AMN- 606

MEMS/NEMS Technology and Devices
Lecture 7-9 :
Industrial and Automobile Applications

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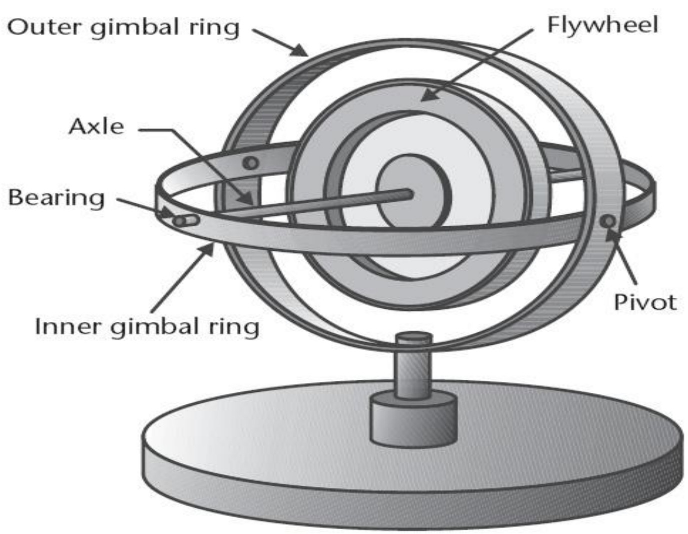
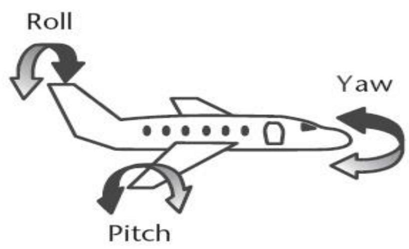
Angular Rate Sensors and Gyroscopes

- The gyroscope maintains a fixed orientation with great accuracy, regardless of Earth rotation
- It consisted of a flywheel mounted in gimbal rings
- The large angular momentum of the flywheel counteracts externally applied torques and keeps the orientation of the spin axis unaltered
- The gyroscope derives its precision from the large angular momentum that is proportional to the heavy mass of the flywheel, its substantial size, and its high rate of spin





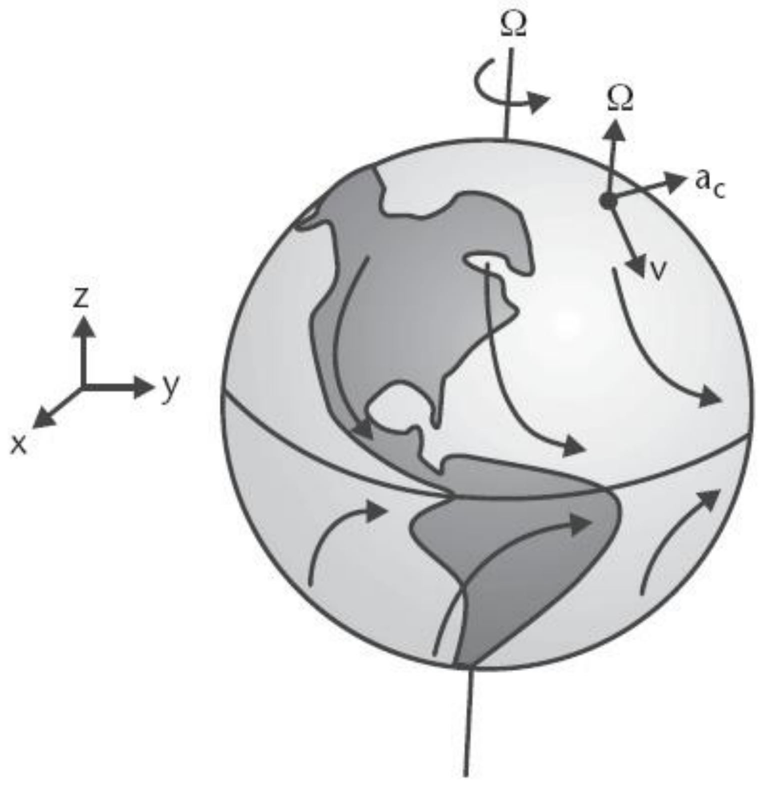
Angular Rate Sensors and Gyroscopes

Angular Rate Sensors and Gyroscopes

- The use of miniature devices is not good to produce useful gyroscopic action because the angular momentum of a miniature flywheel is small
- Instead, micro-machined sensors that detect angular rotation utilize the Coriolis effect
- These devices are angular-rate or yaw-rate sensors, measuring angular velocity, however, they are incorrectly referred to as gyroscopes

Angular Rate Sensors and Gyroscopes

- The Coriolis effect is a direct consequence of a body's motion in a rotating frame of reference

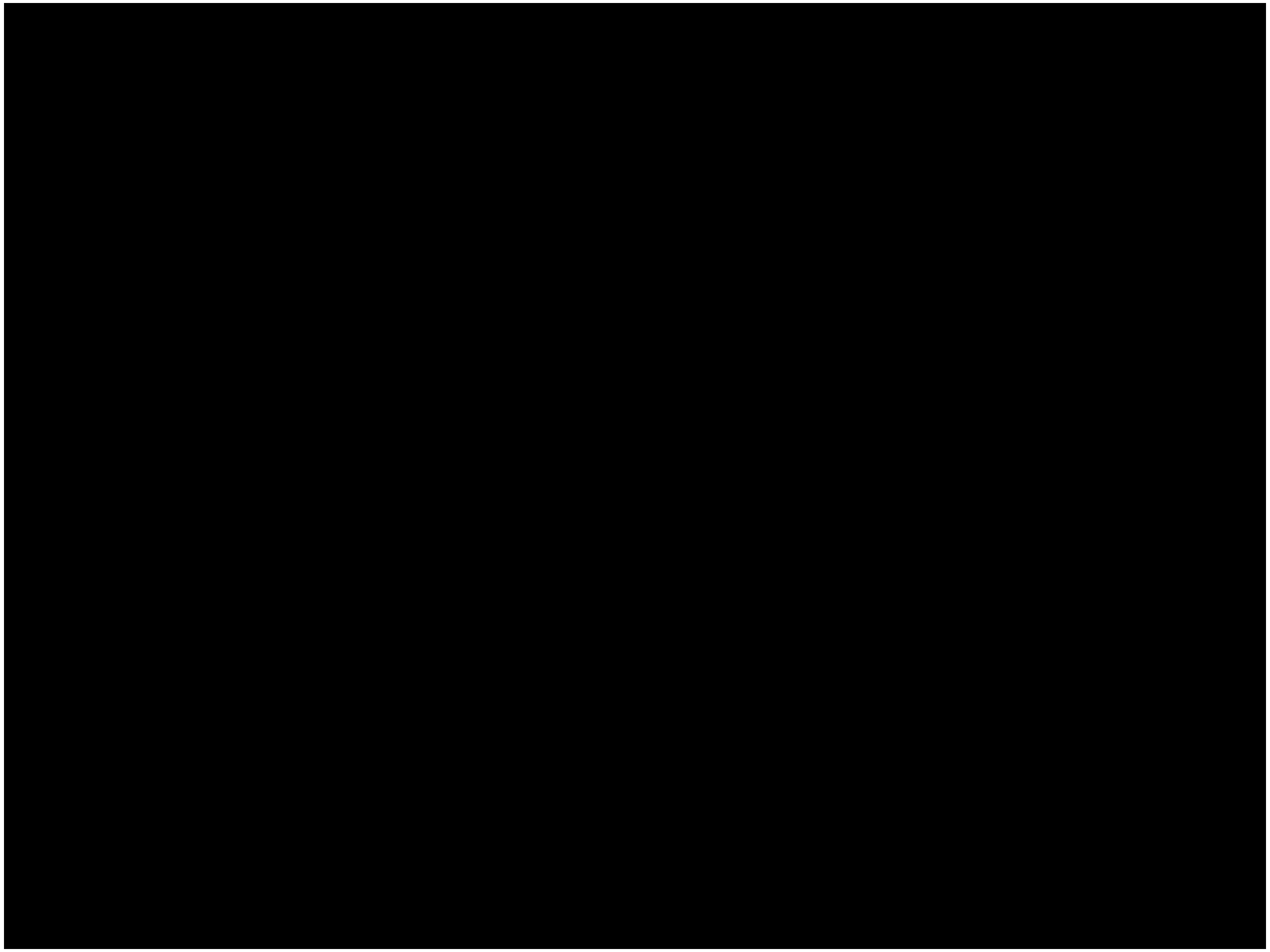


Coriolis acceleration:

$a_c = 2\Omega \times \mathbf{v}$

Angular Rate Sensors and Gyroscopes

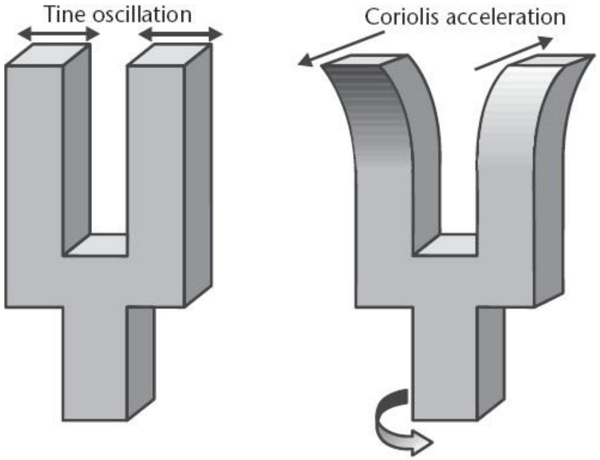
- The Coriolis effect



micromachined angular rate sensors

Basic idea

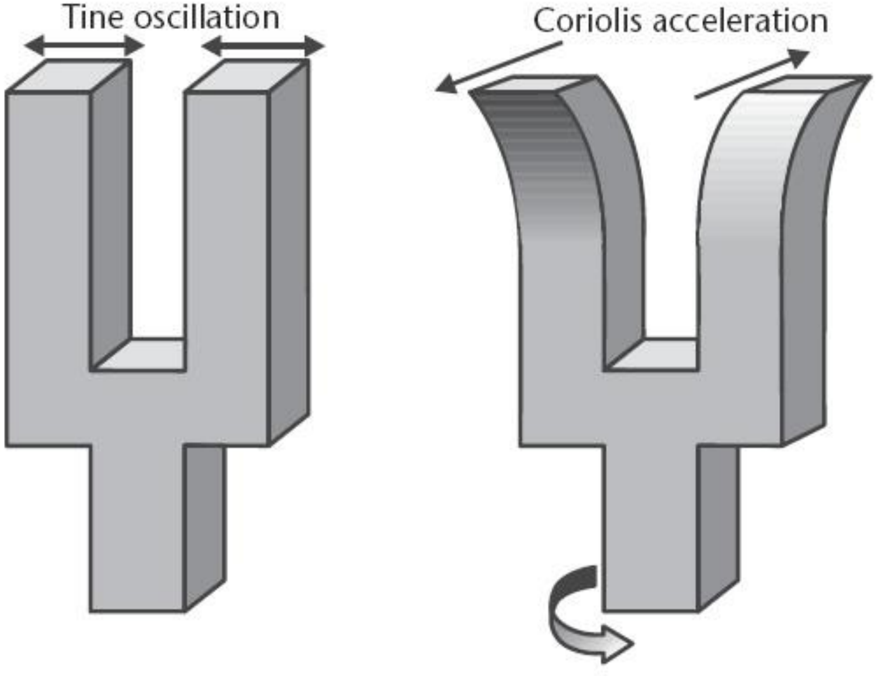
- A vibrating element at their core (the moving body)
- In a fixed frame of reference, a point on this element oscillates with a velocity vector **v**
- If the frame of reference begins to rotate at a rate Ω, this point is then subject to a Coriolis force and a corresponding acceleration equal to $2\Omega \times \mathbf{v}$
- The vector cross operation implies that the Coriolis acceleration and the resulting displacement at that point are perpendicular to the oscillation



micromachined angular rate sensors

Basic idea

- An energy transfer process from the primary mode of oscillation into the secondary mode that can be measured
- This excitation of a secondary resonance mode forms the basis of detection using the Coriolis effect



micromachined angular rate sensors

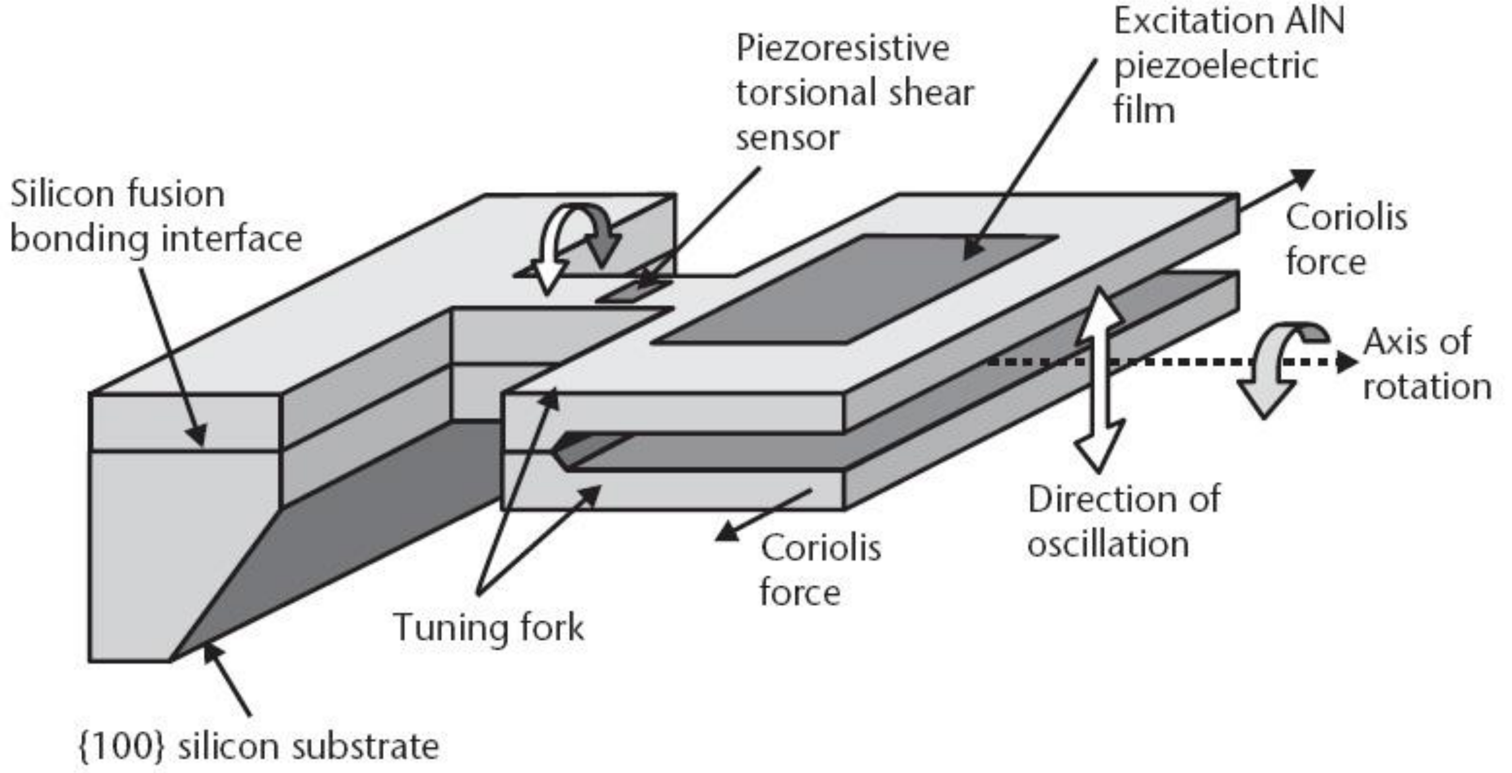
- **Main Specifications:**
  - Full-scale range (expressed in º/s or º/hr)
  - sensitivity [V/(º/s)]
  - Noise, also known as angle random walk[º/(*s· (Hz)*$^{1/2}$*)]*
  - *Bandwidth (Hz)*
  - *Resolution (º/s)*
  - *B*ias (output) drift (expressed in º/s or º/hr)
  - As is the case for most sensors, angular-rate sensors must withstand shocks

Angular-Rate Sensor from Benz

- It is a strict implementation of a tuning fork using micromachining technology
- The tines of the silicon tuning fork vibrate out of the plane of the die, driven by a thin-film piezoelectric actuator on top of one of the tines
- The Coriolis forces on the tines produce a torque around the stem of the tuning fork, giving rise to shear stresses that can be sensed with piezoresistive elements
- The shear stress is maximal on the center line of the stem and corresponds with the optimal location for the piezoresistive sense elements

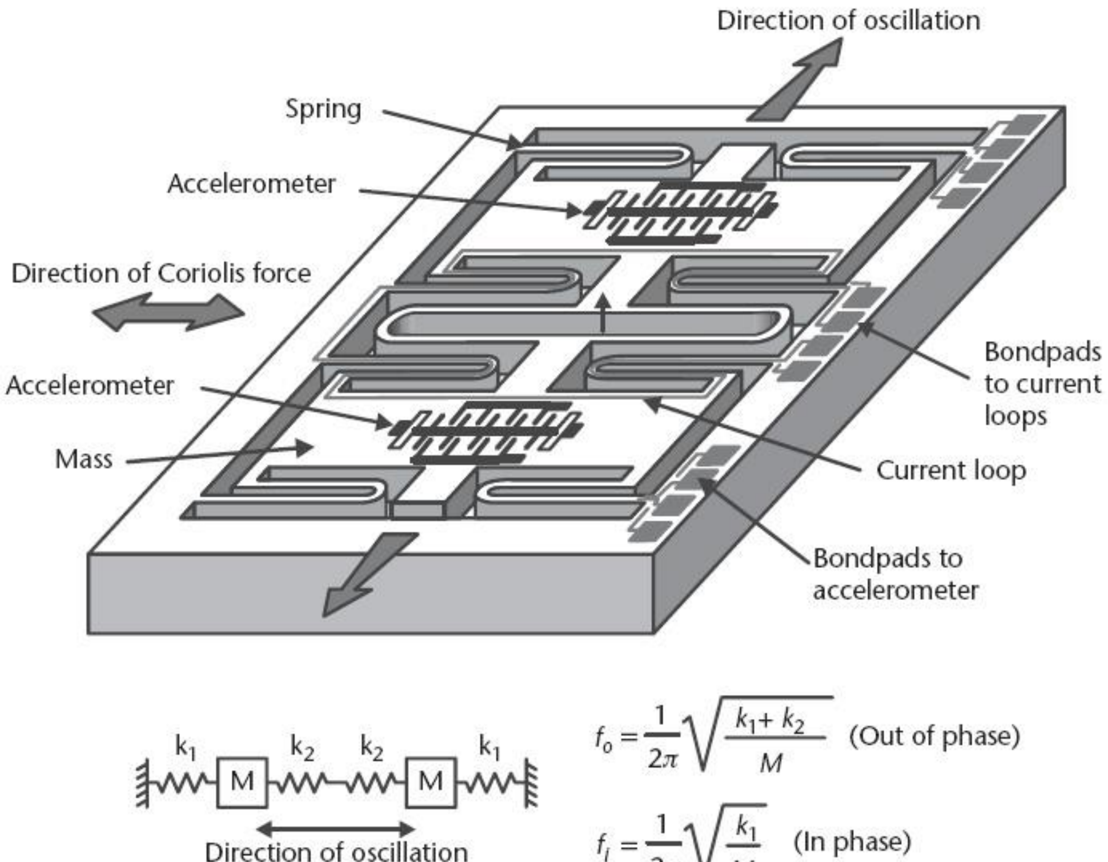
Angular-Rate Sensor from Benz

- The measured frequency of the primary mode (excitation mode) is 32.2 kHz, whereas the torsional secondary mode (sense mode) was 245 Hz lower



Reading Assignment (Included in the exam)

- **Angular-Rate Sensor from Robert Bosch**
- **Pages: 112-113**



$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_1 + k_2}{M}} \quad \text{(Out of phase)}$$

$$f_i = \frac{1}{2\pi}\sqrt{\frac{k_1}{M}} \quad \text{(In phase)}$$

Actuators and Actuated Microsystems

- If sensors extend our abilities of sight, hearing, smell, and touch <to sense>, then actuators must be the extension to our hands and fingers <to act>

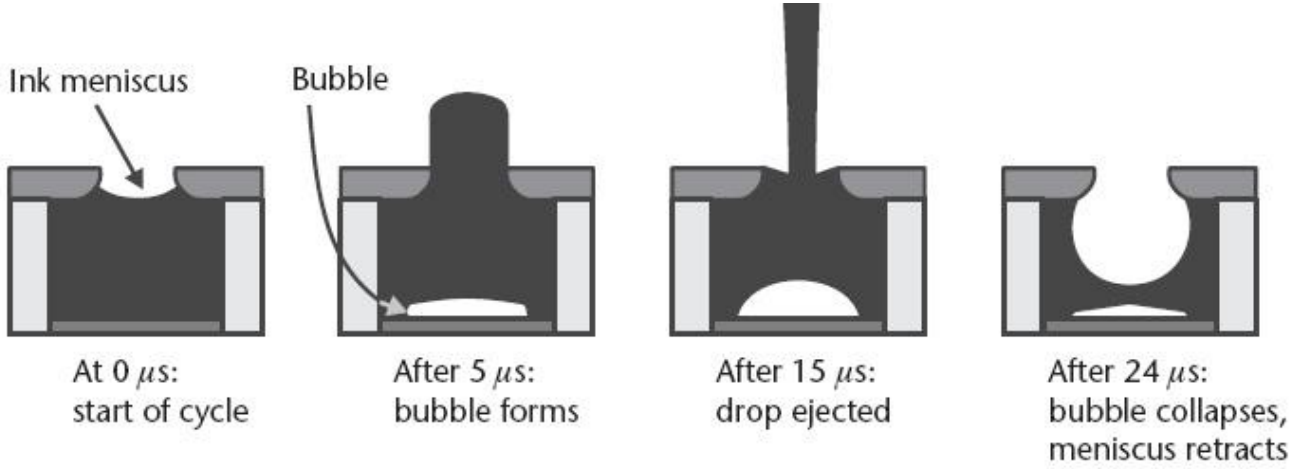
- Examples:
  - **Thermal Inkjet Heads**
  - **Micromachined Valves**
  - **Micropumps**

Thermal Inkjet Heads

- Silicon micromachined nozzles provide high resolution in printing
- A resolution of 1200 dots per inch (dpi), the spacing between adjacent nozzles in a linear array is a mere 21 μm
- The device from Hewlett-Packard illustrates the basic principle of thermal inkjet printing

Thermal Inkjet Heads

- A well contains a small volume of ink held in place by surface tension
- To fire a droplet, a thin-film resistor locally superheats the ink beneath an exit nozzle to over 250ºC
- Within 5 µs, a bubble forms and begins to expel ink out
- After 15 µs, the ink droplet is ejected from the nozzle
- Within 24 µs, the tail of the ink droplet separates, and the bubble collapses inside the nozzle
- Within less than 50 µs, the chamber refills, and the ink meniscus settles



Thermal Inkjet Heads

Micromachined Valves

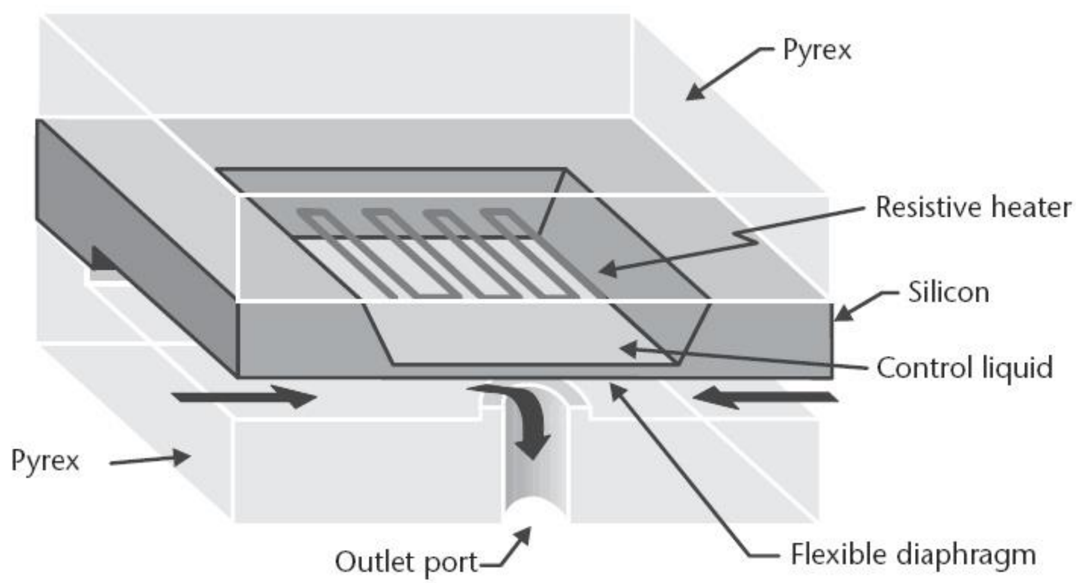
- **Potential applications:**
  - Electronic flow regulation of refrigerant for increased energy savings
  - Electronically programmable gas cooking stoves
  - Electronically programmable pressure regulators for gas cylinders
  - Accurate mass flow controllers for high-purity gas delivery systems
  - Accurate drug delivery systems
  - Control of fluid flow in portable biochemical analysis systems

Fluistor Micromachined Valve

- Fluistor = Fluid transistor
- The actuation mechanism of either normally open or normally closed valves depends on the electrical heating of a control liquid sealed inside a cavity
- When the temperature of the liquid rises, its pressure increases, thus exerting a force on a thin diaphragm wall and flexing it outward
- The Fluistor is either
  - Normally open
  - Normally closed

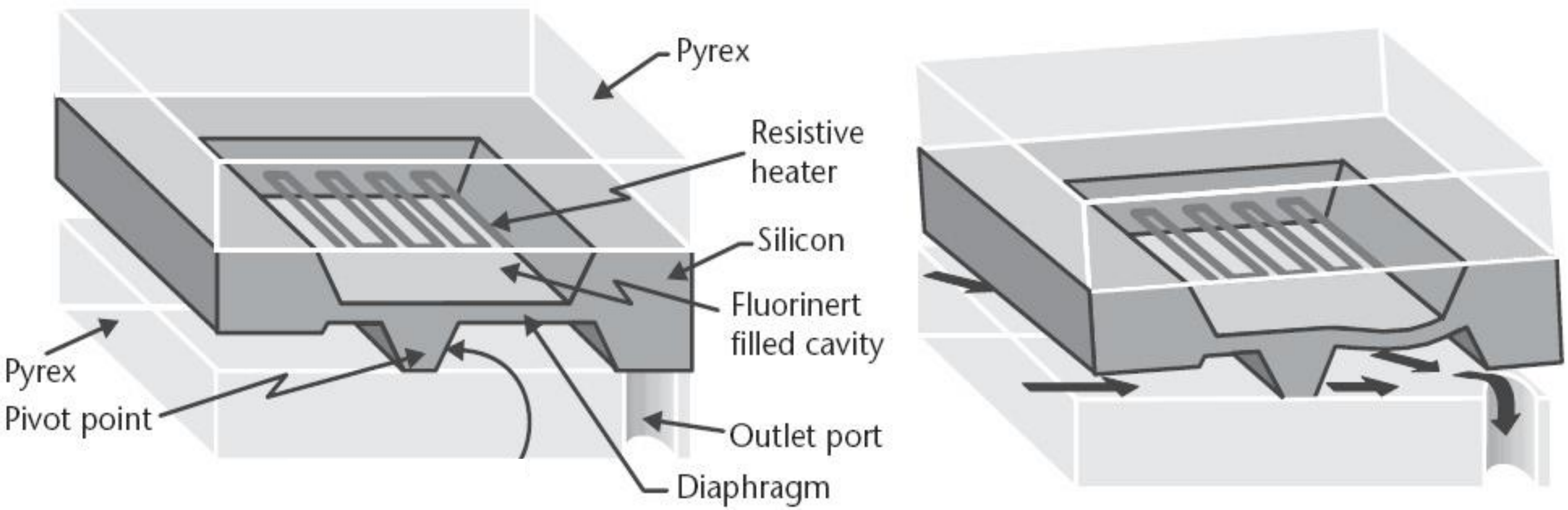
Fluistor Micromachined Valve

- **Normally open Fluistor**
  - In a normally open valve, the diaphragm blocks the fluid flow from the outlet port by its flexing action
  - Upon removal of electrical power, the control liquid entrapped in the sealed cavity cools down, and the diaphragm returns to its flat position, consequently allowing flow through the port
  - The flexing membrane is in intimate contact with the fluid flow, which increases heat loss by conduction and severely restricts the operation of the valve



Fluistor Micromachined Valve

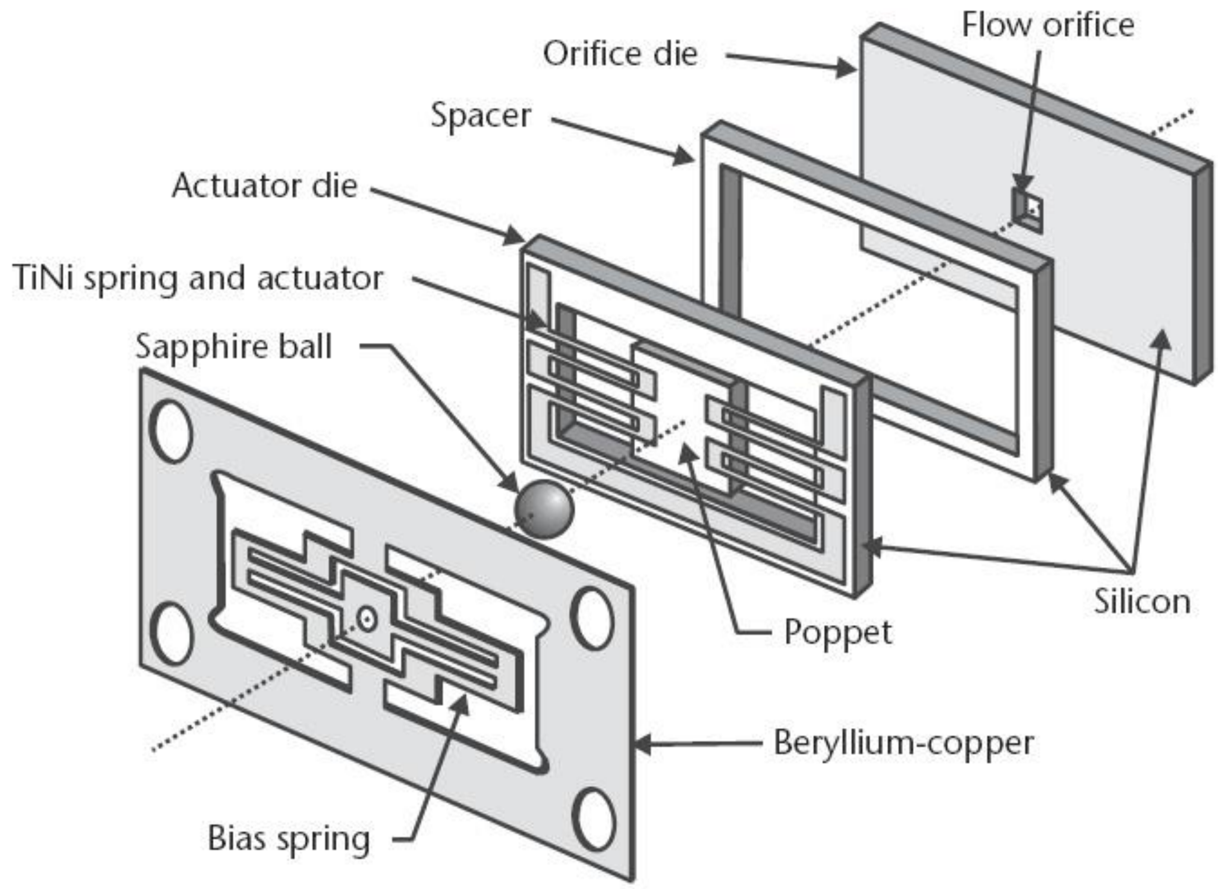
- **Normally closed Fluistor**
  - The normally closed valve uses mechanical levering activated by a liquid-filled thermo pneumatic actuator to open an outlet port
  - The outward flexing action of the diaphragm under the effect of internal pressure develops a torque about a silicon fulcrum
  - Consequently, the upper portion of the valve containing the actuation element lifts the valve plug above the valve seat, permitting flow through the outlet port



Micromachined Valve from TiNi Alloy Company

- Normally closed valve
- The complete valve assembly consists of three silicon wafers and one bias spring to maintain a closing force on the valve poppet
- One silicon wafer incorporates an orifice
- The second wafer is simply a spacer defining the stroke of the poppet as it actuates
- The third silicon wafer contains the valve poppet suspended from a spring structure made of a thin-film titanium nickel (TiNi) alloy
- A ball between the spring and the third silicon wafer pushes the poppet out of the plane of the third wafer through the spacer of the second wafer to close the orifice in the first wafer

Micromachined Valve from TiNi Alloy Company

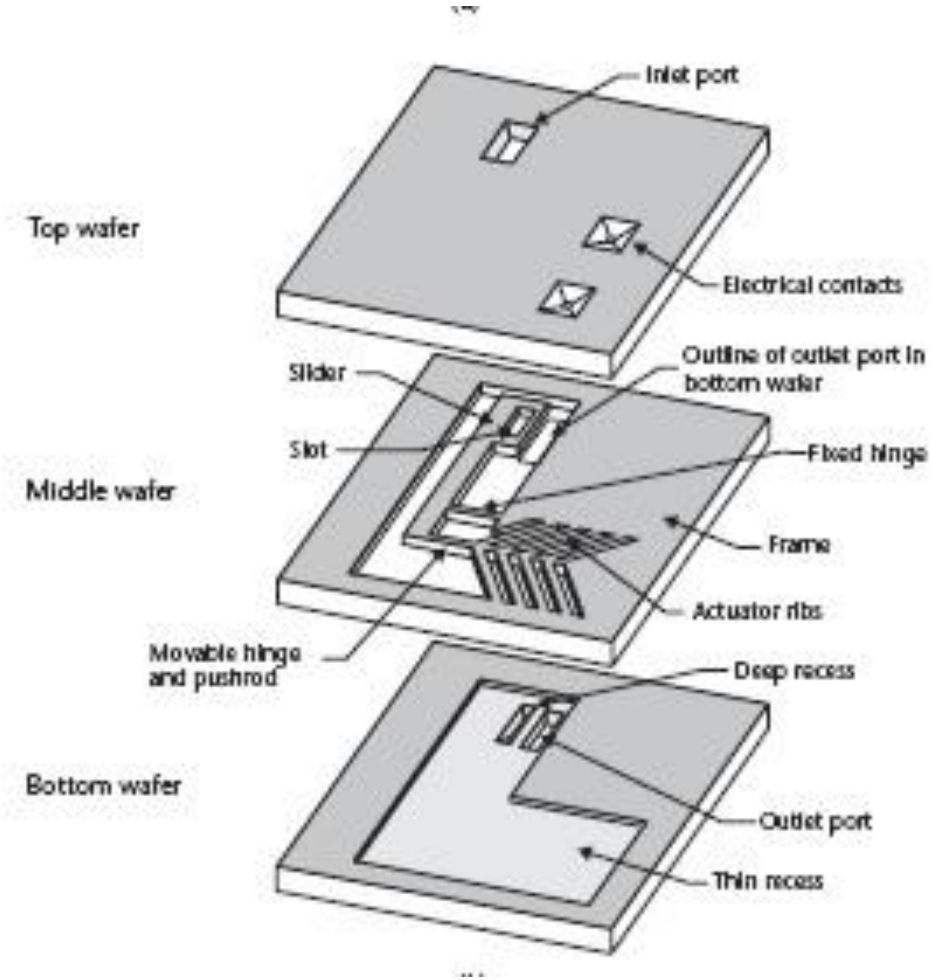


Micromachined Valve from TiNi Alloy Company

- Current flow through the titanium-nickel alloy heats the spring above its transition temperature (~ 100ºC), causing it to contract and recover its original undeflected position in the plane of the third wafer
- This action pulls the poppet back from the orifice, hence permitting fluid flow

Reading Assignment (Included in the exam)

- Sliding Plate Microvalve
- Pages: 124-126



Micromachined Valve from TiNi Alloy Company

- **Micropumps**
  - Micropumps are likely used in the automated handling of fluids for chemical analysis and drug delivery systems
  - The basic structure of the micropump is consisting of four wafers
  - The bottom two wafers define two check valves at the inlet & outlet
  - The top two wafers form the electrostatic actuation unit

reverse direction—hence its bidirectionality. At first glance, it appears that such a

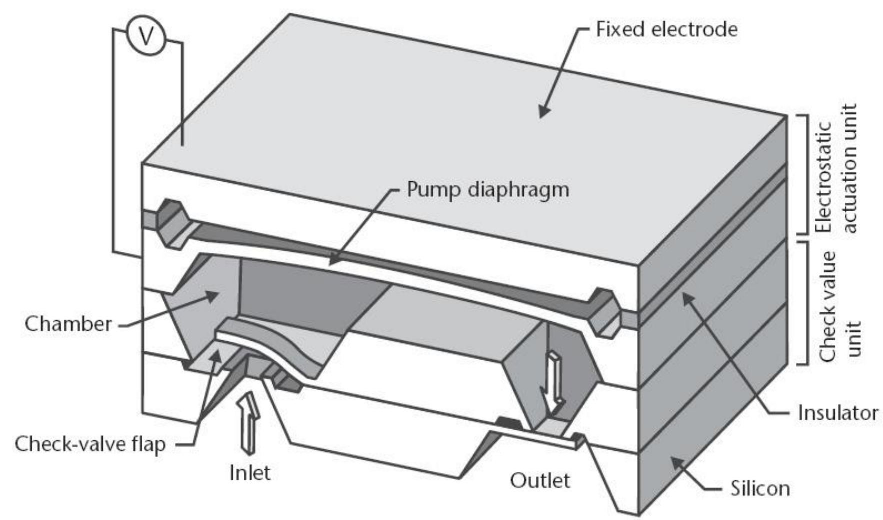


Figure 4.37 Illustration of a cutout of a silicon micropump from the Fraunhofer Institute for Solid State Technology of Munich, Germany [48]. The overall device measures 7 × 7 × 2 mm^3. The

Micromachined Valve from TiNi Alloy Company

Micropumps

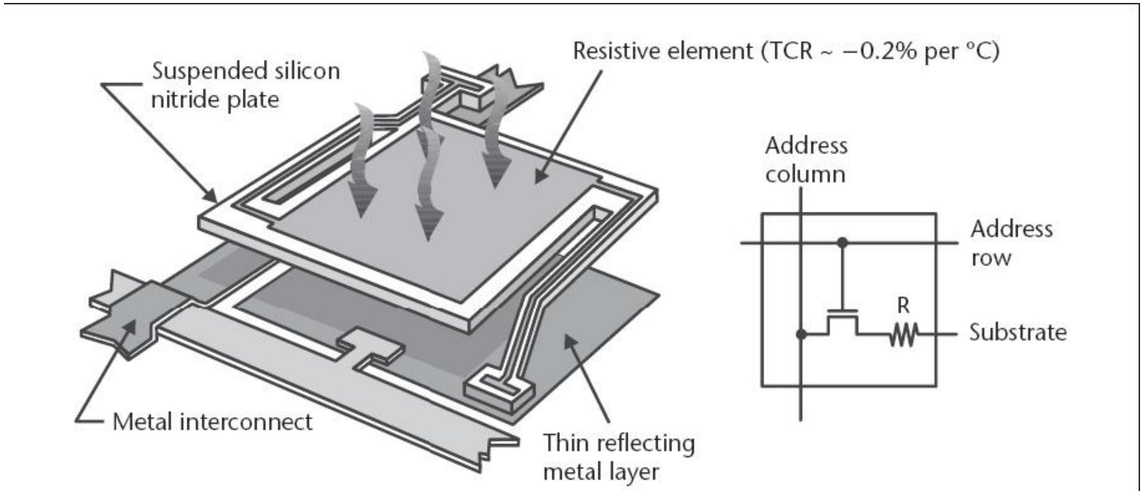
- The application of a voltage between the top two wafers actuates the pump diaphragm, thus expanding the volume of the pump inner chamber
- This draws liquid through the inlet check valve to fill the additional chamber volume
- When the applied ac voltage goes through its null point, the diaphragm relaxes and pushes the drawn liquid out through the outlet check valve
- Each of the check valves comprises a flap that can move only in a single direction:
  - The flap of the inlet check valve moves only as liquid enters to fill the pump inner chamber
  - The opposite is true for the outlet check valve

MEMS/NEMS in Photonic Applications

- MEMS currently exist in
  - Imaging and Displays
    - Infrared radiation imager
    - DMD
    - Grating light valve display
  - Optical fiber communications
    - Optical switch
    - Wavelength locker

Infrared Radiation Imager (Sensor)

- It provides high sensitivity to radiation by providing extreme thermal isolation for a temperature-sensitive resistive element
- Incident infrared radiation heats a suspended sense resistor, producing a change in its resistance that is directly proportional to the radiation intensity
- The two-level structure, consisting of an upper silicon nitride plate suspended over a substrate, provides a high degree of thermal isolation

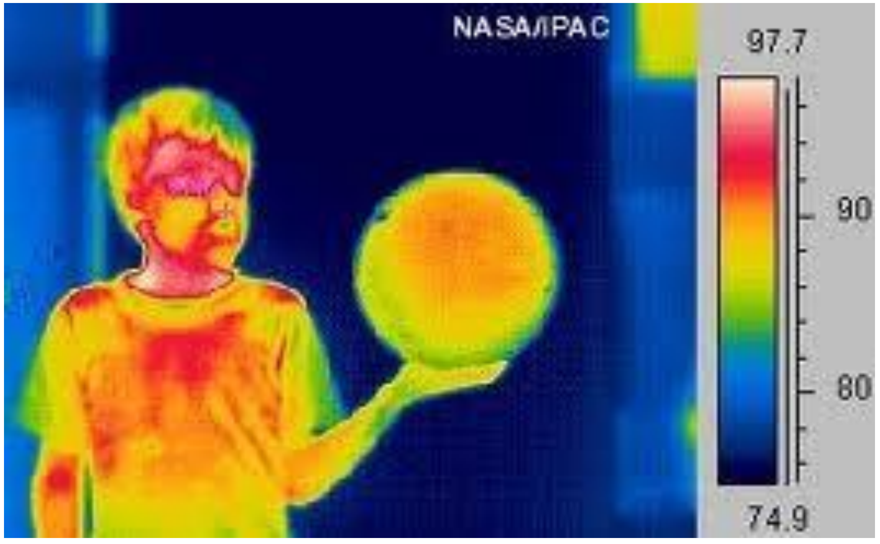


Infrared Radiation Imager (Sensor)

- The thin (~50nm) resistive element rests on the silicon-nitride and has a large temperature coefficient of resistance in the range of –0.2 to –0.3% per degree Celsius
- In order to capture most or all of the incident radiation, the fill factor must approach unity
- Fill factor is the ratio between the area covered by the sensitive resistive element and the overall pixel area
- Surface micromachining process is used
- CMOS electronic circuits are fabricated first on the substrate and then the deposition of the resistive element
- The readout electronics activate a column of pixels by applying a voltage to their corresponding address column, then they measure the current from each transistor

Infrared Radiation Imager (Sensor)

- Calibration:
  - a calibration step that subtracts from the active image the signal of a blank scene
  - The blank scene signal incorporates the effects of non-uniform pixel resistance across the array
  - An intermittent shutter provides the blank scene signal, therefore allowing continuous calibration

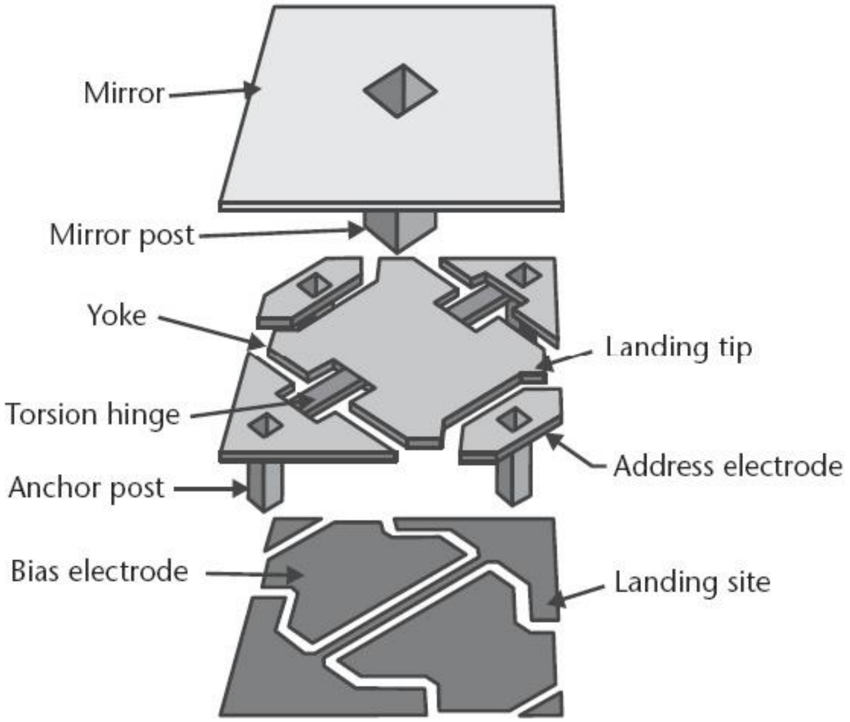


Digital Micromirror Device (DMD)

- DMD has been commercialized by TI in Digital Light Processing (DLP) technology
- DMD consists of a two-dimensional array of optical switching elements (pixels) on a silicon substrate
- Each pixel consists of a reflective micromirror supported from a central post
- This post is mounted on a lower metal platform—the yoke—itself suspended by thin and compliant torsional hinges from two stationary posts anchored directly to the substrate
- Two electrodes positioned underneath the yoke provide electrostatic actuation
- A 24-V bias voltage between one of the electrodes and the yoke tilts the mirror towards that electrode

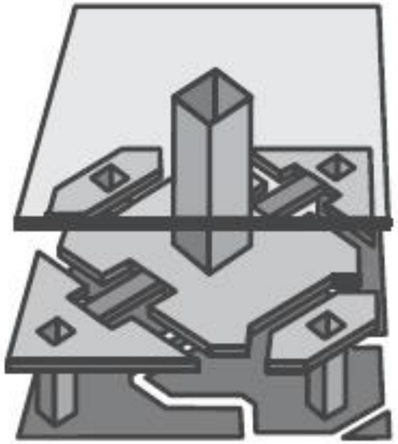
Digital Micromirror Device (DMD)

- The nonlinear electrostatic and restoring mechanical forces make it impossible to accurately control the tilt angle
- Instead, the yoke snaps into a fully deflected position, touching a landing site biased at the same potential to prevent electrical shorting
- The angle of tilt is limited by geometry to ±10º

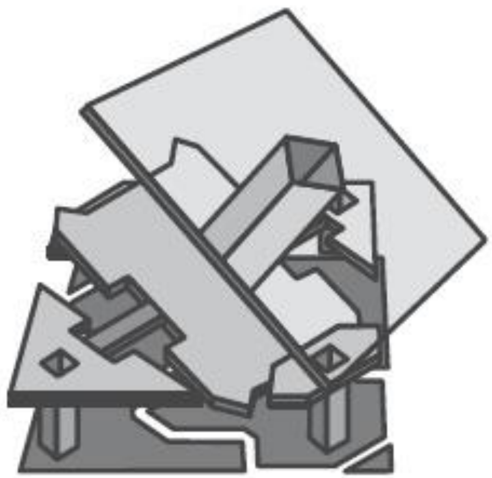


Digital Micromirror Device (DMD)

- The angle of tilt is limited by geometry to ±10º
- The restoring torque of the hinges returns the micro-mirror to its initial state once the applied voltage is removed
- CMOS static random-access memory (SRAM) cells fabricated underneath the micro-mirror array control the individual actuation states of each pixel and their duration



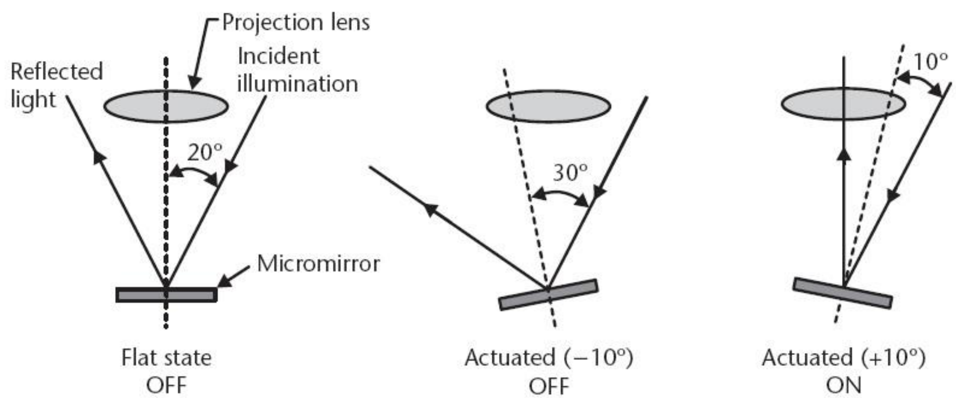
Unactuated state



Actuated state

Digital Micromirror Device (DMD)

- The *OFF state of the memory cell tilts the mirror by* –10º, whereas the *ON state tilts it by +10º*
- In the *ON state, off-axis illumination* reflects from the micro-mirror into the projection lens, causing this particular pixel to appear bright
- In the other two tilt states (0º and –10º), an aperture blocks the reflected light giving the pixel a dark appearance
- This beam-steering approach provides high contrast between the bright and dark states



Digital Micromirror Device (DMD)

- Each micromirror is 16 μm square and is made of aluminum for high reflectivity in the visible range
- The pixels are normally arrayed in two dimensions on a pitch of 14 μm to form displays with standard resolutions
- The fill factor, defined as the ratio of reflective area to total area, is approximately 0.9
- Modulating the duration of the pulse, or the dwell time, gives the eye the sensation of gray by varying the integrated intensity between bright and dark
- The pixel switching speed is 1,000 times faster than the eye's response time → it is possible to fit up to about 1,000 different gray levels (equivalent to 10 bits)

Digital Micromirror Device (DMD)

- Full-color projection
  - uses three DMD chips, one for each primary color (red, green, and blue), with each chip accommodating 8-bit color depth for a total of 16 million discrete colors
    - **$2^8 * 2^8 * 2^8 = 2^{24} = 16$ Million**
  - OR: uses filters on a color wheel, the three primary colors can be switched and projected using a single DMD chip

Reading Assignment (Included in Exam)

- Grating Light Valve Display..pages 139-141

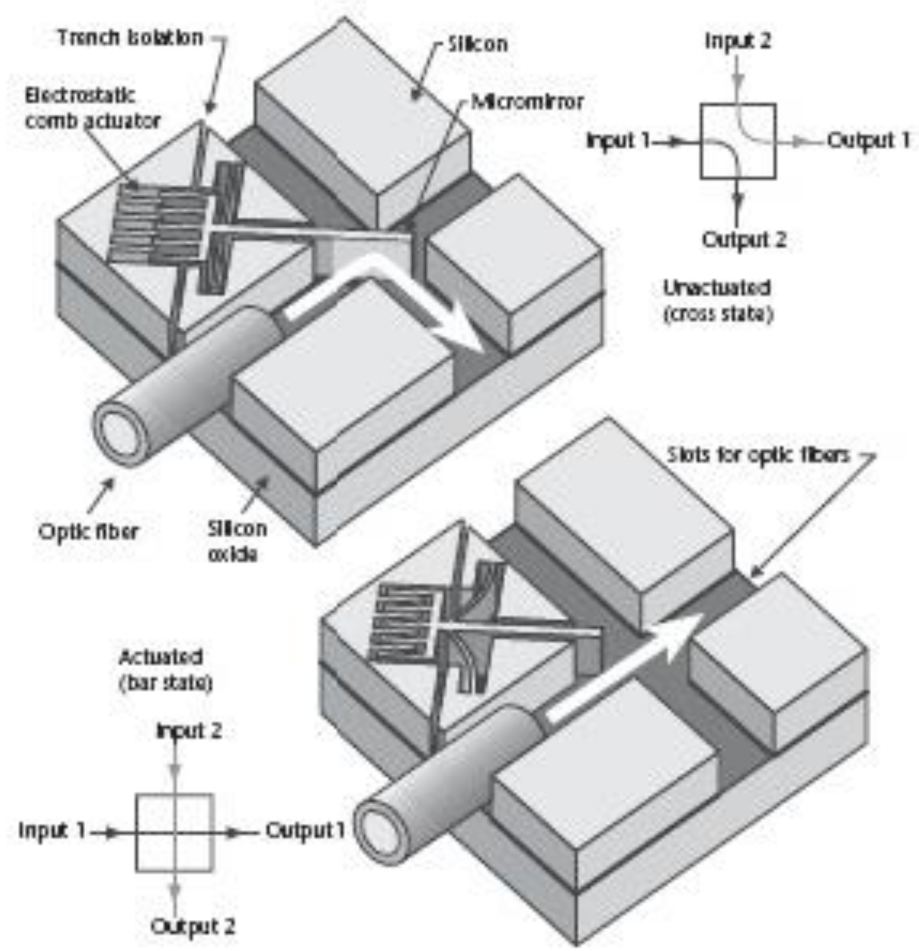
Optical fiber communications

Digital *M × N Optical Switch*

- The basic cell for a 2×2 switch element consists of an electrostatic comb actuator controlling the position of a vertical mirror plate at the intersection of two perpendicular slots
- Within each slot lie two optical fibers, one on each slot end
- In the actuator's normal unbiased position, the mirror plate sits in the middle of the intersection and reflects the light by 90º, thereby altering the path of data communication—this is the cross state
- Applying approximately 70V to the actuator combs causes the mirror to retract, letting the light pass through unobstructed—this is the bar state

Optical fiber communications

- **Digital *M × N Optical Switch***
  - Arraying the 2 × 2 switch element in both directions creates a generalized *M × N switch matrix*

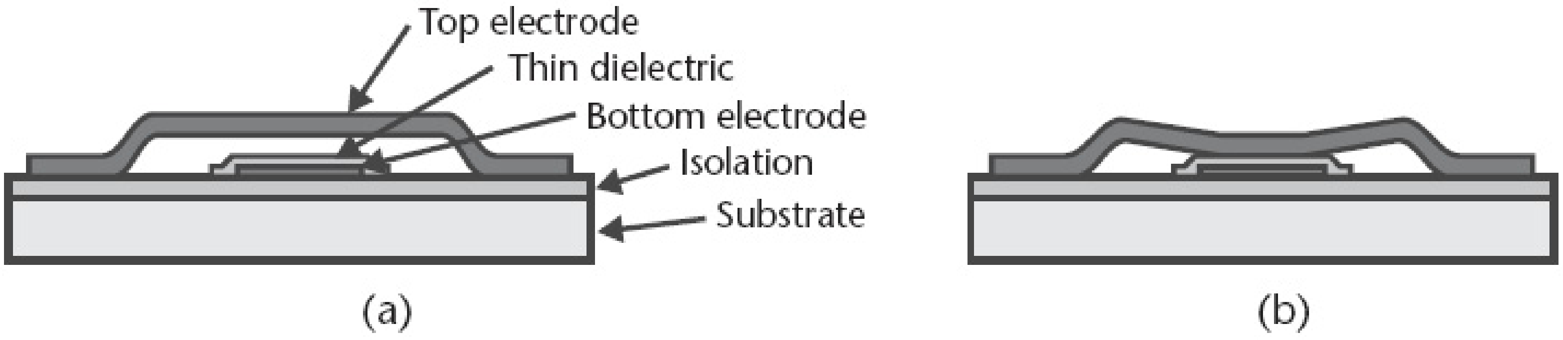


MEMS/NEMS in RF Applications

- **Microelectromechanical Switches**
  - In cellular phones, they can rapidly isolate and connect the send and receive channels to a common antenna
  - The key desirable parameters in RF switches are
    - low insertion loss and return loss (reflection) in the closed state
    - high isolation in the open state
    - high linearity
    - high power-handling capability during switching
    - low operating voltage (for portables)
    - high reliability (particularly a large number of cycles before failure)
    - small size and low cost.

Membrane shunt switch

- 2-μm-thick layer of gold is suspended 2 μm above a 0.8-μm-thick gold signal line, which is coated with about 0.15 μm of insulating silicon nitride
- The membranes have a span of 300 μm and lengths of 20 to 140 μm
- Application of a 15-V dc voltage to the signal line (in addition to the ac signal) pulls the gold membrane down to the nitride, shunting the signal line to ground
- The use of an insulator prevents this switch from working at dc and low frequency



Membrane shunt switch

- **In the closed state,**
  - The connection is made by capacitive coupling, which is only useful at high frequency
  - Insertion loss in the closed state is less than 0.6 dB over the range of 10–40 GHz, with a return loss of less than −20 dB
  - The silicon nitride could be made even thinner for a lower insertion loss, but it is already at the minimum thickness required to prevent breakdown with the required dc operation voltage
- **In the open state,**
  - There is clearly a capacitor that causes undesired coupling
  - The gap could be increased for greater isolation (at least 20 dB is desired), but this would require an even greater actuation voltage
  - The measured ratio of open to closed capacitance in this design is about 17

Discussion and Course Evaluation

COMSOL Ideas and Names