LIGA Process**
 - Uses lithographic techniques (deep X-ray or UV), microelectroforming and micromolding
 - X-ray or UV reacts through a mask with a sensitive photoresist (PMMA)
 - Exposed material is washed away
 - The mold is connected to a substrate where metal is electrodeposited into the mold
 - The existing mold and substrate are removed or dissolved while the LIGA components remain

Example: LIGA process overview

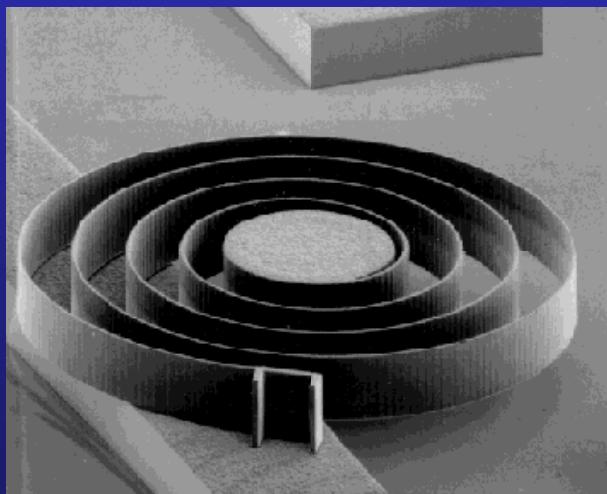
- **LIGA fabrication process**

- Lithography defining the PMMA mold
- Metal deposition
- Removal of the mold



Example: LIGA process

- Electrodeposited material is released from the PMMA mold and used to fabricate LIGA components
 - LIGA process can be used to fabricate metal based springs, actuators and other mechanical structures

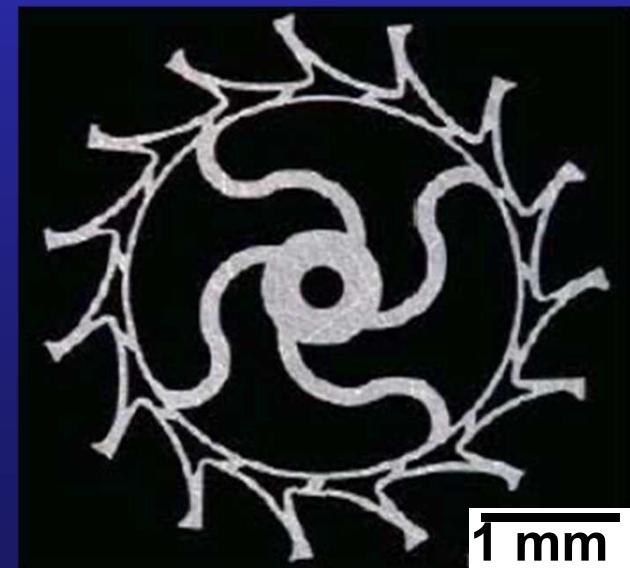


Gold and gold nickel deposited into a PMMA mold are used to fabricate a spring and mechanical actuator

LIGA components used in today's mechanical movement watches



Tourbillon – designed to reduce eliminate the effect of gravity



Escape wheel used to reduce inertia
Manufactured using LIGA process

LIGA: pros and cons

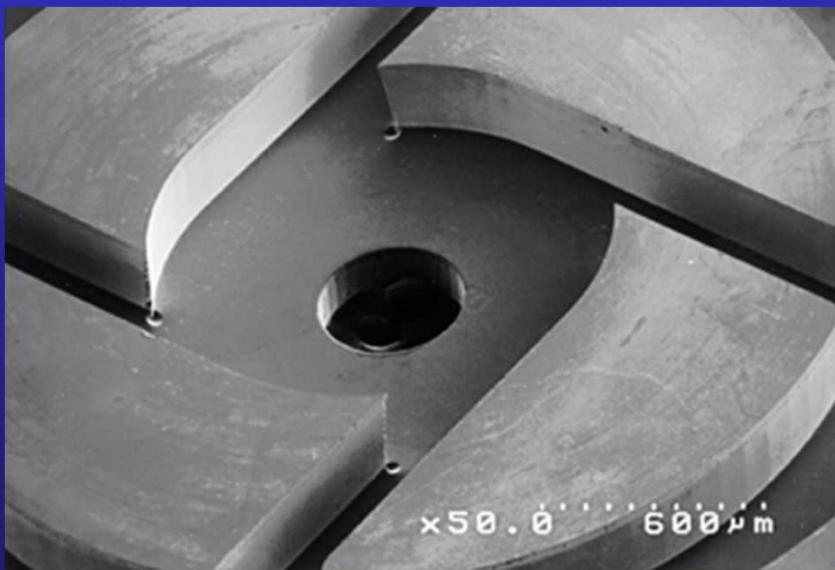
- Pros
 - UV-LIGA uses standard microelectronic fabrication process equipment
 - Can fabricate devices with high aspect ratios
 - 1 - 10 μm wide by 2 – 4 mm thick
 - LIGA electroplating uses less current than bulk electroplating
 - Can fabricate many LIGA parts on a single wafer
- Cons
 - Deep x-ray method requires a synchrotron source
 - Non-standard and limited availability
 - Assembly is required
 - LIGA components must be assembled for operation

Silicon carbide micromachining

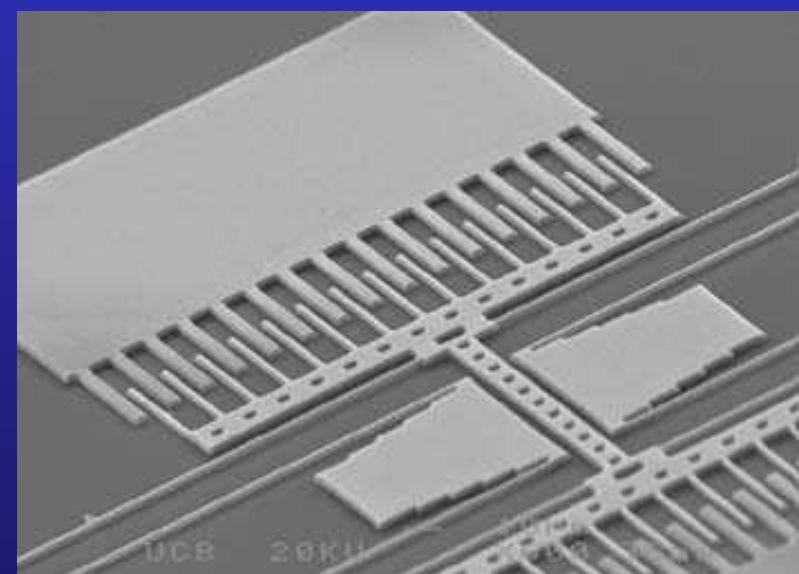
- **MEMS fabrication using SiC as structural material is under development**
 - Many structures are fabricated and tested at the research level
 - SiC offers better tribological properties than Si
- **SiC MEMS can be processed on SiO₂ or Si substrates using chemical vapor deposition (CVD)**
 - Substrates and sacrificial materials are etched away
- **SiC fabrication processes**
 - SiC can be deposited using a liquid 1,3 – disilabutane precursor at 800 – 1000°C with a vapor pressure of ~ 20 mTorr
 - Deposition of SiC at 10^{-4} – 10^{-5} Torr
 - SiC can be deposited in a polysilicon mold
- **SiC thin film can be deposited on a polysilicon device**
 - Improves wear and chemical resistance

Example: SiC micromachining

- CVD deposition of SiC MEMS components
 - SiC coated polysilicon MEMS atomizer
 - Used for highly corrosive fuel applications
 - SiC fabricated electrostatically driven resonator



**Swirl chamber and exit orifice
of a fuel atomizer**



SiC based MEMS resonator
Photo courtesy of UC Berkeley

SiC micromachining : pros and cons

- Pros
 - SiC offers better chemical, electrical, and mechanical properties over poly
 - Can be used in harsh environments
 - High temperatures
 - Corrosive fluids
- Cons
 - Deposition process is difficult and expensive
 - Harsh chemicals used in manufacturing
 - 1,3 - disilabutane, SiH₄, acetylene, etc.
 - SiC film properties depend on substrate
 - Requires expensive gas handling and distribution systems
 - Difficult to integrate into IC technology

Diamond and diamond-like carbon

- Good chemical, electrical, and mechanical properties for MEMS
 - Excellent wear resistance and low stiction
 - Can use conventional wet chemical processes with no concern over stiction induced failure
- Diamond processes are performed using CVD based techniques
- Diamond fabricated MEMS can made in
 - Polycrystalline
 - Nanocrystalline
 - Amorphous

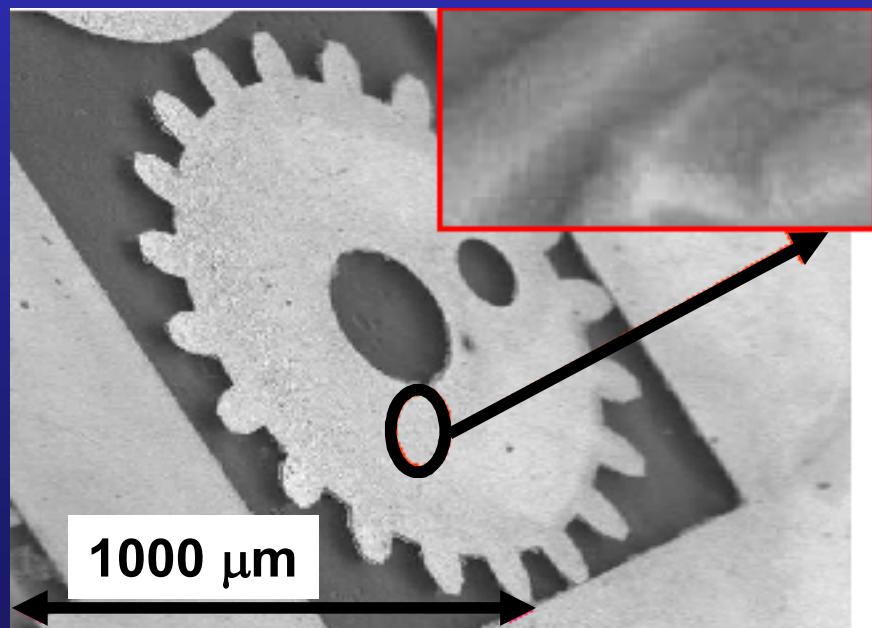
Example: diamond micromachining

- **Nano and polycrystalline diamond fabricated by:**
 - Hot flame CVD for polycrystalline films (grains $\sim 1 \mu\text{m}$)
 - Microwave plasma enhanced CVD for nanocrystalline films (grains $\sim 3 - 5 \text{ nm}$)
 - Multiple thermal anneals are required on each layer of diamond to relieve thin film stresses
- **Amorphous diamond (or diamond like carbon) is fabricated at room temperature**
 - Pure carbon beam with is energized around 100 eV
 - 600°C anneal is used for stress relief
 - SiO_2 is used as sacrificial material between layers
 - Timed wet etches (HF) are used to release the MEMS structure

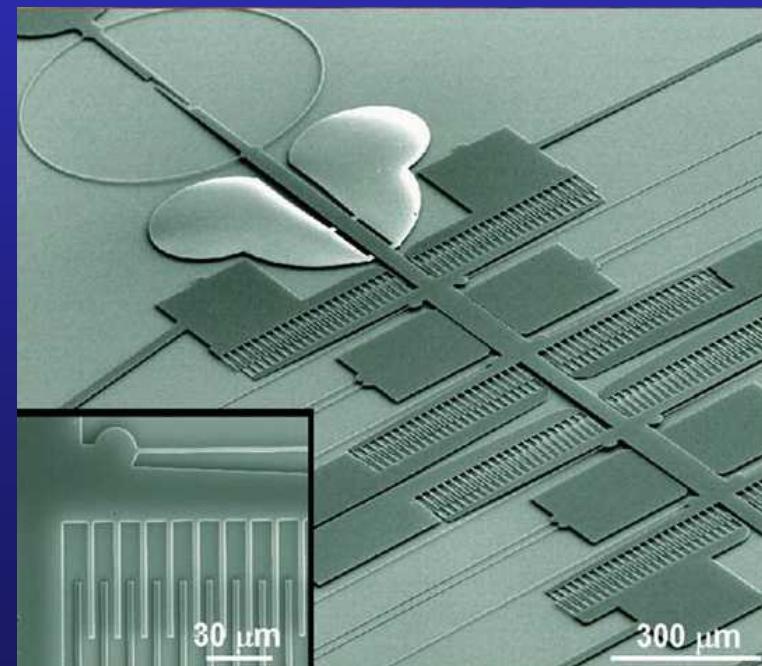
Example: diamond micromachining

- Nanocrystalline and amorphous diamond are deposited and patterned to form mechanical structures

Diamond gear fabricated on a silicon substrate



Free standing amorphous diamond MEMS



Diamond and DLC micromachining : pros and cons

- Pros
 - Excellent tribological properties
 - Low friction
 - Excellent mechanical properties
 - ~10,000x more wear resistant than polysilicon
 - Chemical inertness
 - Applications for harsh environments
 - High elastic modulus
 - Good resistance to wear, rubbing and impact
- Cons
 - Processing is time consuming and expensive
 - Large scale processing infrastructure not in place for crystalline or amorphous diamond
 - Process integration with other technology is difficult

Polymer micromachining

- Polymers used in MEMS fabrication are typically UV curable
- Typical MEMS polymer materials include
 - Urethane acrylate
 - Epoxy acrylate
 - Acryloxy silane
 - Low viscosities allow for easy molding and elimination of solvents

Example: Polymer micromachining

- **Polymer based MEMS can be fabricated using a microstereo lithography (MSL) technique**
 - Polymer MEMS are fabricated using a focused laser beam ($\sim 1 \mu\text{m}$ spot size)
 - Polymer surface begins polymerization upon exposure to the laser
 - Repeated scanning and exposure can be used on single or multiple layers of polymer to fabricate a true 3-d device
- **Other fabrication techniques include**
 - Micromolding
 - Jet molding
 - Embossing

Example: Polymer micromachining

- Polymer MEMS fabrication can produce true 3-d mechanical structures
 - Biological compatibility makes them excellent choices for biomedical applications

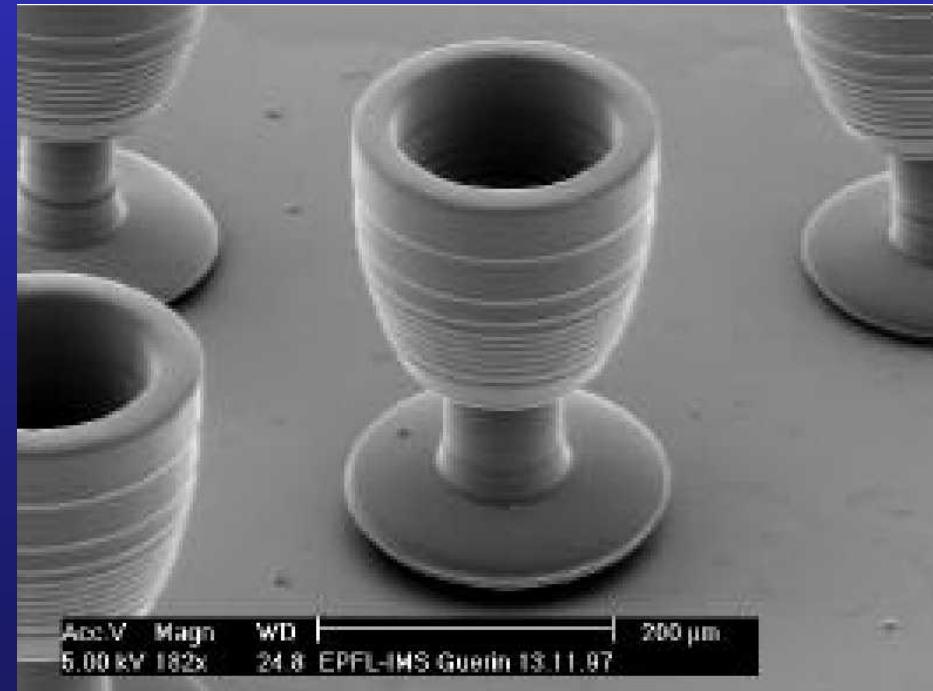
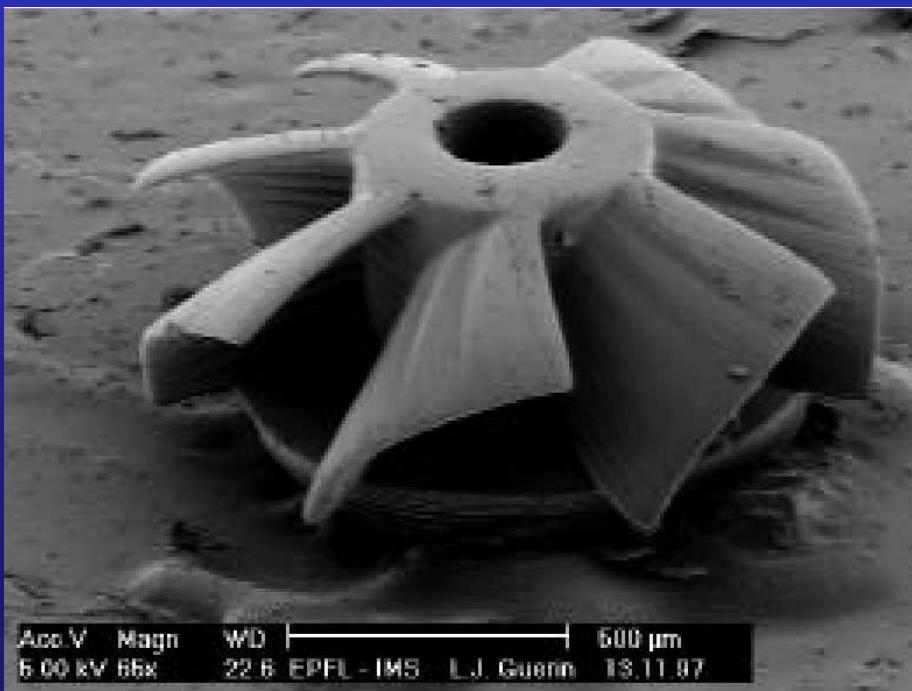


Photo courtesy of Vijay K. Varadan, Pennsylvania State University

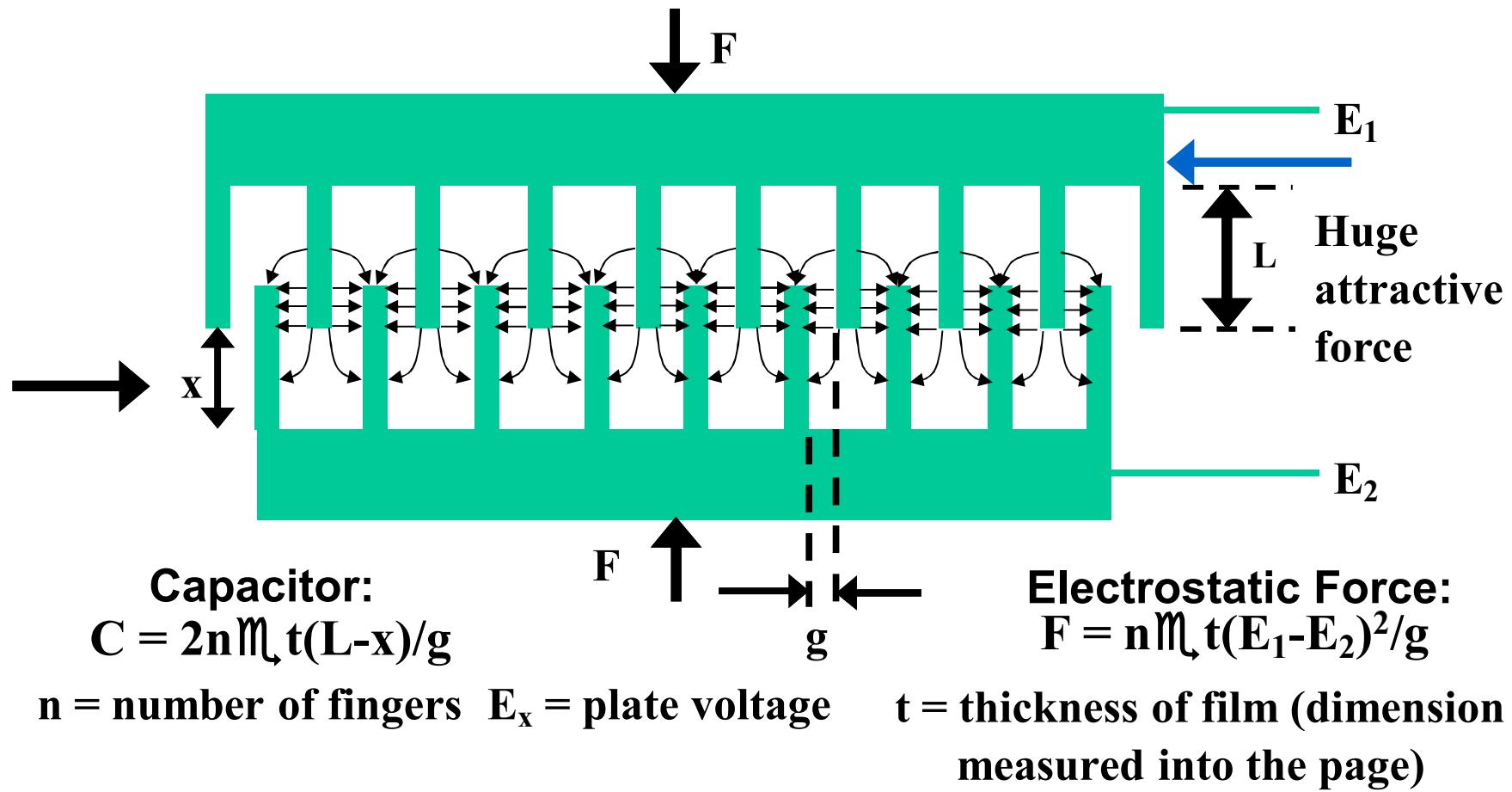
Polymer micromachining : pros and cons

- Pros
 - Fabricated MEMS are true 3-d components
 - Readily adaptable to biological applications
 - Low Young's modulus
 - Good for bending and flexing applications
 - Easily fabricated
 - Micromold process
- Cons
 - Newly developed field
 - Much more research and development is needed
 - Process integration with current silicon electronics is difficult
 - Will require polymer based electronics system

MEMS operation/actuation

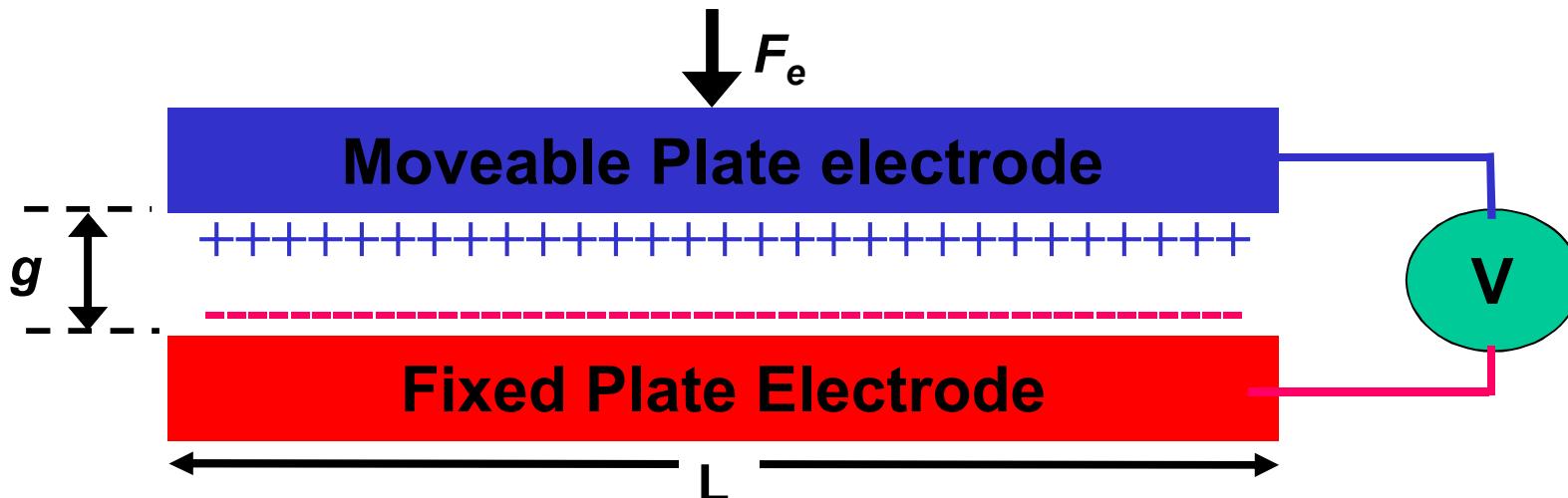
- Two common methods for operating MEMS components include thermal actuation and electrostatic actuation
 - Electrostatic actuation
 - An electric field is applied to a fixed structure creating a fringing field which is used to attract a mobile structure to produce motion
 - Electrothermal actuation
 - Specific elements of the MEMS device are heated where the coefficient of thermal expansion of the MES material is used to produce motion

Electrostatic principle (Interdigitated Fingers)



- Examples include capacitive sensors (Accelerometers) and electrostatically driven microengines

Electrostatic principle (Parallel Plate)



Parallel Plate Capacitor:

$$C = \frac{(\epsilon_0 \epsilon_r L w)}{g}$$

ϵ_0 = permittivity
of free space

Potential Energy:

$$U = \frac{1}{2} CV^2$$

ϵ_r = dielectric
const.

L = Plate Length
w = Plate Width
g = gap
V = Voltage

Electrostatic Force:

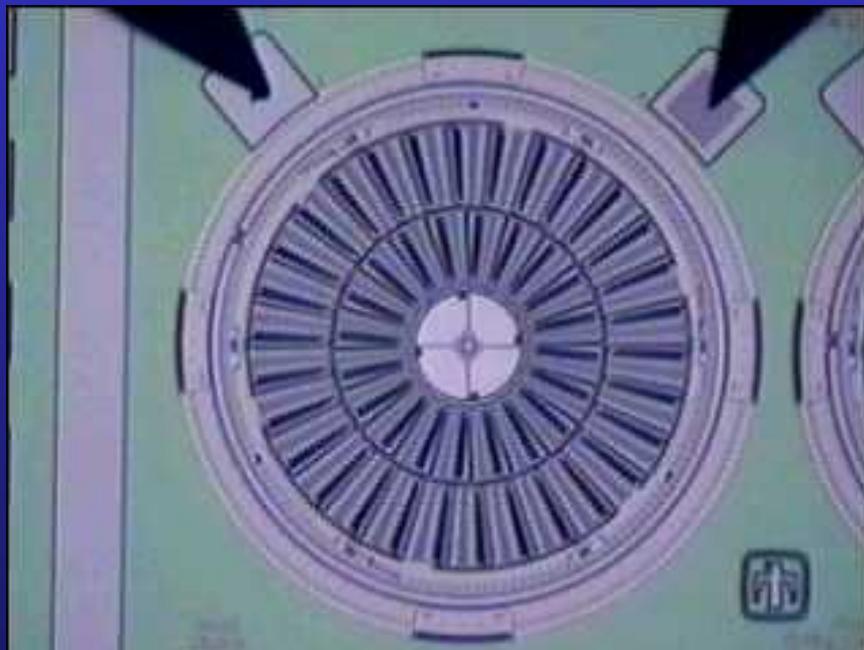
$$F_e = \frac{dU}{dg} = \frac{(\epsilon_0 \epsilon_r L w V^2)}{2g^2}$$

- Examples include some optical micromirrors and microfluidic drop ejectors,

Electrostatic driven devices

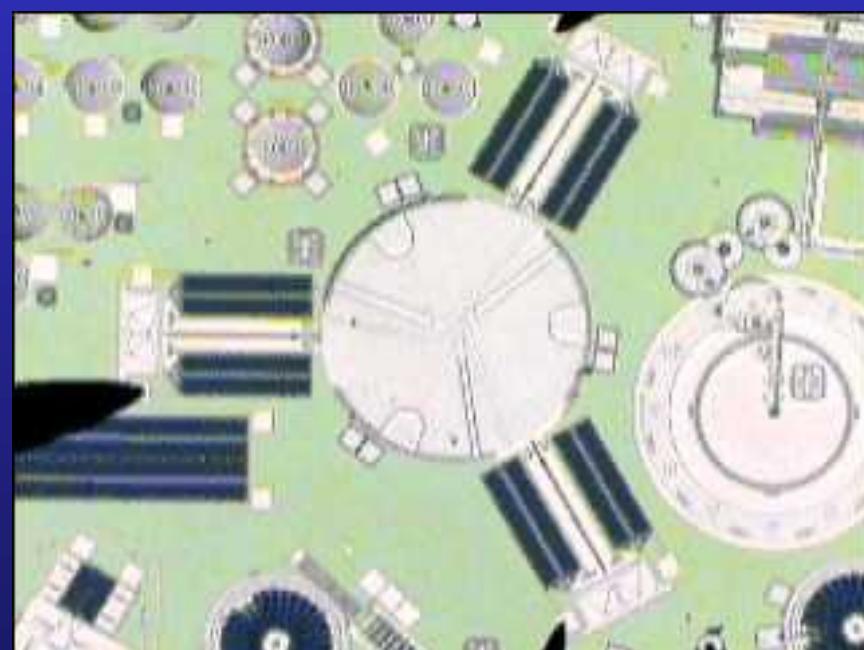
- Electrostatic actuation can be used to move fluids, components, or reposition structures

Torsional Ratcheting Actuator (TRA)



slide_40a.avi

Optical Micromirror



slide_40_b.avi

Electrothermal principle

- Current through the polysilicon legs produces Joule heating
 - Joule heating results in thermal expansion of the polysilicon legs leading to displacement

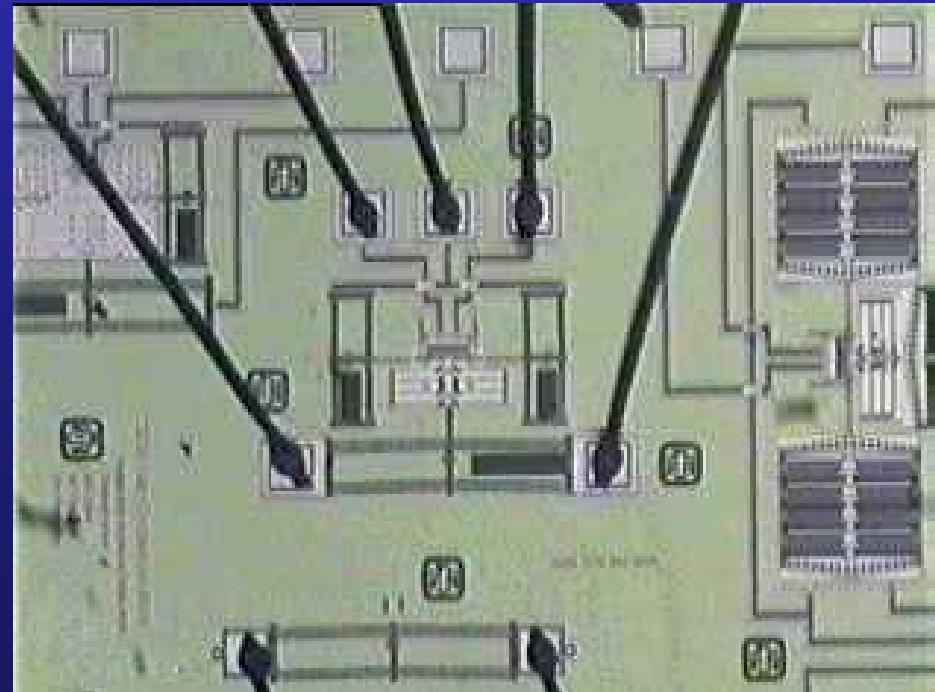
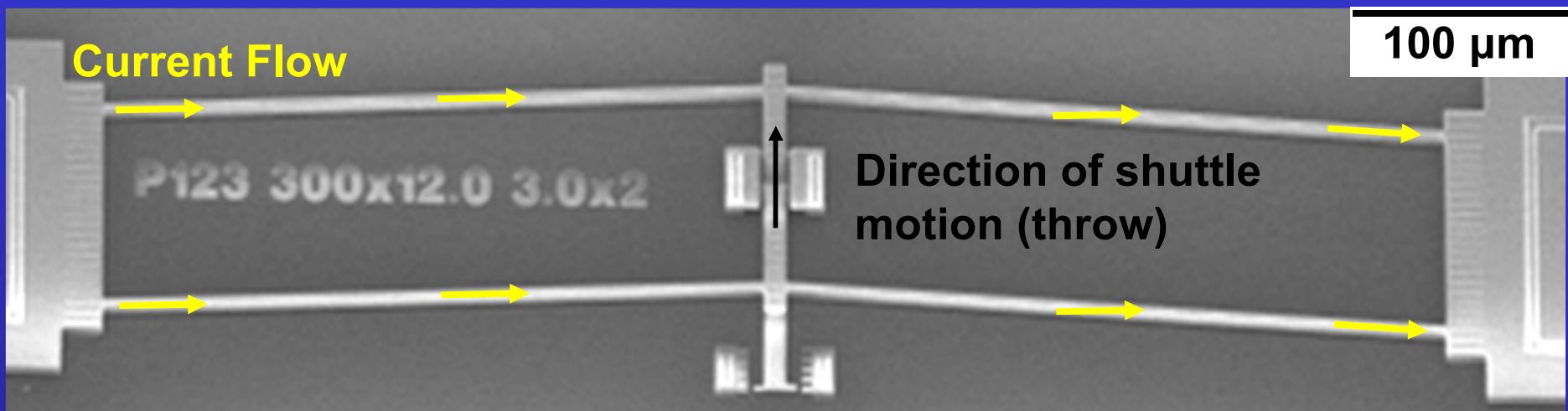
$$\Delta L_n = \int \alpha (T(x) - T_{substrate}) dx$$

α = coefficient of thermal expansion for polysilicon

$T(x)$ = Temp. of the beam at time (x)

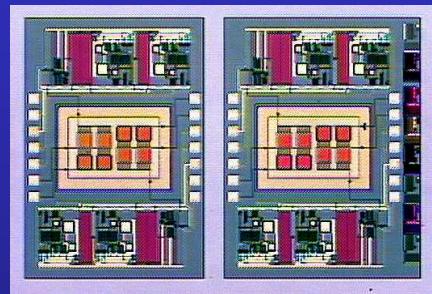
$T_{substrate}$ = substrate temperature

Thermal actuators

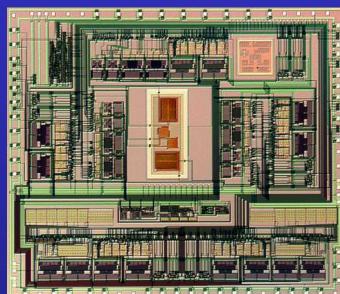


Taxonomy of MEMS Devices

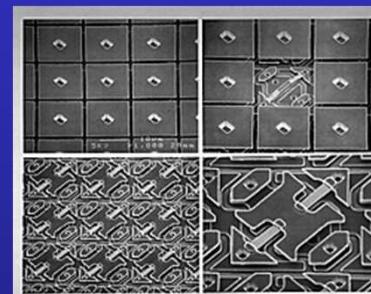
Class I
No Moving parts



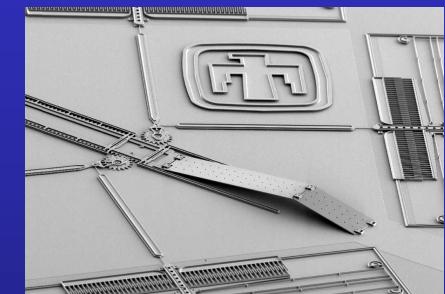
Class II
Moving Parts
No Rubbing or Impacting Surfaces



Class III
Moving Parts, Impacting
Surfaces



Class IV
Moving Parts, Impacting and Rubbing Surfaces



Accelerometers
Pressure Sensors
Inkjet Print Heads
Strain Gauge

Gyros
Comb Drives
Resonators
Filters

TI DMD
Relays, Valves
Pumps, Optical
Switches

Optical Switches
Shutters
Scanners, Locks
Discriminators

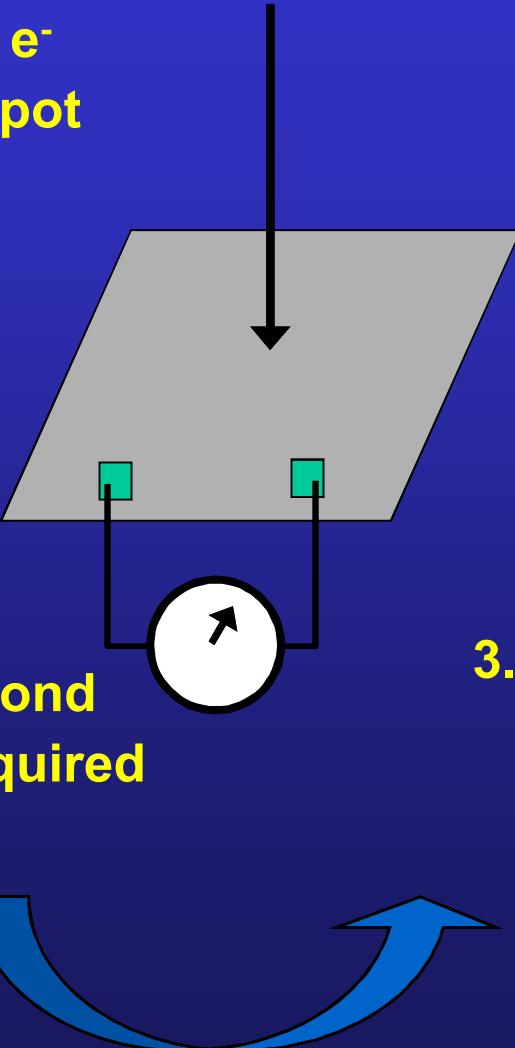
Failure analysis of MEMS

- Failure analysis activities involving MEMS require assessment of the structural, chemical or electrical behavior of the device
 - Structural – device structural integrity
 - Chemical – analysis of chemical constituents
 - Electrical – device operation and performance

The overall success of any MEMS failure analysis activity involves gaining access to the device WITHOUT compromising the failure mechanism

Electrical analysis / response localization techniques: A general strategy

1. Provide a stimulus (e- or laser) at a given spot on the MEMS device



4. Compare the images of good and bad devices (Differences tend to occur at failure sites)

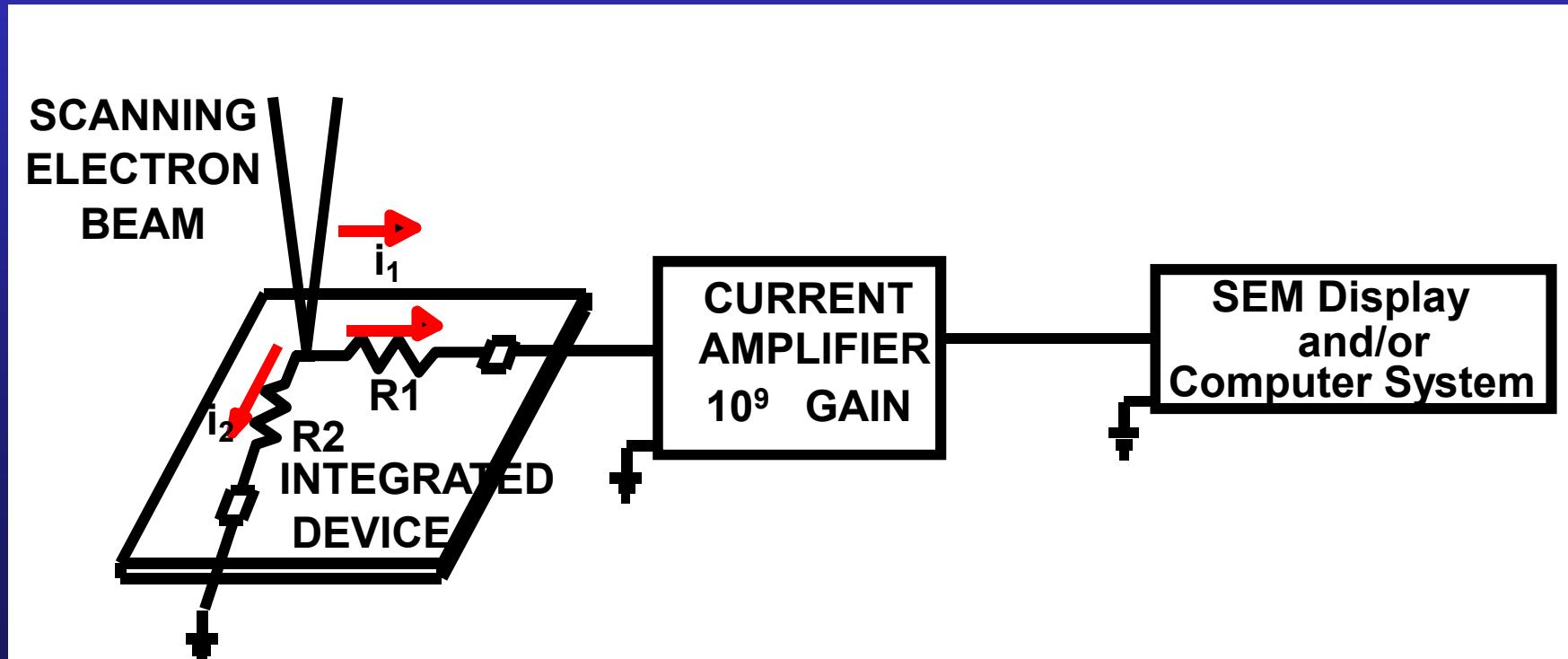


2. Measure an electrical property at external bond pads (e.g., voltage required for constant current)

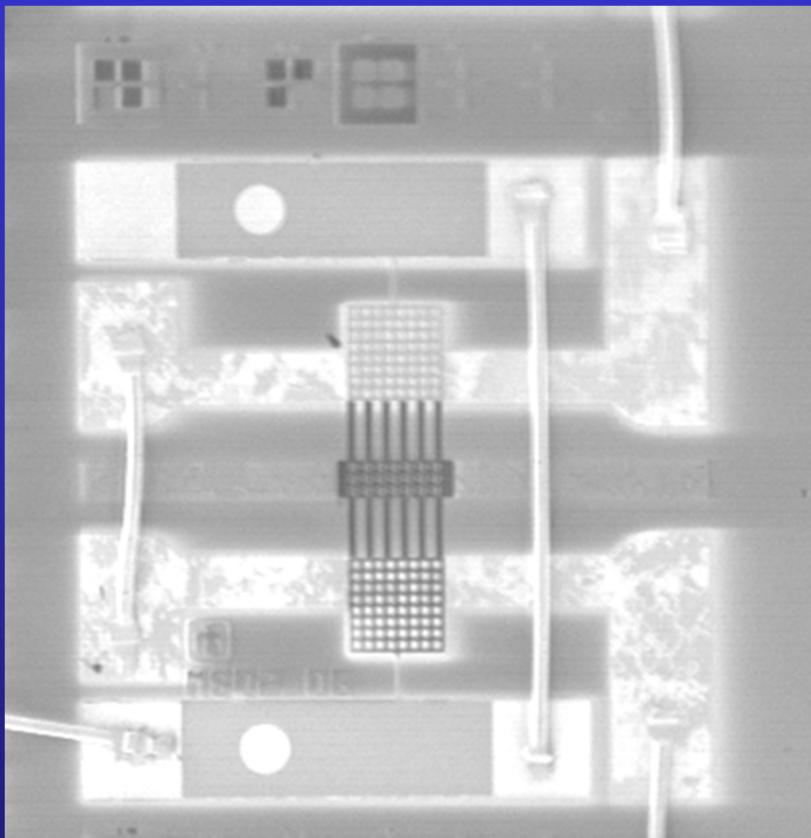
3. Make a false color image whose intensity at a spot is proportional to the electrical measurement at that spot

Electron beam based techniques

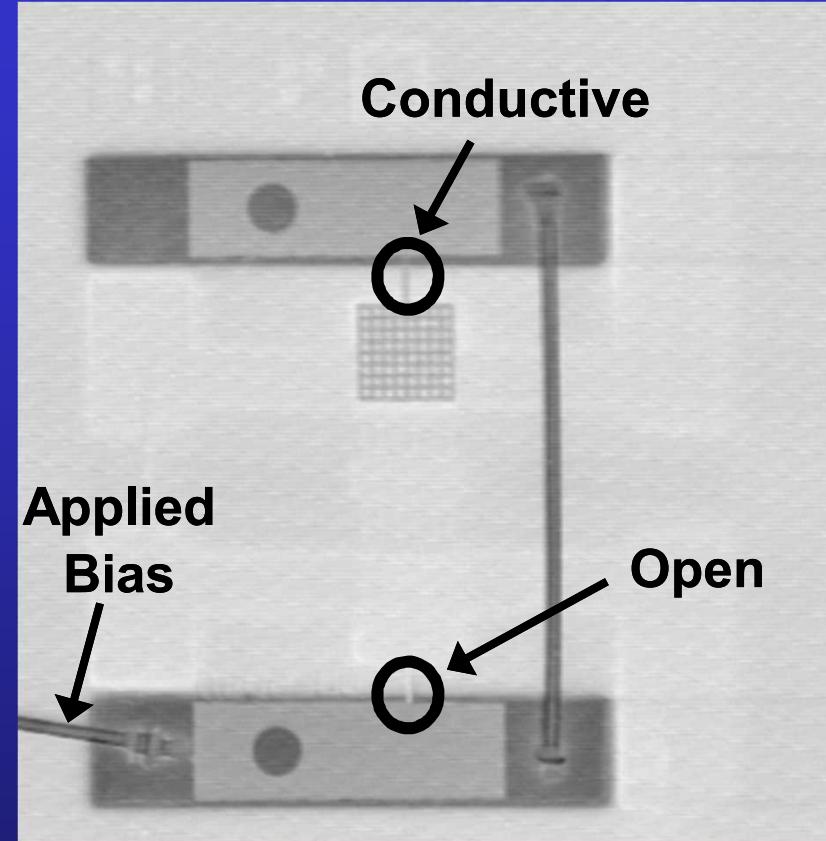
- Resistive Contrast Imaging (RCI)
 - Generates a relative resistance map of an unbiased device
 - Localizes abrupt changes in resistance
- Verifies electrical continuity of the component



MEMS analysis using RCI



Secondary Electron Image



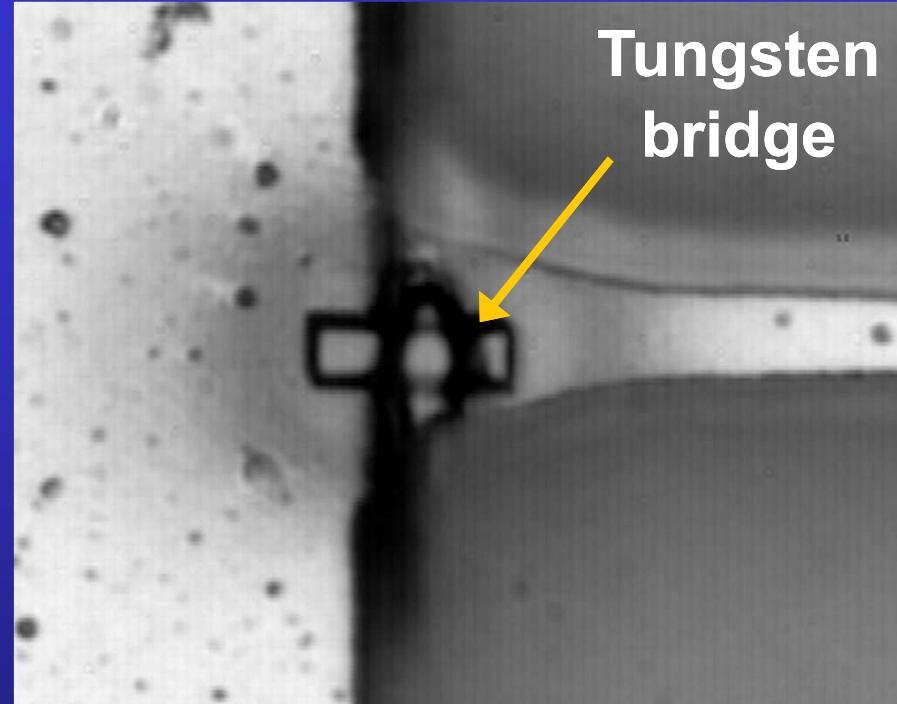
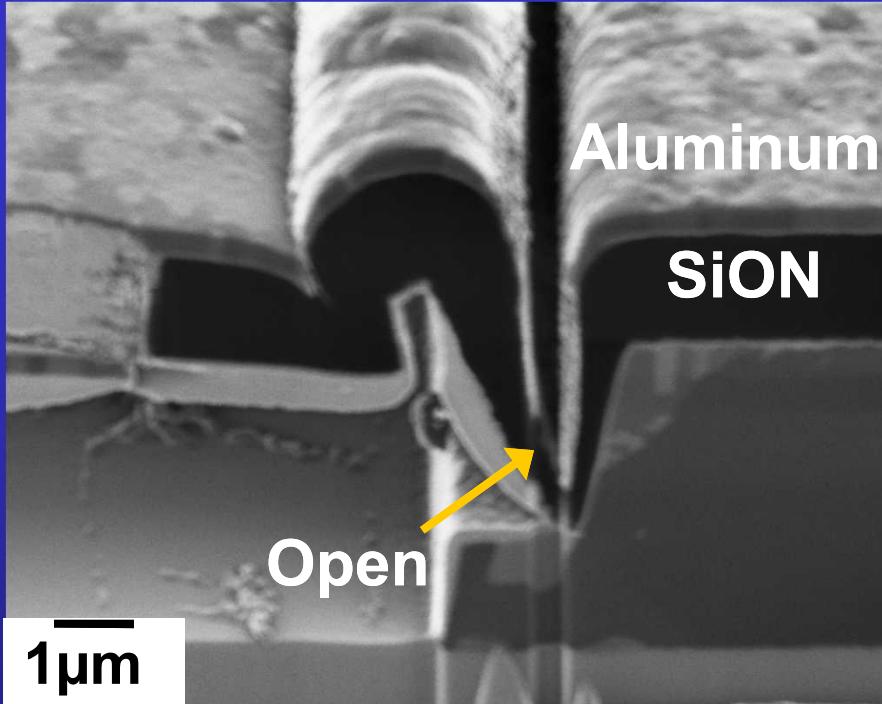
10 keV RCI Image

Top pad is observed with applied bias

Bottom pad is not observed indicating an open state

Open on bottom pad is suspected

Results identify an open circuit



- Non-uniform metal deposition along the cut region resulted in an open during testing
 - Open verified using RCI
- FIB cross-section of failed region shows break in metal
- Ion beam deposited metal bridged the open circuit
 - Switch functioned

Optical beam based MEMS FA

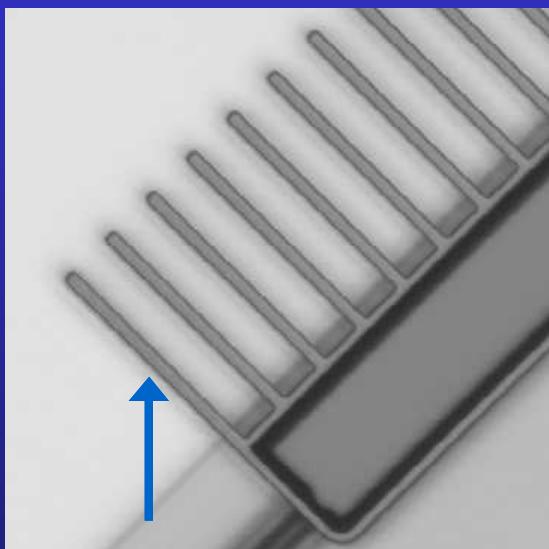
- Scanned laser produces localized heating that changes the resistance of a short (Thermally-Induced Voltage Alteration)
- **TIVA Localizes shorted circuit elements**
 - Employs constant current biasing to increase sensitivity
 - Detects subtle changes device power demand
 - same physics as OBIRCH
 - The resistance change on the power demands are used to produce a TIVA image
 - Normally uses a $1.3 \mu\text{m}$ laser to avoid photocurrent effects
 - Can be performed in biased or unbiased states
 - thermocouple effect

MEMS aspects of TIVA

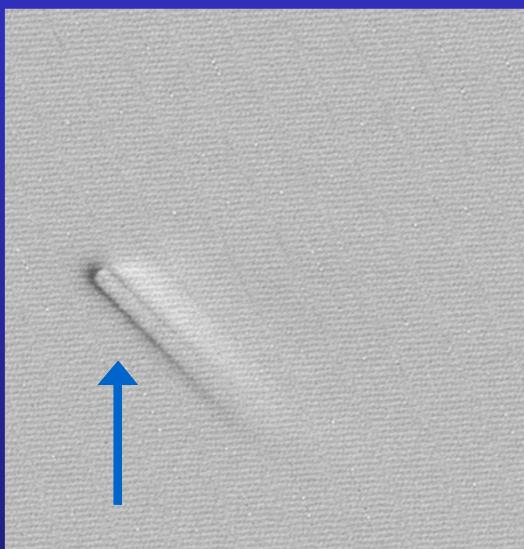
- Shorter wavelength lasers can be used to increase spatial resolution
 - No EHP recombination sites
- MEMS are particularly sensitive due to thermal isolation
 - Unreleased - encased in sacrificial material
 - Released – surrounded by air or other environment
 - thermally isolated structures get hotter
- Images can be acquired in biased or unbiased states
 - Biasing increases sensitivity

Electrostatic actuator comb finger shorted to the ground plane

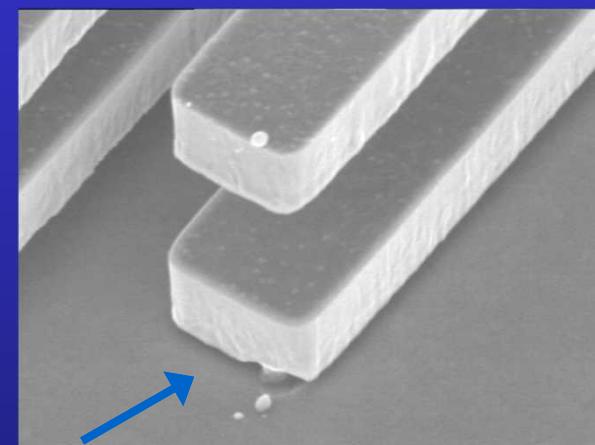
Reflected
Light Image



TIVA Image

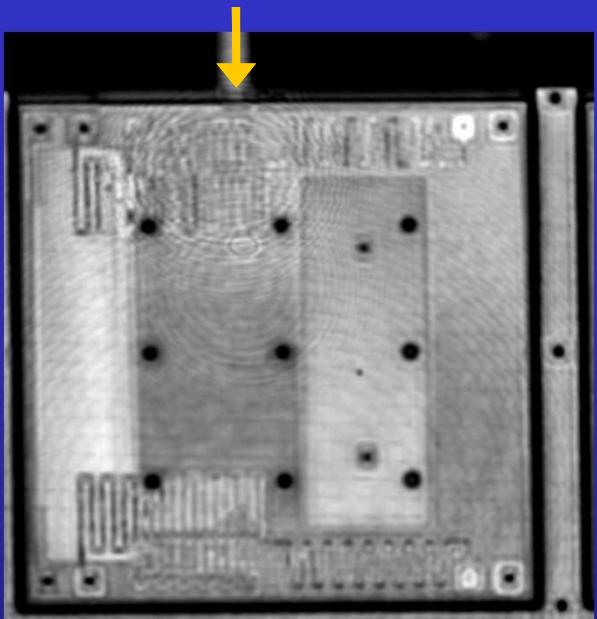


SEM Image

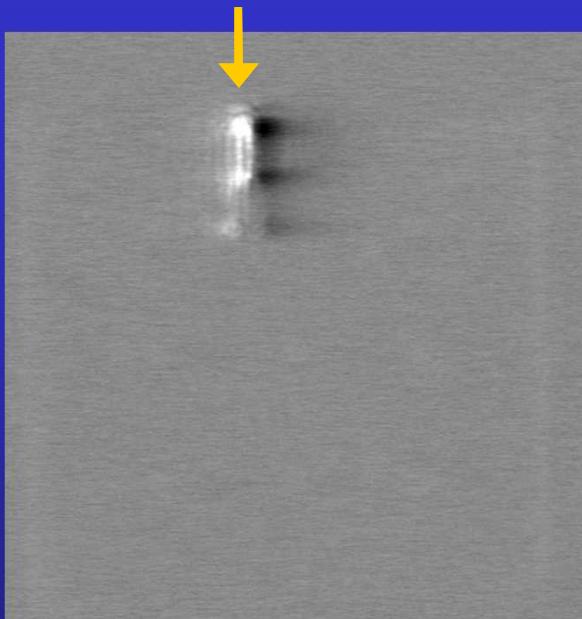


Poly1 comb finger vertically shorted to the poly0 ground plane

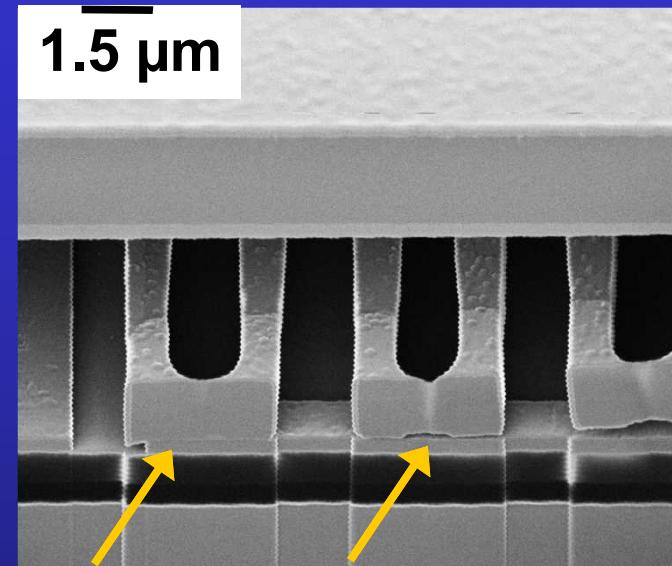
Support spring shorted to the ground plane



Reflected light image



TIVA image



FIB cross section

- Applied voltage pulled the spring into contact with the poly 0 power line prior to mirror actuation
- Short was diagnosed *through* the polysilicon mirror

Package access techniques

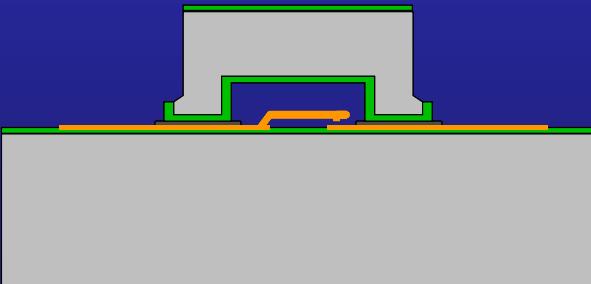
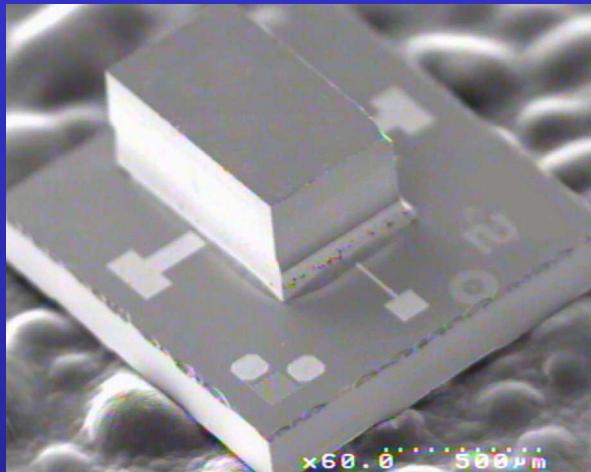
- **MEMS FA generally requires direct access to the structure of interest**
- **What do you do if you want to maintain the package environment?**
 - Removing the lid may generate and/or introduce contamination
 - Create a rapid change in the device environment
- **Many MEMS devices can be analyzed through the backside**
- **MEMS in ceramic or plastic packages can have the backside packaging material removed**
 - Enables direct access to the silicon substrate
 - Enables structural / electrical response failure analysis using IR beam based techniques

Epoxy fill and backside polish/ computer numerically controlled milling & decap

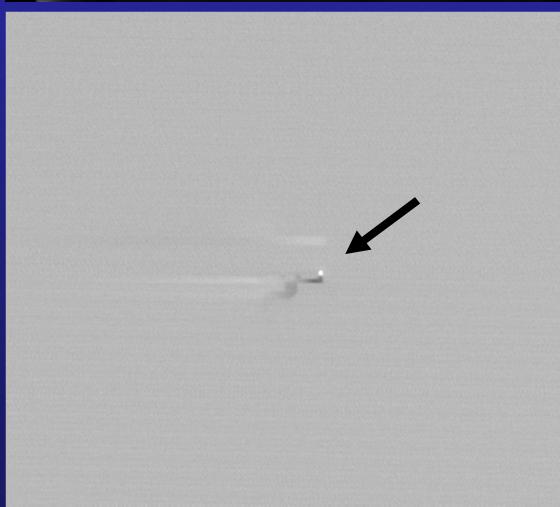
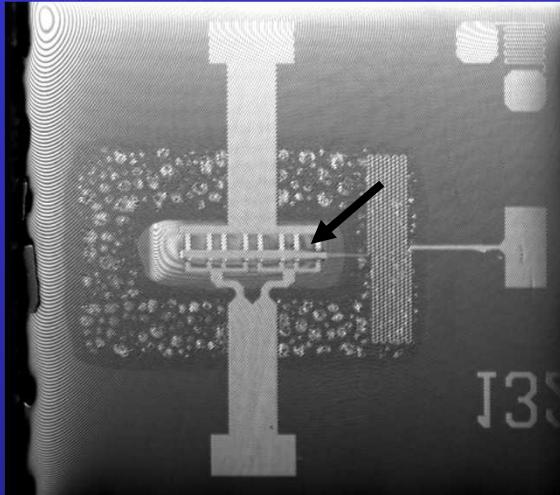
- MEMS components that are anodically bonded and packaged can be backfilled with epoxy and deprocessed from the backside
- CNC milling and/or wet etch deprocessing techniques have been used to open a “window” through the backside of a package
 - Backside “window” must be smaller than the die to prevent a breach in the packaging environment or contamination
- Substrate must either be transparent or polished
 - Enables IR inspection through substrate silicon
 - Enables structural / electrical response failure analysis using IR beam based techniques

Backside MEMS FA

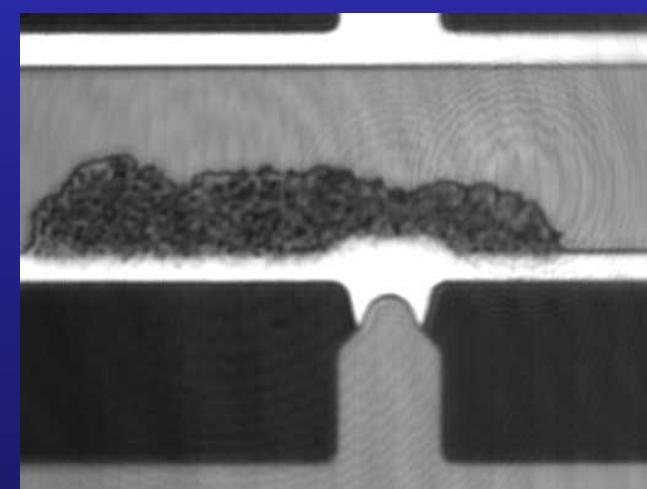
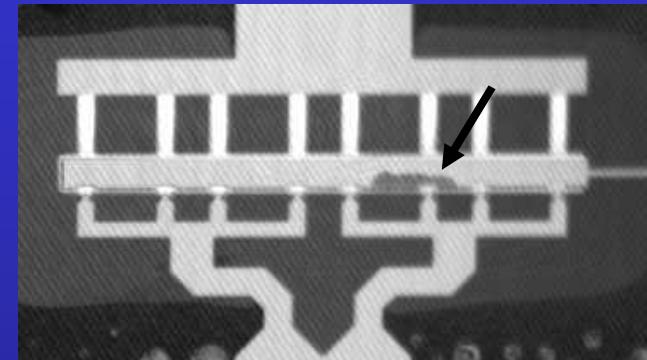
RF MEMS device



Reflected light
& TIVA images



Reflected light images



- Damage identified along short site in a failed RF MEMS device

Conclusions

- **MEMS components can be fabricated in several different processes using many different materials systems**
 - **Successful applications include**
 - Sensors and communication
 - Optical switching and displays
 - Microfluidic drop ejection
- **Fabrication process and materials systems are application dependent**
 - **Many MEMS components can be integrated with IC technology**
- **Failure analysis of MEMS components requires “access” to the device**
 - **Failure analysis techniques used in the IC industry can be leveraged to work on MEMS**