Micro Sensors and MEMS at UT-Austin

MEMS: Microelectromechanical Systems
What's the big deal about little machines?

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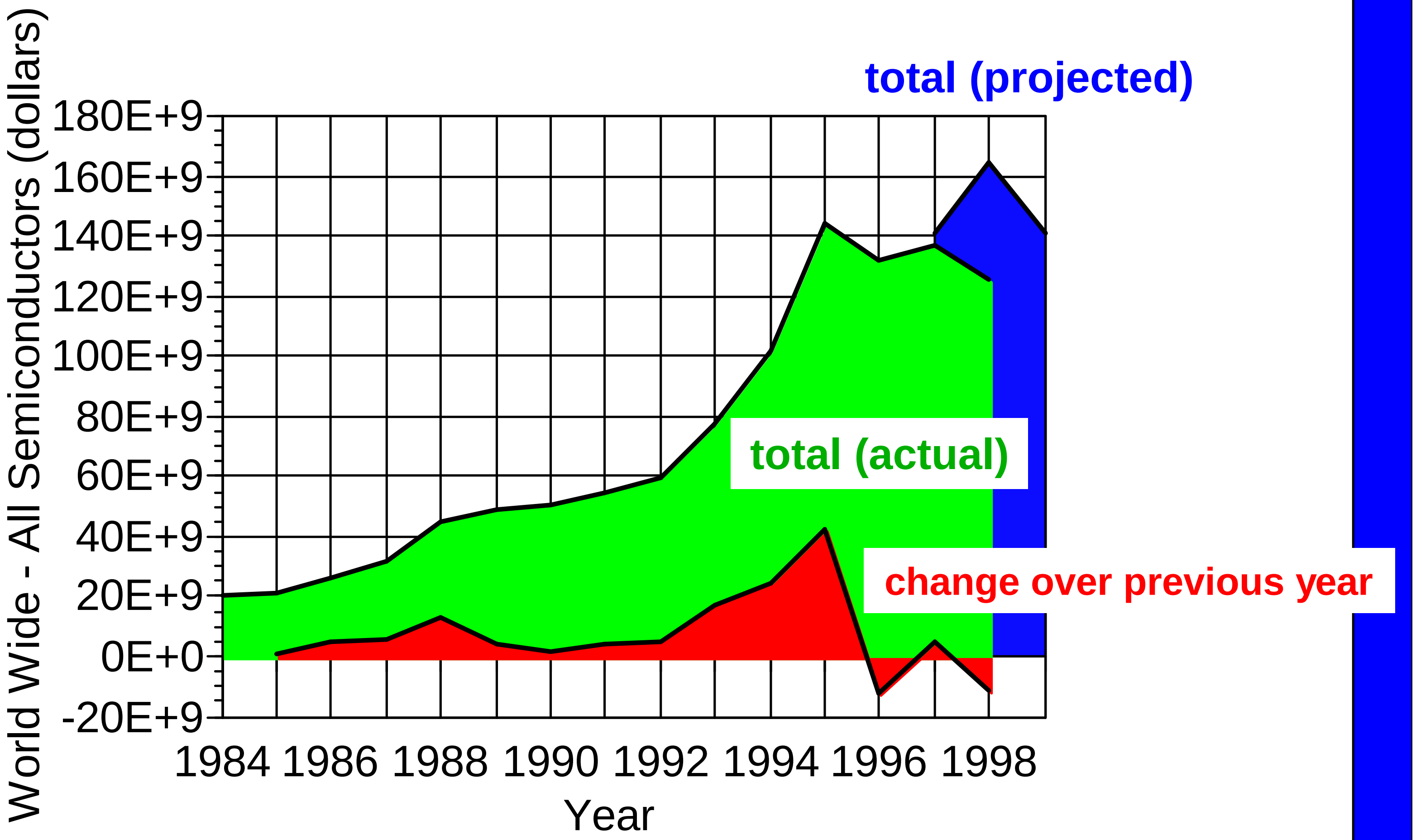
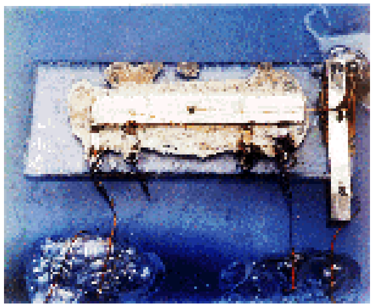
Why use integrated circuit manufacturing techniques?



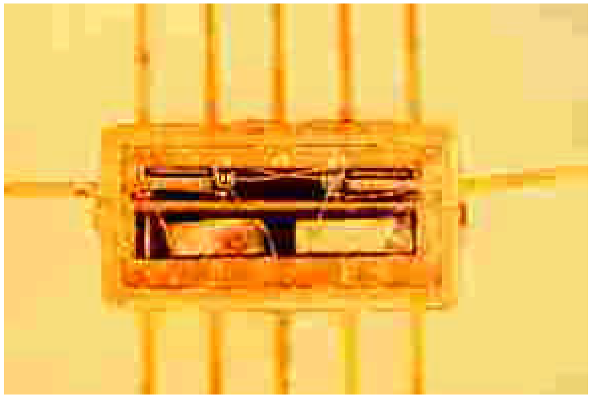
- **World-wide sales (all semiconductors): over $150 billion dollars**

Selected moments in solid-state electronics

- 1951: manufacturable technique demonstrated using "grown junctions"
- 1954: photoresist technology applied to transistor fab
- 1954-58: TI monopoly on silicon transistors
- Sept. 1958: Jack Kilby (TI) patents "Solid Circuit," monolithic Ge Phase-shift oscillator & flip-flop



http://www.ti.com/corp/docs/history/firsticnf.htm



http://www.tcm.org/html/history/detail/1958-intcirc.html

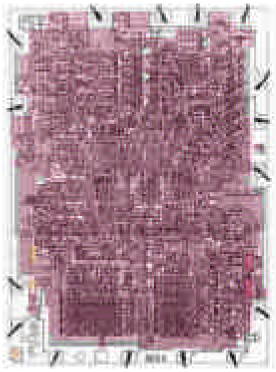
Selected moments in solid-state electronics

- **1959: truly planar IC process by Noyce (Fairchild)**

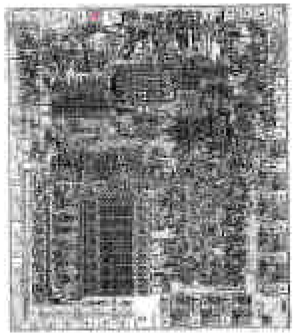
- **Early 1960's: Motorola joins "Big Three" (TI, Fairchild, Motorola)**
- **1960's: Bipolar versus MOSFET debate rages**
- **1966: TI's first MOS IC (binary-to decimal decoder)**
- **1968ish: Intel founded by ex-Fairchild employees (Noyce & Moore)**

Selected moments in solid-state electronics

- **1971: first "microprocessor": Intel 4004, 2300 transistors**

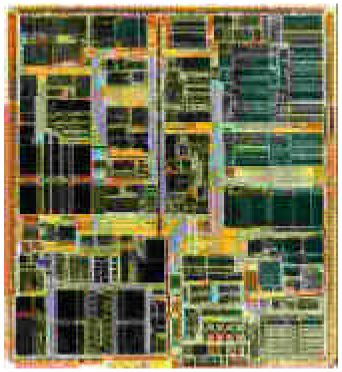


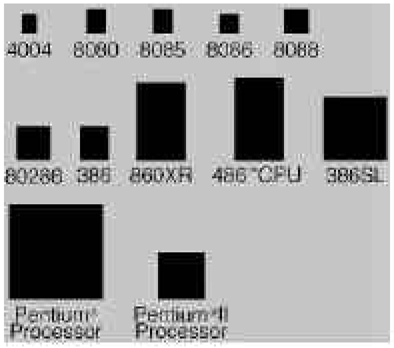
- **1974: first "PC" (the Altair), Intel 8080 microprocessor**



- **1978: IBM PC, Intel 8086/8088**
- **1997: Intel Pentium® II, 7.5 million-transistors**

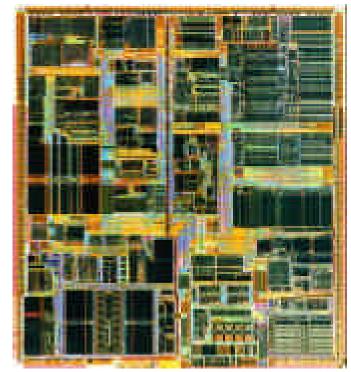
http://www.intel.com/intel/museum/25anniv/hof/hof_main.htm



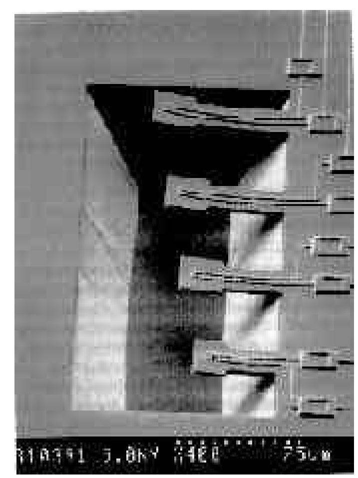


Using integrated circuit manufacturing to make “micro” machines

- **Intel Pentium® II, 7.5 million-transistors**
  - **about the size of a quarter, few square microns per transistor**

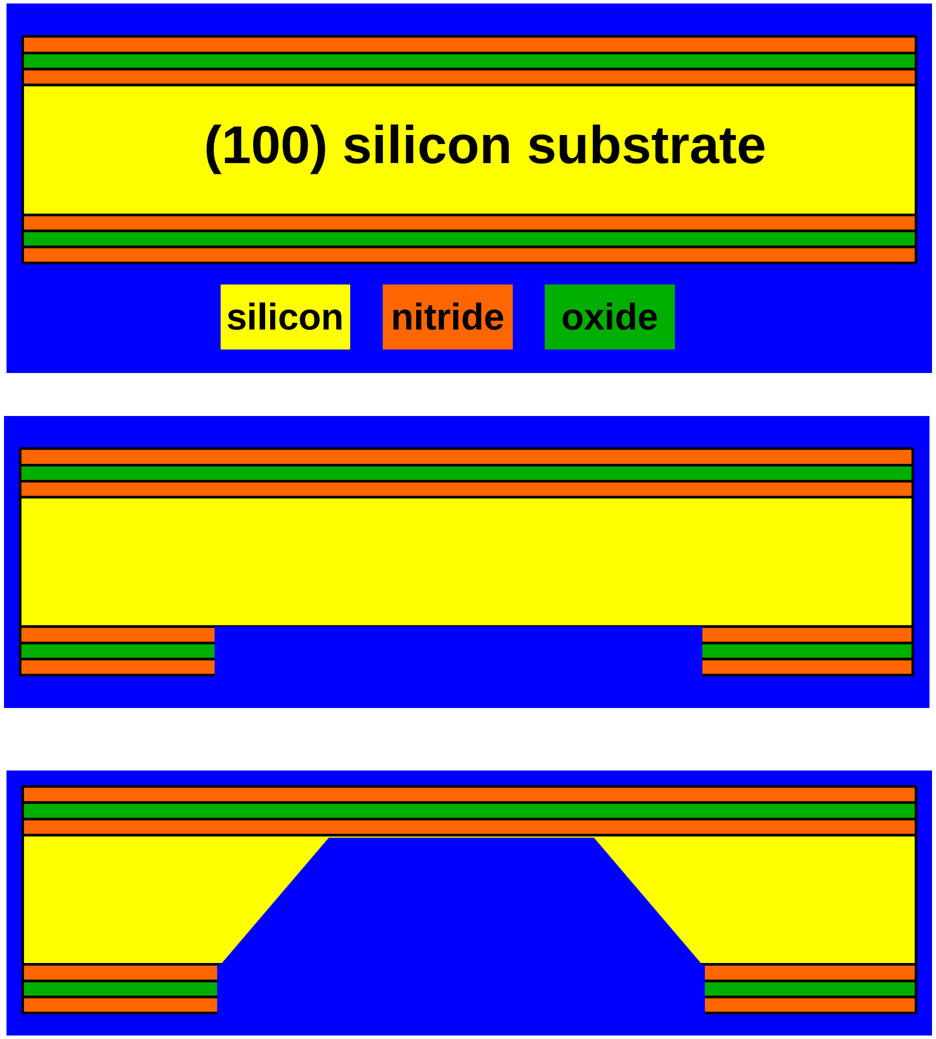


- **“Diving boards” made out of glass on a silicon substrate**
  - **~tens to hundreds of square microns per device**



Ristic, Sensor Technology & Devices

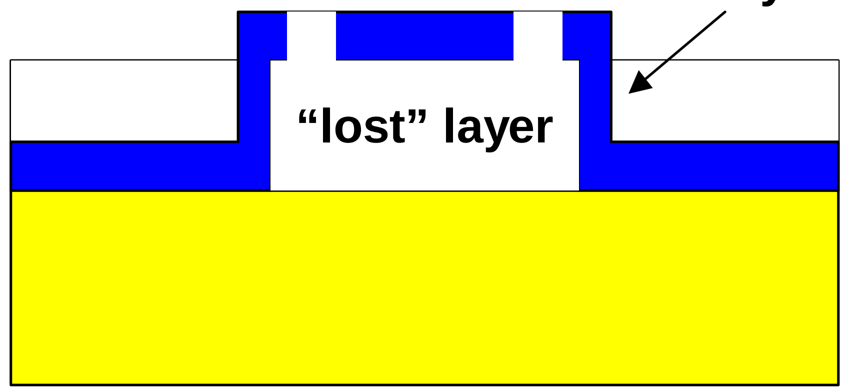
Basic micromachining processes: bulk micromachining

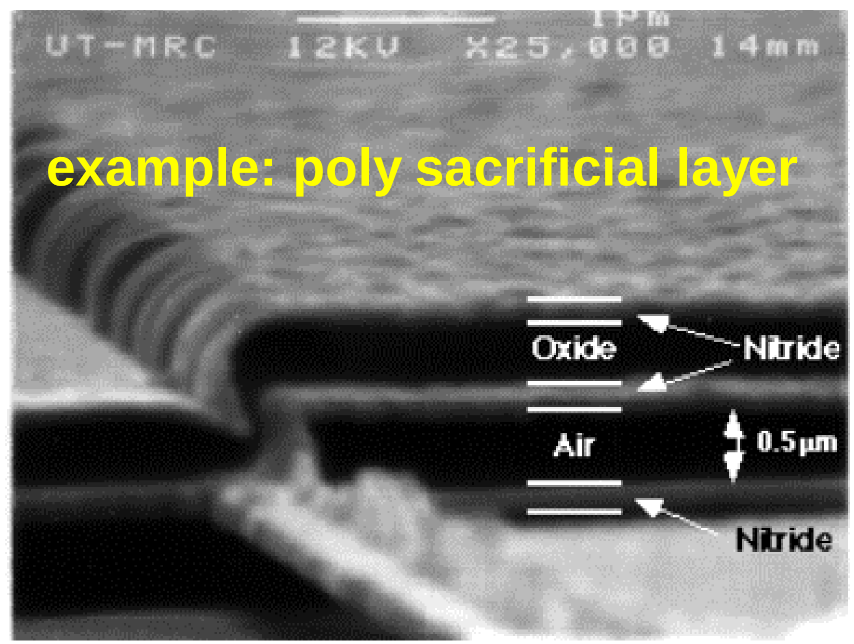


- schematic view of fabrication procedure for a planar diaphragm:
  - deposition of silicon nitride, silicon dioxide, and silicon nitride by LPCVD;
  - patterning and plasma etching on the back side of wafer;
  - anisotropic etching using KOH at 110? C

Basic micromachining processes: surface micromachining

- process is essentially a "lost layer" approach
  - deposit and pattern layer
  - overcoat to make "mold"
  - selectively remove "sacrificial layer"
    - "lost layer" is usually either poly or oxide





Why try to use IC fabrication tools to make machines?

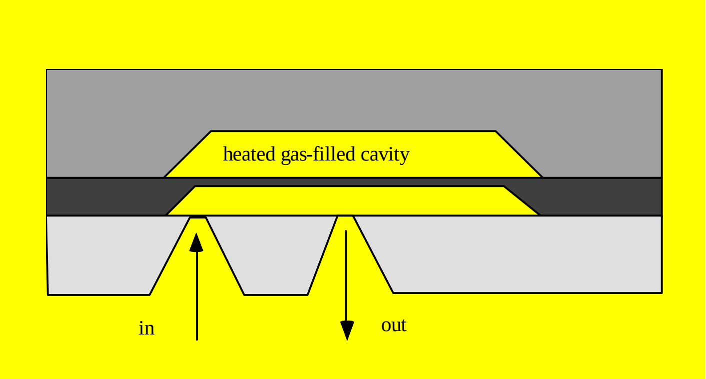
- **belief: silicon technology is cheap**
  - **$1 Billion fabs are NOT cheap, but the unit cost can be low at very large volume**
- **fact: IC fabrication is "cheap" only in really big volume**
  - **when might we really need that many machines??**
- **(microelectronics) belief: everything gets better when you make it smaller**
  - **obviously NOT true for EVERYTHING!**

Where are the targets of opportunity for "small" machines?

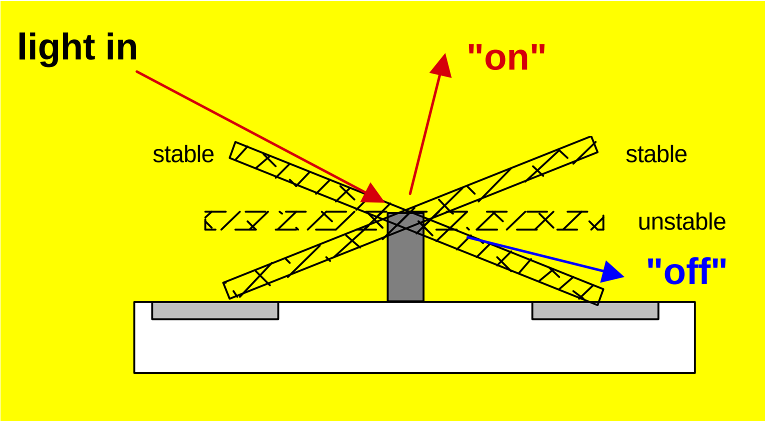
- (If you know, tell me, please)
- sensing?
  - velocity, acceleration, temperature, pressure, distance are main "mechanical state variables”
  - chemical detection / analysis
- actuation?
  - what do you control?: fluid flow, object position
  - motors?
- other application domains?
  - optics? electronics (field emission devices, vacuum microelectronics)?

MEM actuators that might work

- "mini" valves to replace solenoid-actuated valves
  - many used in systems to control "macro" pneumatic actuators
  - uses resistively-heated, gas-filled, sealed cavity for actuation

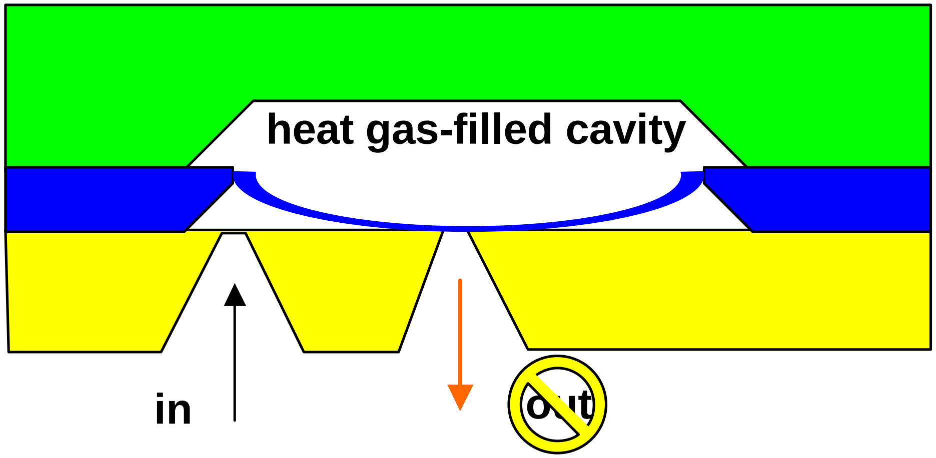


- optical applications
  - optical beams apply "no" force on system
    - only work needed is that to move the MEM device itself
  - TI's "Deformable Mirror Devices" (DMDs)



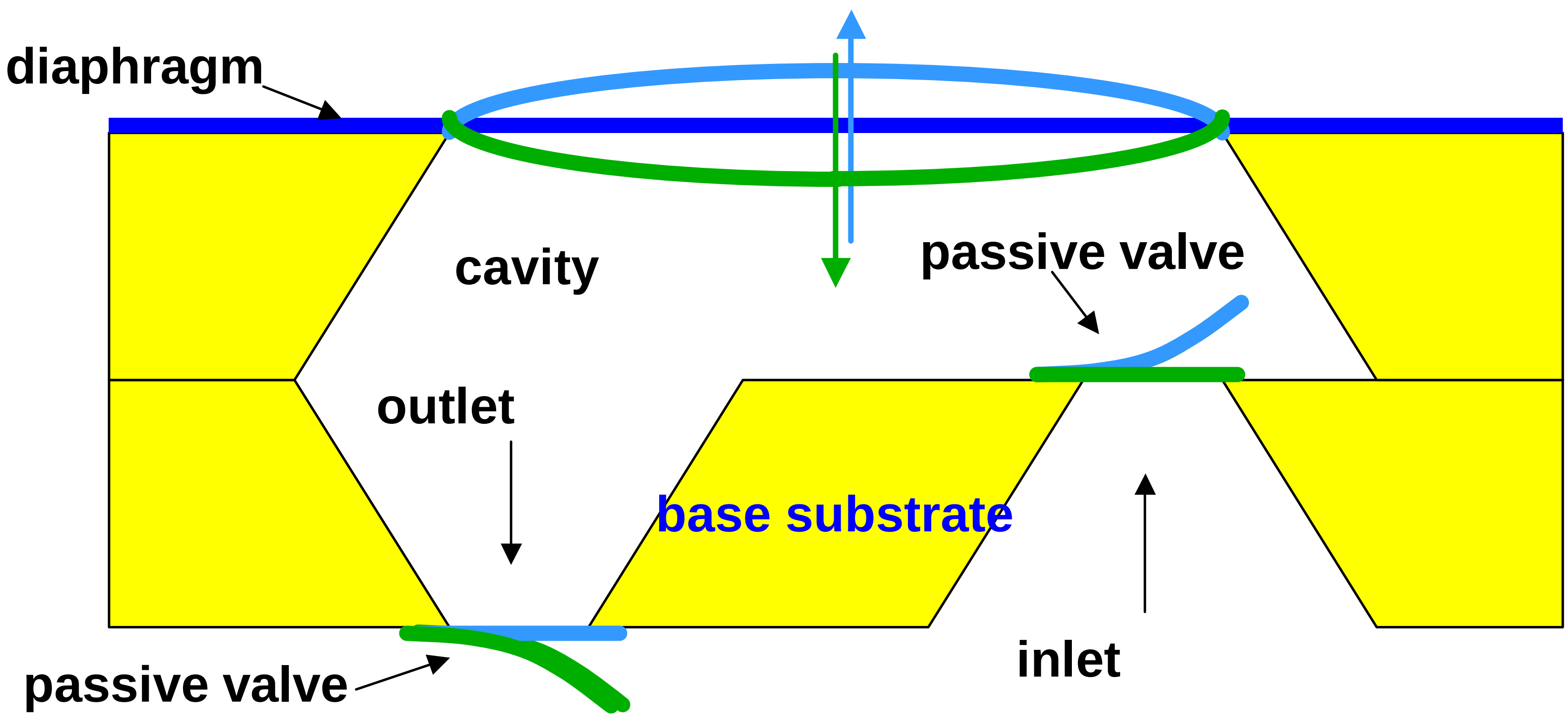
A "mini" MEM device that seems to make sense

- "mini" valves to replace solenoid-actuated valves
  - many used in systems to control "macro" pneumatic actuators
  - many used in "analytical chemistry" equipment
- uses wafer bonding, simple "bulk" micromachining
  - Redwood Systems attempting to commercialize
  - uses resistively-heated, gas-filled, sealed cavity for actuation



Other fluidic components: basic pumps

- membrane actuation via
  - bimorph
  - piezo-electric
  - thermo-pneumatic

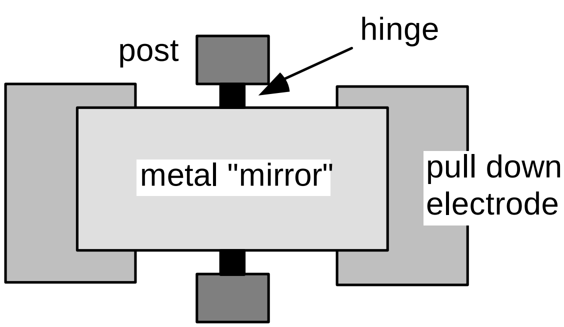


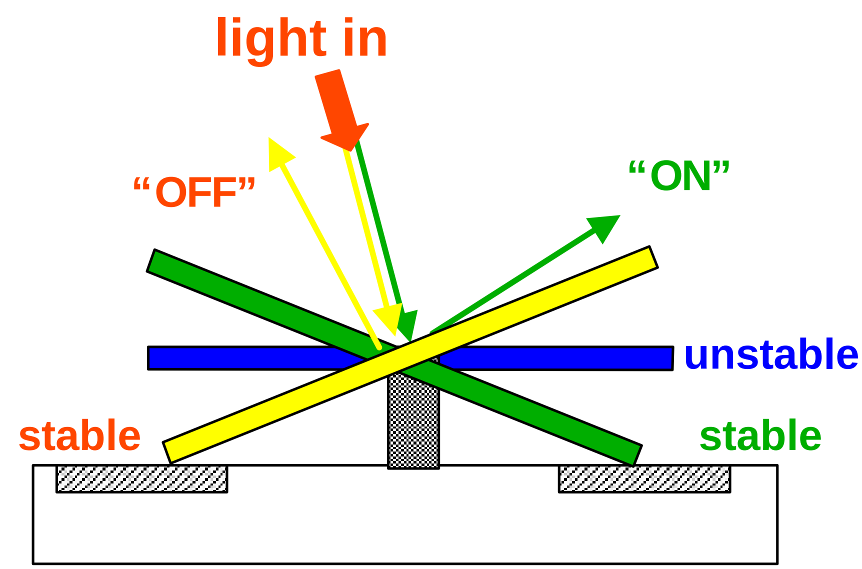
Summary of micro pumps and valves

- micropumps use moving parts:
  - piezoelectric, thermo-pneumatic, pneumatic , electrostatic actuation
    - flap or membrane is used for the definition of flow direction of the fluid
  - problems: high temperature processing for wafer bonding, blockage of optical paths for detection, long term reliability
    - room temperature HF bonding
    - lamination using dry film resists
- micropumps without moving parts:
  - micro bubble pump: use variation in vapor pressure and surface tension
    - requires vaporization
  - Electro-Hydro- Dynamic (EHD) pump

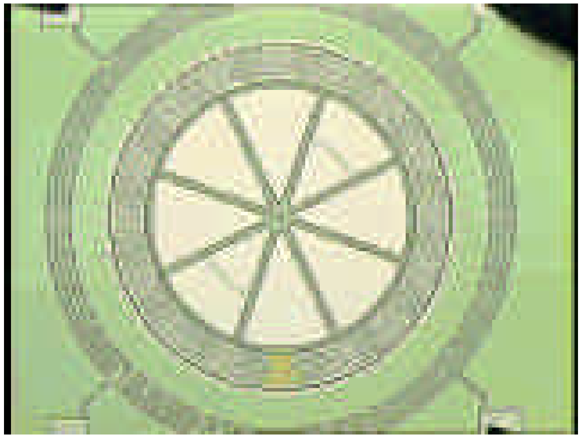
MEM actuators for optical applications

- optical beams apply "no" force on system
  - only work needed is that to move the MEM device itself
  - electrostatic pull-down commonly used
- modulators, "tunable" filters, display devices
  - Bloom at Stanford: deformable grating light valves
  - TI's "Deformable Mirror Devices" (DMDs)
    - ARPA sponsored Fab line (Dean Collins)
    - patented in early '80s

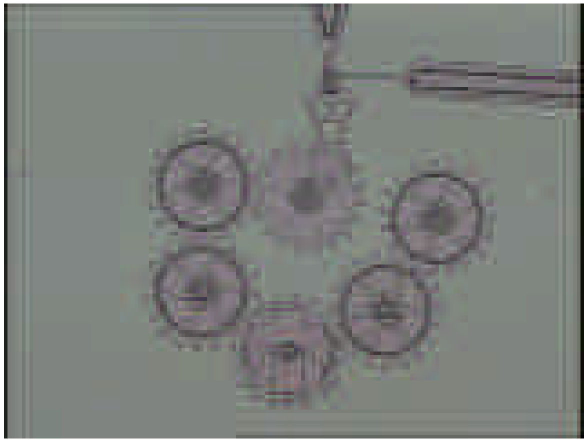




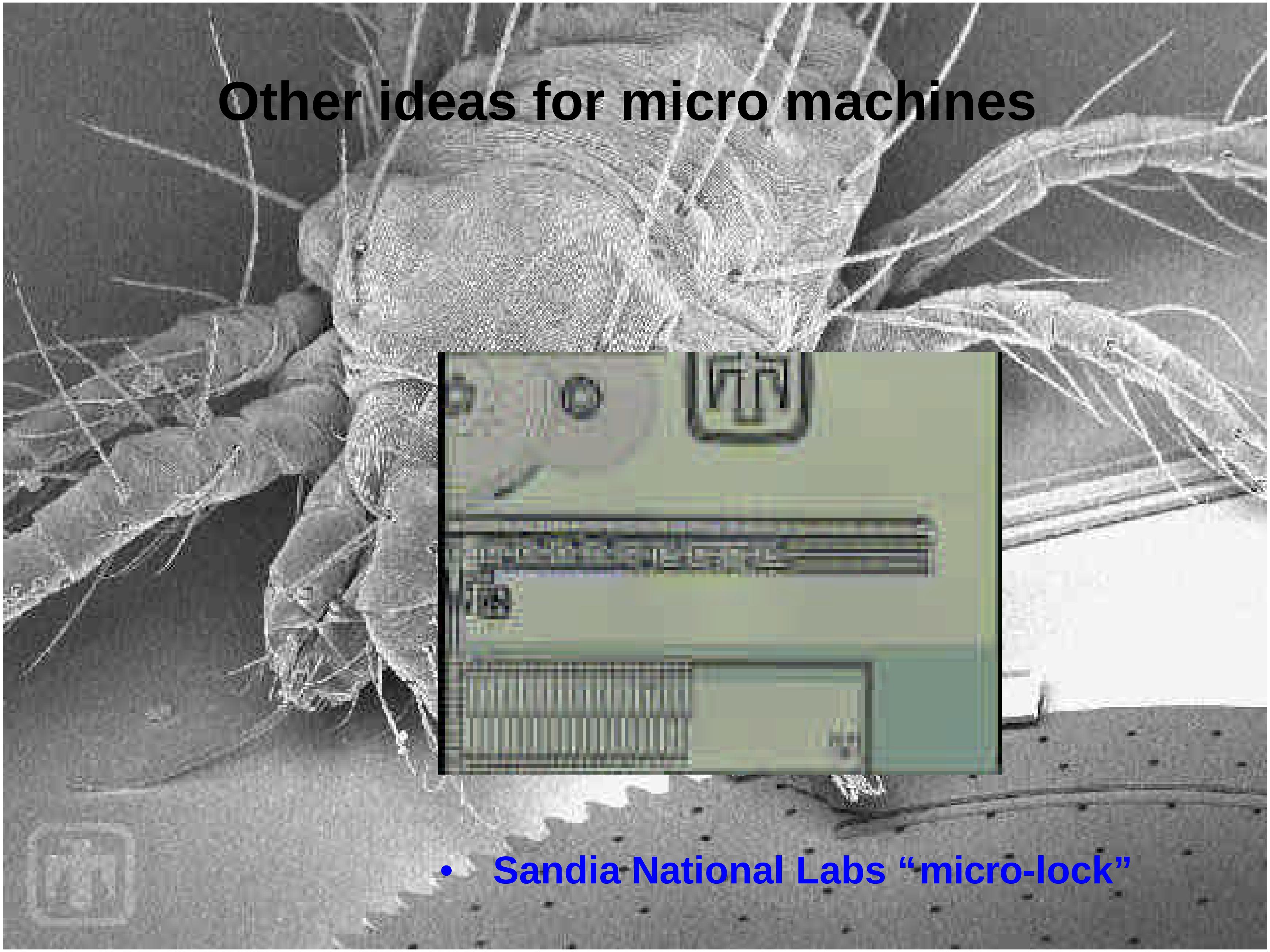
mems micro-motors - a tour-de-force in processing



Sandia National Labs



Other ideas for micro machines



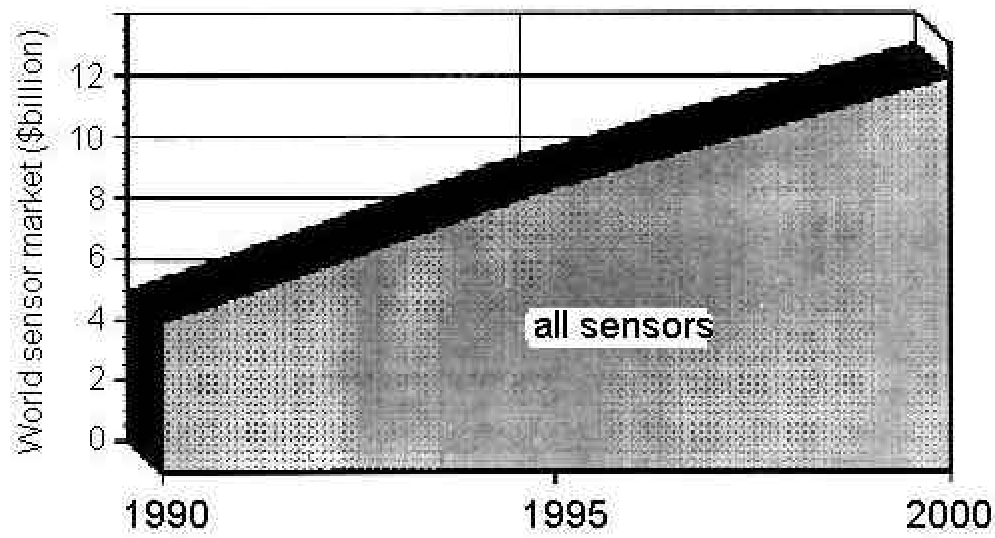
- Sandia National Labs “micro-lock”

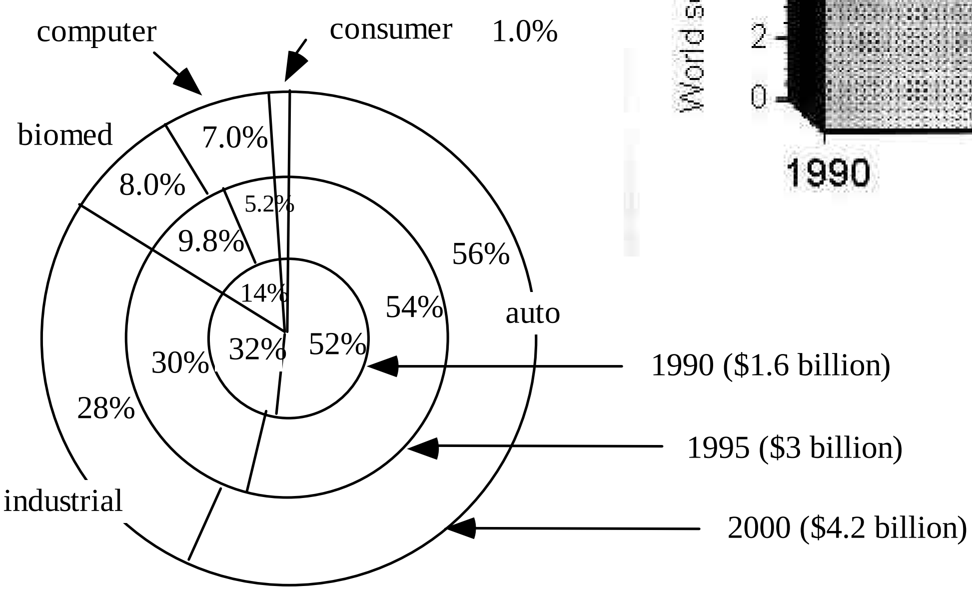
Actuation problems

- actuators must do work on the environment
  - may require large forces, or force “density”
  - most machines require at least 3-axis motion
    - hard to do lithography on things that are not flat
    - IC fabrication is basically a planar (2-D) process
  - result: MEMS have been primarily 1-D systems, motion usually contained in plane of sample
- friction is critical
  - typical machining tolerances: 1 mil out of tens of inches (1 part in 10^5)
  - IC rule of thumb: at l_{min}, "alignment" accuracy 1/3 to 1/5 of l_{min} (2 parts in ten)
  - surface finish in micromachining generally stinks compared to "conventional" machining
- result: motor life times limited, shaft wobble limits ability to do work!

Sensors: a more reasonable MEMS market

- **Automotive applications are by far the largest segment**





from L. Ristic, Ed., Sensor Technology and Devices. Boston: Artech House, 1994.

What do you sense?

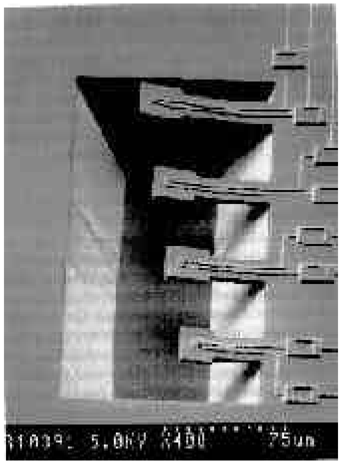
- velocity, acceleration, temperature, pressure, distance are main "mechanical state variables"
  - mechanical part of most MEM sensors produce displacement in response to the environmental stimulus
    - how do you sense the mechanical movement?
      - electrical: resistance, capacitance, inductance
      - optical: interference, reflectance, transmittance
- design?
  - sense movement
  - sense restraining force needed to prevent motion

Other micromachining examples

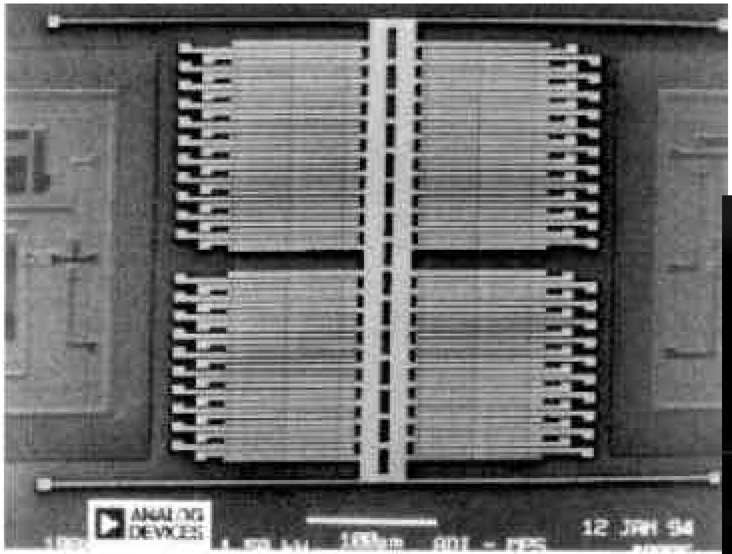
- use microfabrication techniques to make structures that are not necessarily mechanical
  - basically electronic devices
    - "chemFETs," Hall effect and the like
  - thermal devices: use micromachining to form structures with “tailored” thermal properties
    - bolometers (a radiation sensor)
    - hot wire anemometers, TC pressure gauges, flow gauges
  - chemically-induced changes
    - electrical, optical

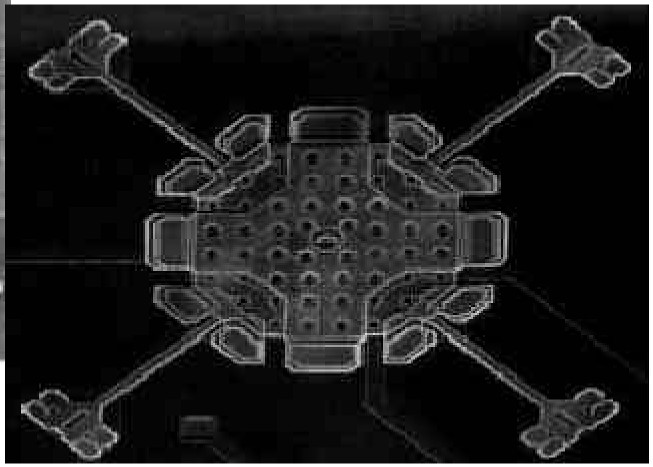
MEM accelerometer: commercially viable for air bag switches

- “integrated” accelerometers
- use "proof" weight suspended by micromachined “springs”
  - force-induced displacement converted to an electronic signal (piezoresitive or capacitive measurement)



Ristic, Sensor Technology & Devices





Ristic, Motorola, from "Interface," Electrochem Soc. 1994

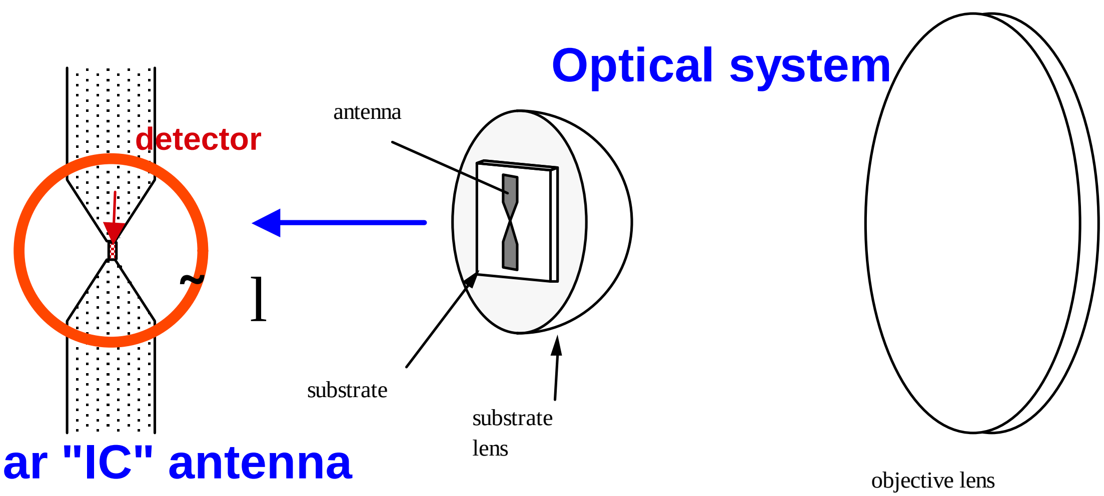
MEMS pressure sensors

- fairly common
  - Motorola has product line, as do others
- most use piezoresistive effects
  - implanted resistors in silicon membrane
  - pressure differential bends membrane, inducing stress, shifts R's
- some use capacitance change
- optical? (use fiber interconnect?)
- inductive?

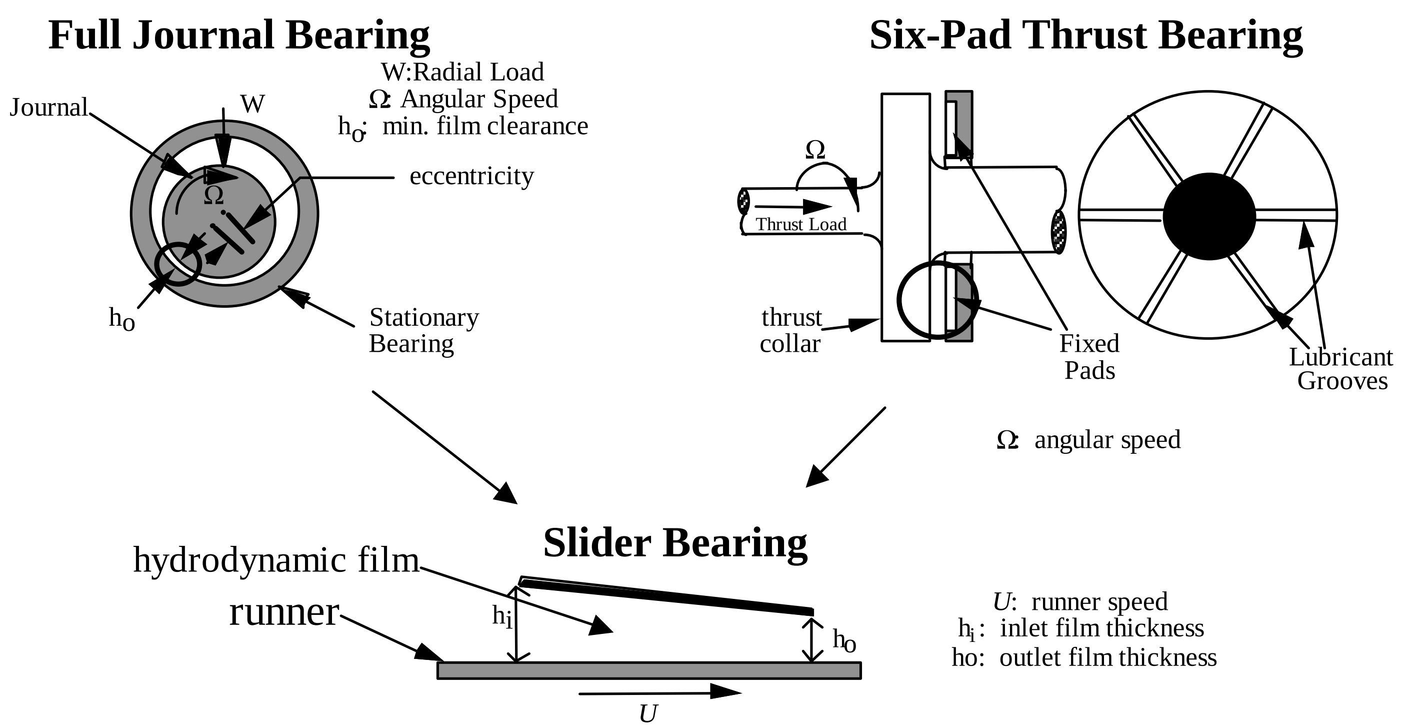
My group: background

- use of IC fabrication techniques in "non-IC" applications
  - original work in the area of focal plane arrays for millimeter to far infrared wavelength radiation
    - planar antennas and microbolometer detectors
  - thin film metal patterns designed primarily for electromagnetic function

- "micro-detectors" much smaller than wavelength
  - requires optical focusing and "antenna" structure



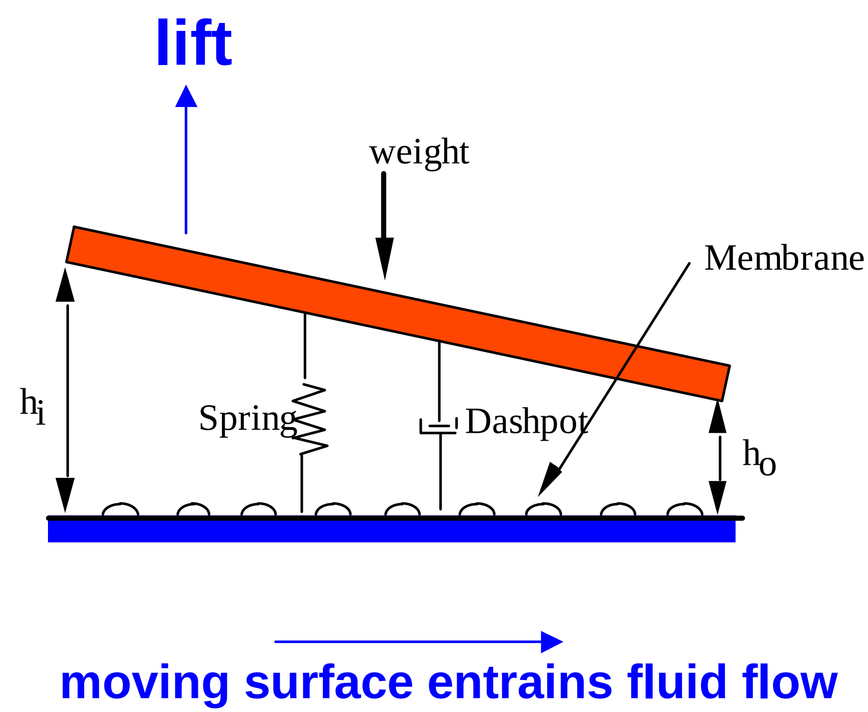
A mechanical system that matches mems size scale: bearings!



- gap is critical dimension in hydrodynamic bearings
  - independent of "size"
  - ten's of microns

Lubricant flow in hydrodynamic bearings

- load capacity of a bearing
  - area of pad
  - velocity of fluid, gap between runner and pad
  - there is no lift when stopped!
- surface features can have significant impact
  - simple, fixed features (etched)
    - change fluid flow during operation
  - active features: pneumatically actuated
    - "lift off" before start-up
- critical quantities to sense:
  - local pressure
  - gap between surfaces



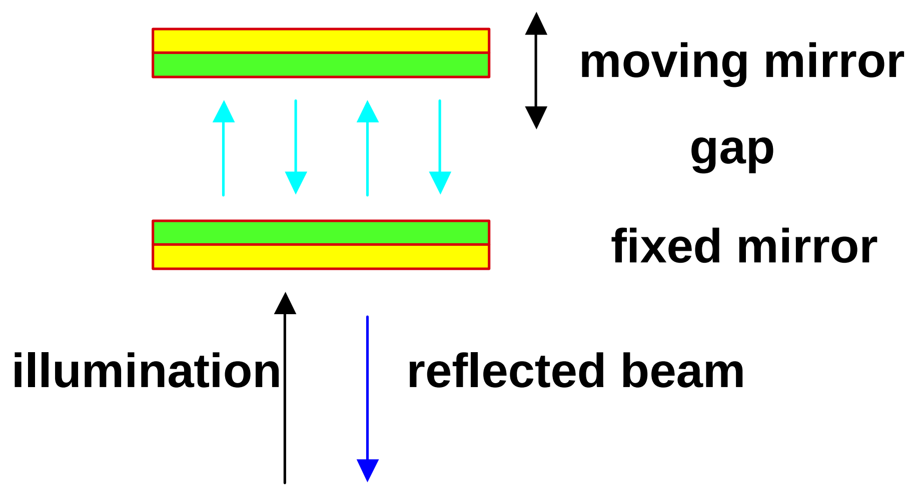
Optically-interrogated pressure sensors

- why use optical sensing?
  - bearing is hostile environment
  - immunity from EMI / noise
- if optical, what to sense?
  - displacement via changes in reflectance
    - need absolute displacement measurement!
  - interference gives highest sensitivity
- Fabry-Perot cavities
  - strong interference possible
    - "short" cavity: less ambiguity
    - design for linearity, sensitivity, yield?
  - how to fabricate?

Fabry-Perot based displacement sensors

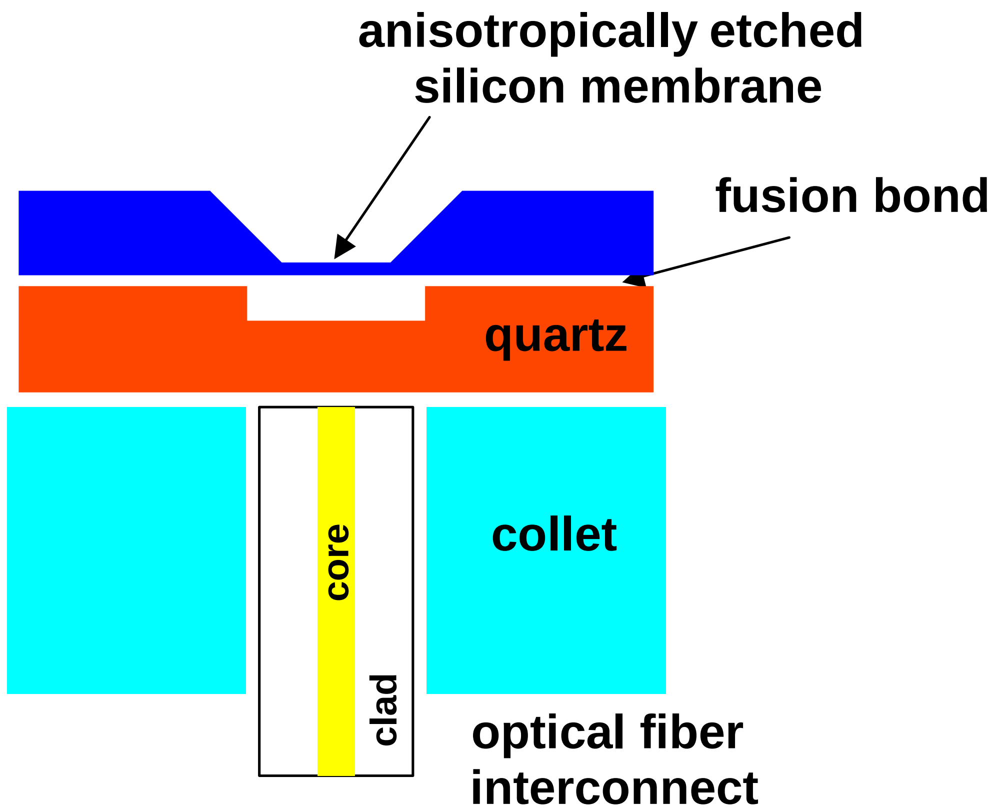
- motion of mirror changes reflectance
  - wavelength dependent
  - mirror-reflectivity dependent
- short cavity can use lower coherence source
  - g order l
- micromachined version
  - membrane supports moving mirror
  - optical fiber "interconnect"

Fabry-Perot cavity



Conventional F-P sensor

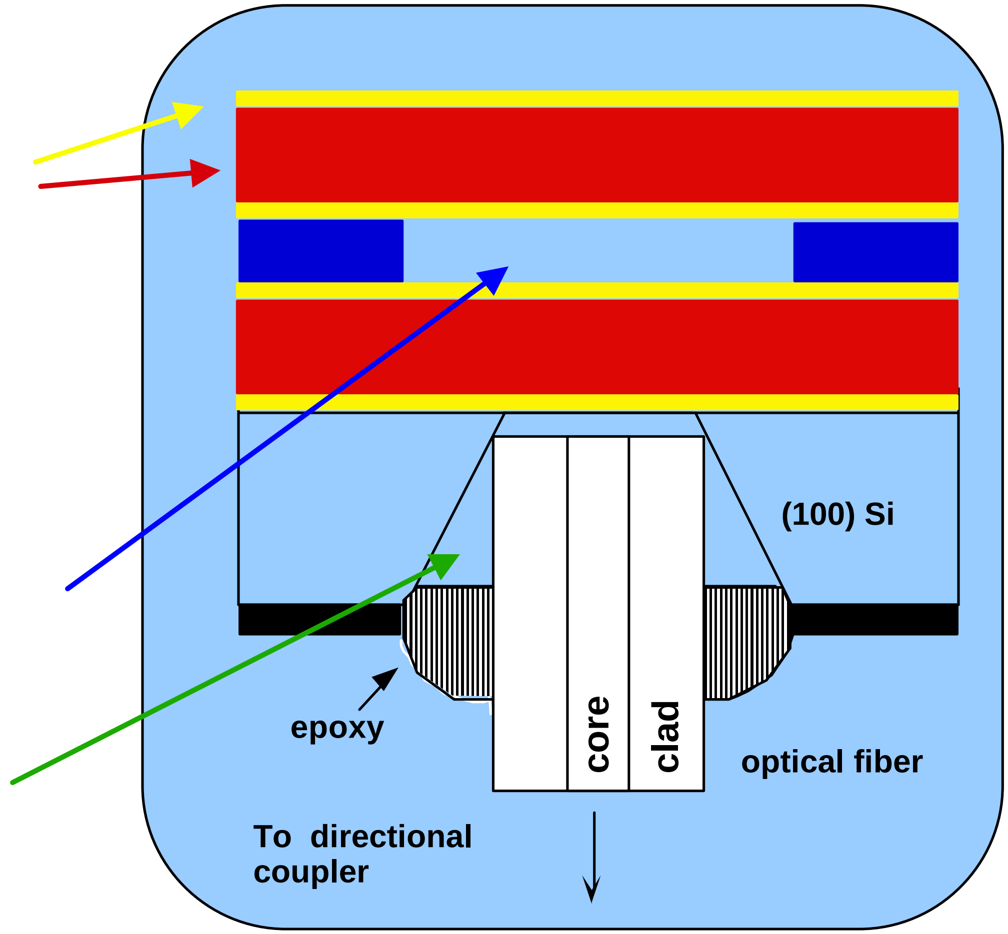
- requires three separate parts
  - top two etched, then fusion bonded
- membrane layer
  - boron-doped
  - doping depth sets thickness
- "gap" layer
  - wet-etched quartz
  - etch time sets g
- collet
  - drilled quartz to hold fiber



R. Wolthuis, G. Mitchell, E. Saaski, J. Hartl, and M. Afromowitz, "Development of Medical Pressure and Temperature Sensors Employing Optical Spectrum Modulation," IEEE Trans. Biomed. Engin., vol. 38, pp. 974-980, 1991, MetriCor Inc.

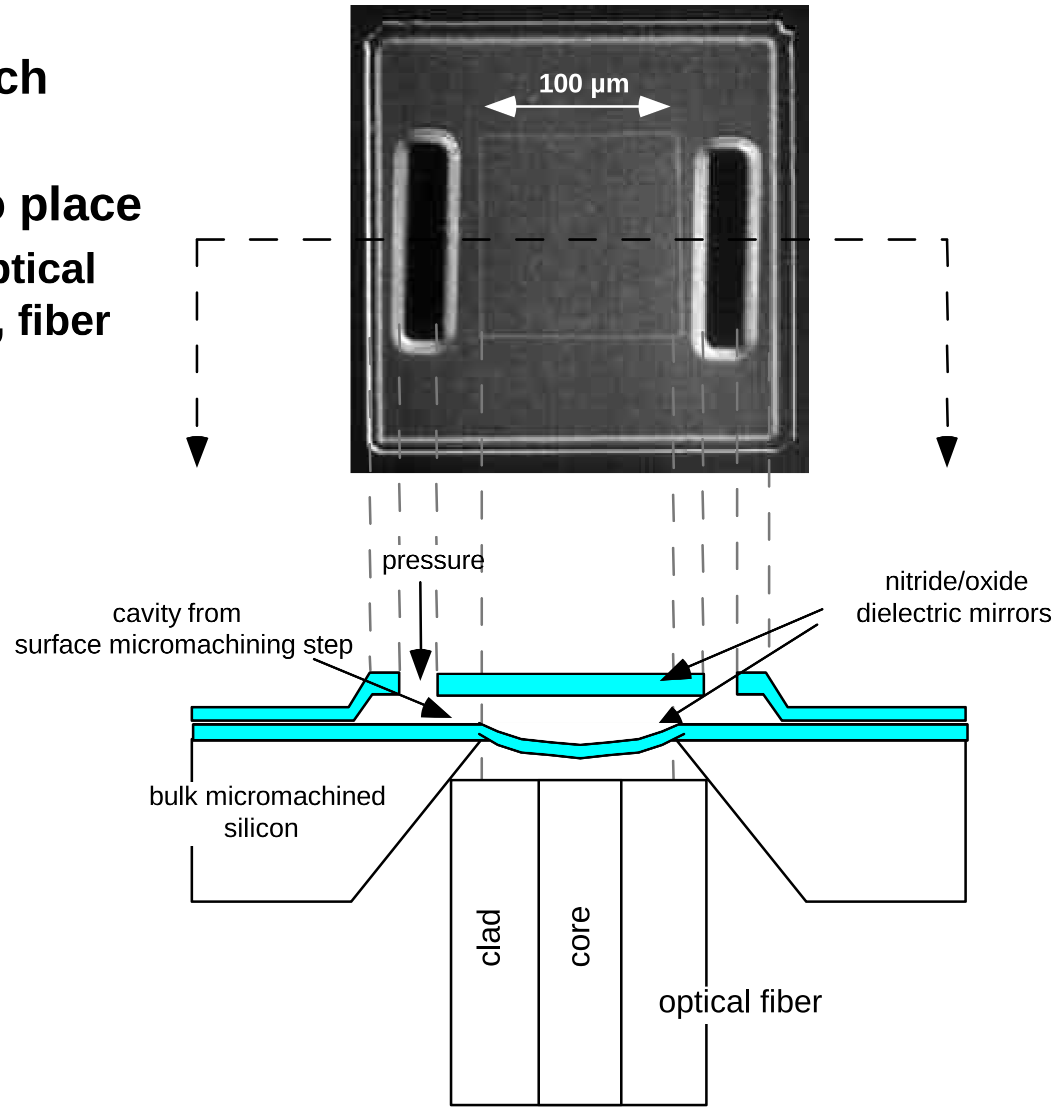
Surface micromachined F-P device

- use LPCVD to deposit layers
  - SiO2 / Si3N4 stacks used for mirrors/membranes
    - layer thicknesses tailor stress and reflectivity
    - 3:1 oxide/nitride thickness ratio for our process
  - poly used for sacrificial layer
    - thickness determines gap
- bulk anisotropic etch for optical access
  - no fusion bonding used



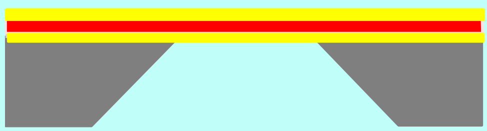
Complete micromachined F-P device

- prototype has "front" etch windows
- optical fiber "locks" into place
  - after insertion using optical positioner, apply force, fiber does not move

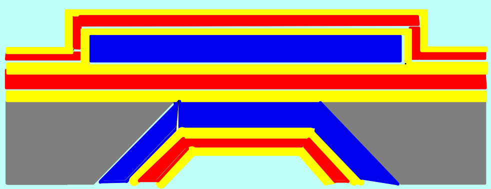


Fabrication of top and bottom diaphragm devices

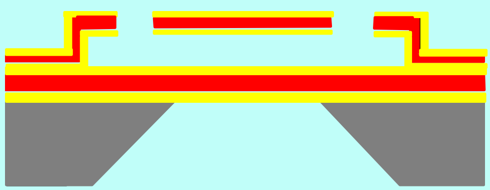
•bottom diaphragm
•top vented



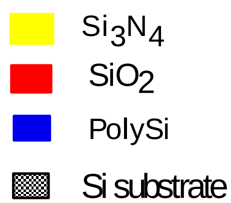
first LPCVD mirror



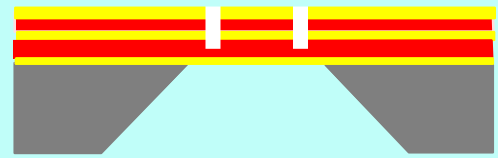
both mirrors, before poly etch



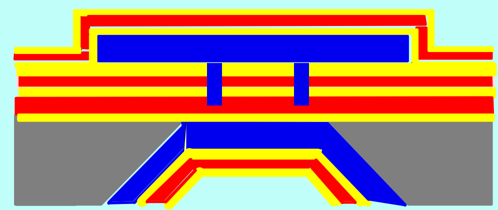
final device



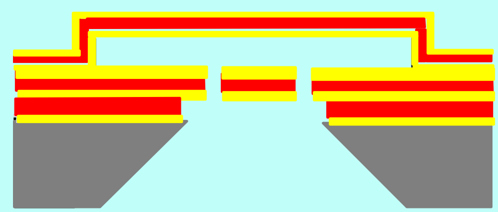
•top diaphragm
•bottom vented



first LPCVD mirror



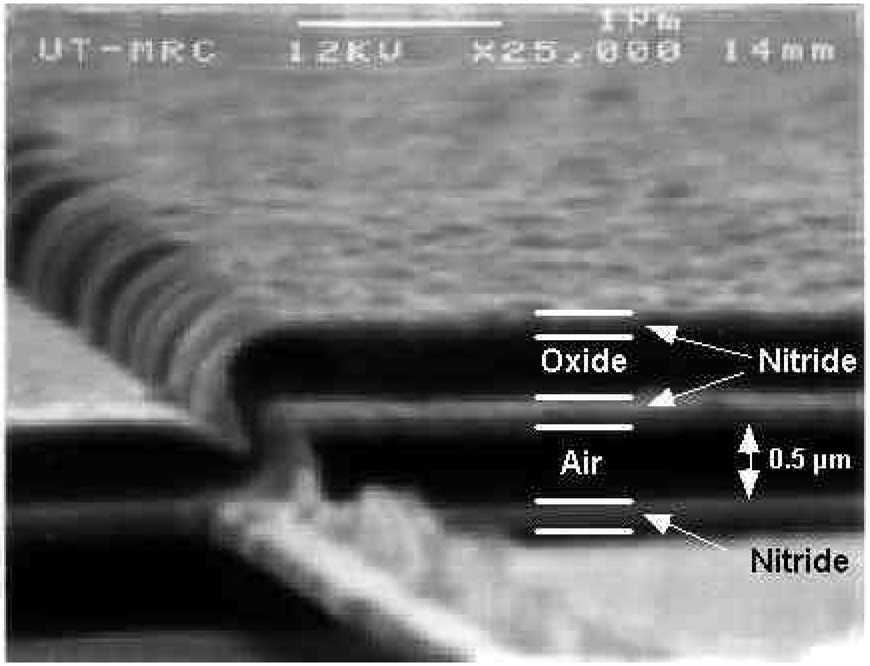
both mirrors, before poly etch



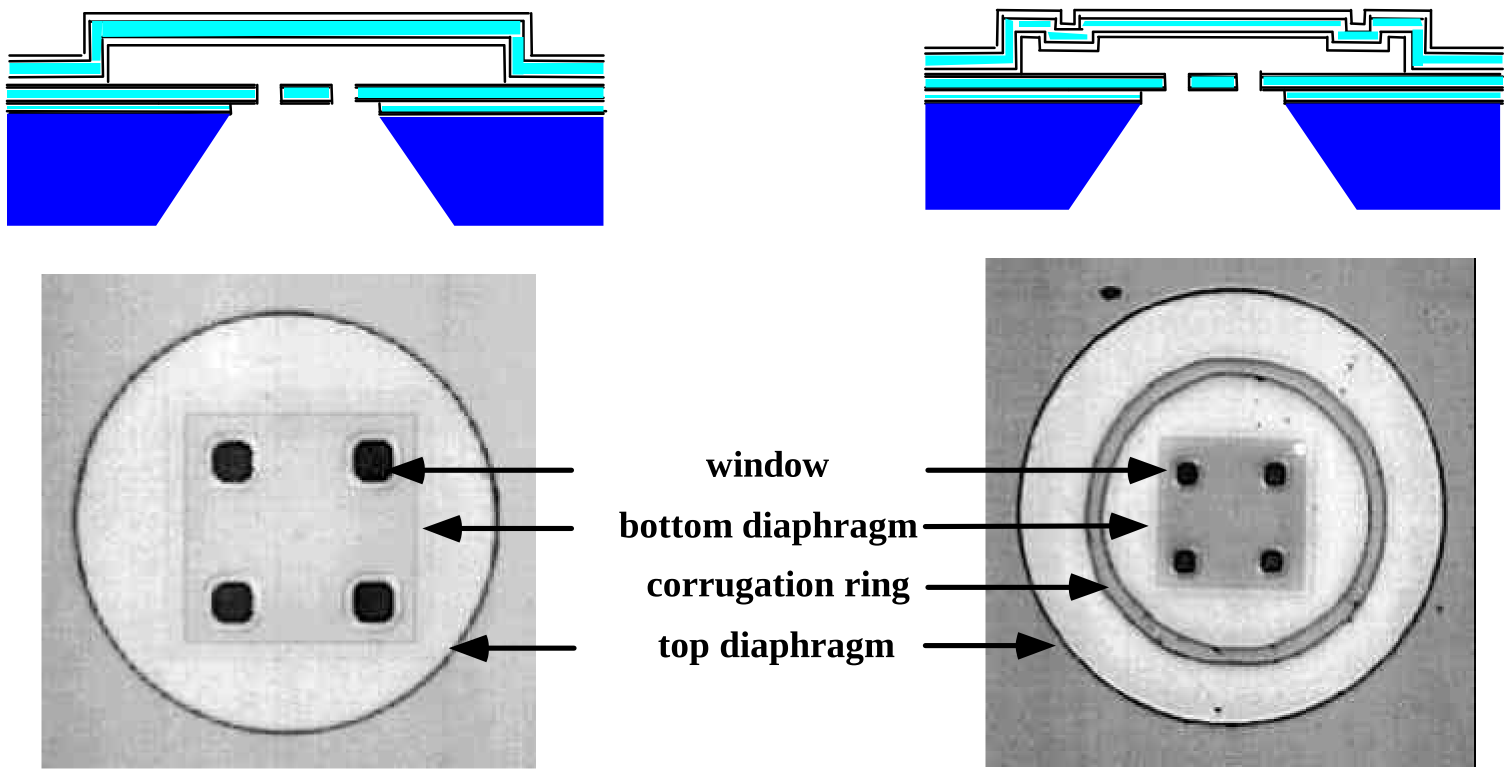
final device

Fabry-Perot cross section

- Si_3N_4 / SiO_2 / Si_3N_4 three layer stacks for mirrors
- membranes must remain flat after release!
  - net tensile stress
  - geometry important
    - poly sacrificial layer
    - etch window for poly removal



Top diaphragm pressure sensors: planar vs. corrugated

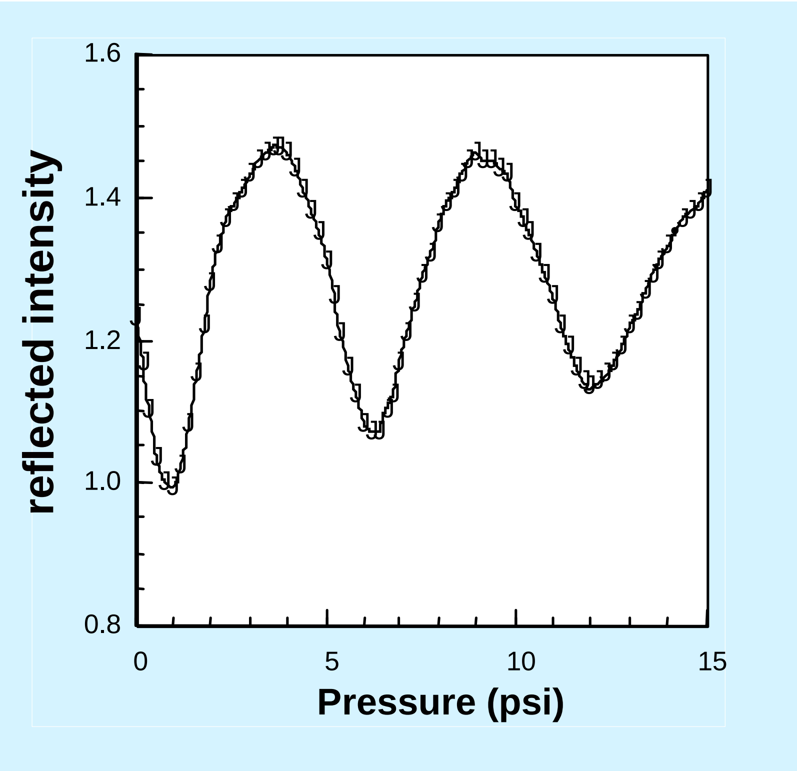


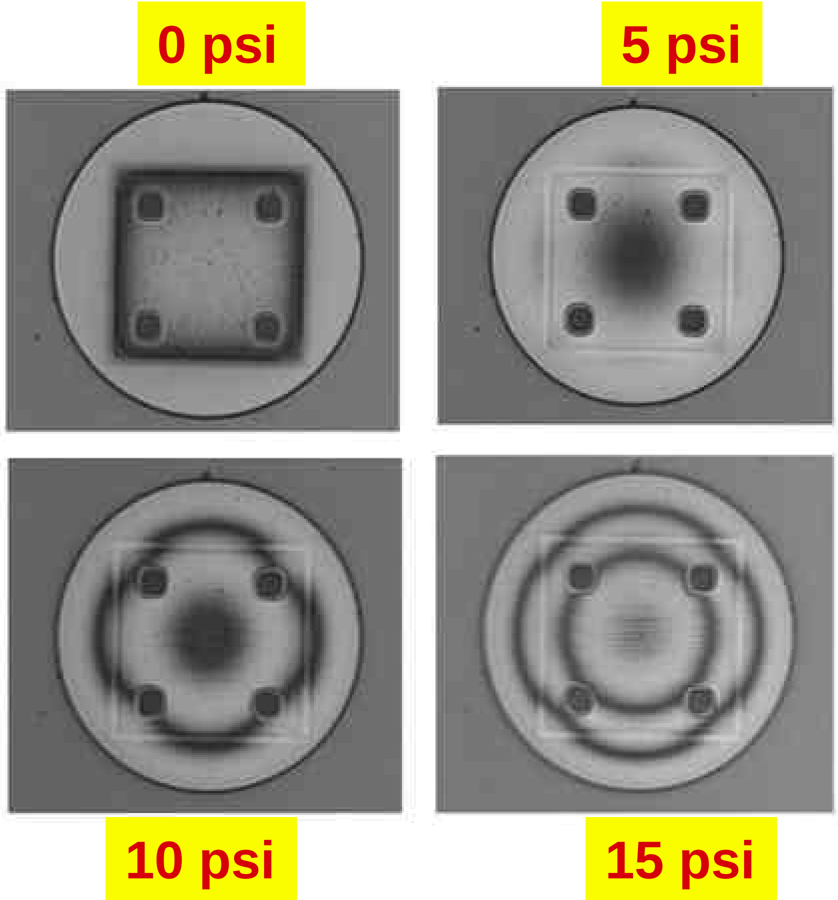
planar device

corrugated device

Interferograms

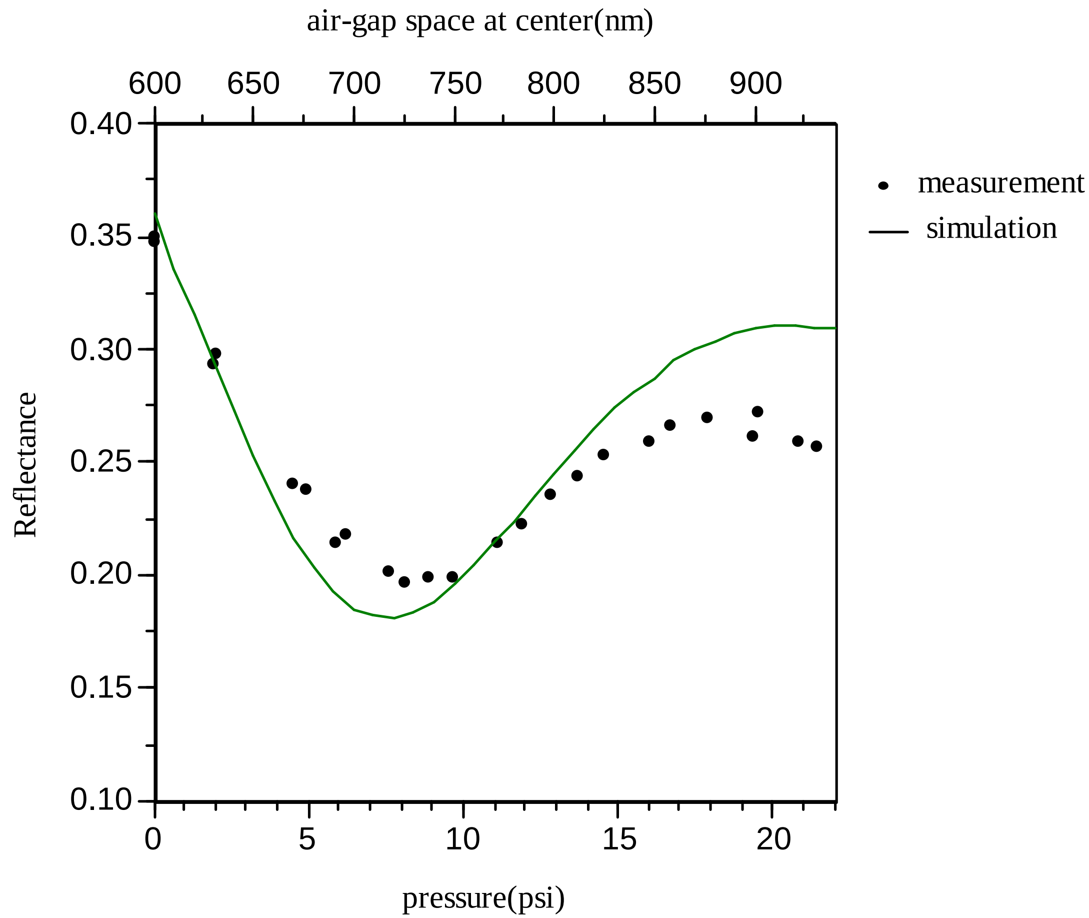
- 200 micron diameter top diaphragm
- 0.15 µm / 1.05µm / 0.15 µm thick





F-P sensor pressure measurement

- HeNe laser used for source
  - multimode fiber interconnect
- reduced sensitivity due to "averaging"
  - moving mirror pinned at perimeter
  - optically illuminated area large compared to membrane size
- plane wave model in excellent agreement with measurement



Manufacturing issues for Fabry-Perot pressure sensors

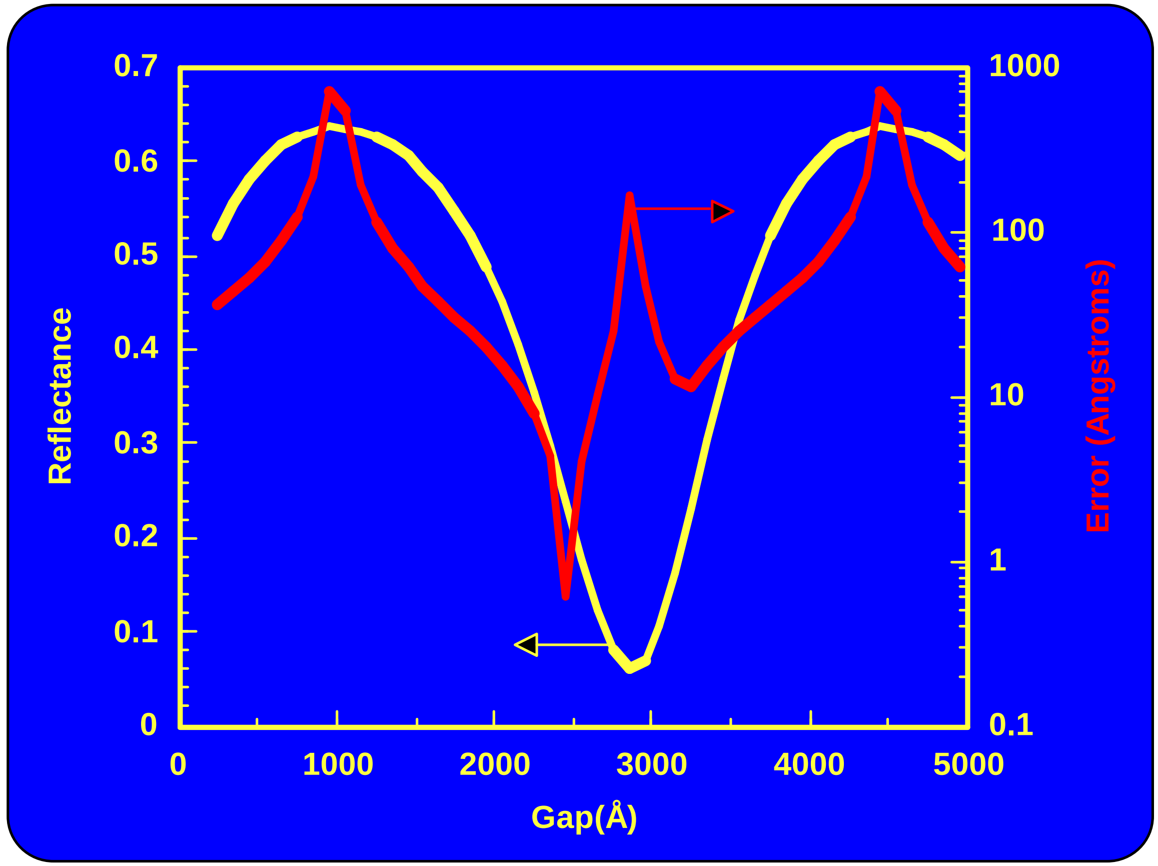
- basic sensor is VERY sensitive to variations in structure
  - reflectivity function of
    - actual gap
    - actual mirror layer thicknesses
  - "measured" gap unknown if layer thicknesses unknown
- possible solutions
  - individual calibration
    - not practical for low cost, high volume sensor
  - sort after manufacture
    - must design for maximum in-spec yield

FP design for maximum in-spec yield

- performance metric: accuracy
  - how close is given manufactured sensor to "ideal" response curve
- design space
  - initial gap (sacrificial layer thickness)
  - dielectric mirror layers: number and thicknesses
  - mechanical travel
    - compliance adjusted to match pressure range to travel
- is it possible to design the FP structure to maximize number of individual sensors with accuracy better than specified limit?

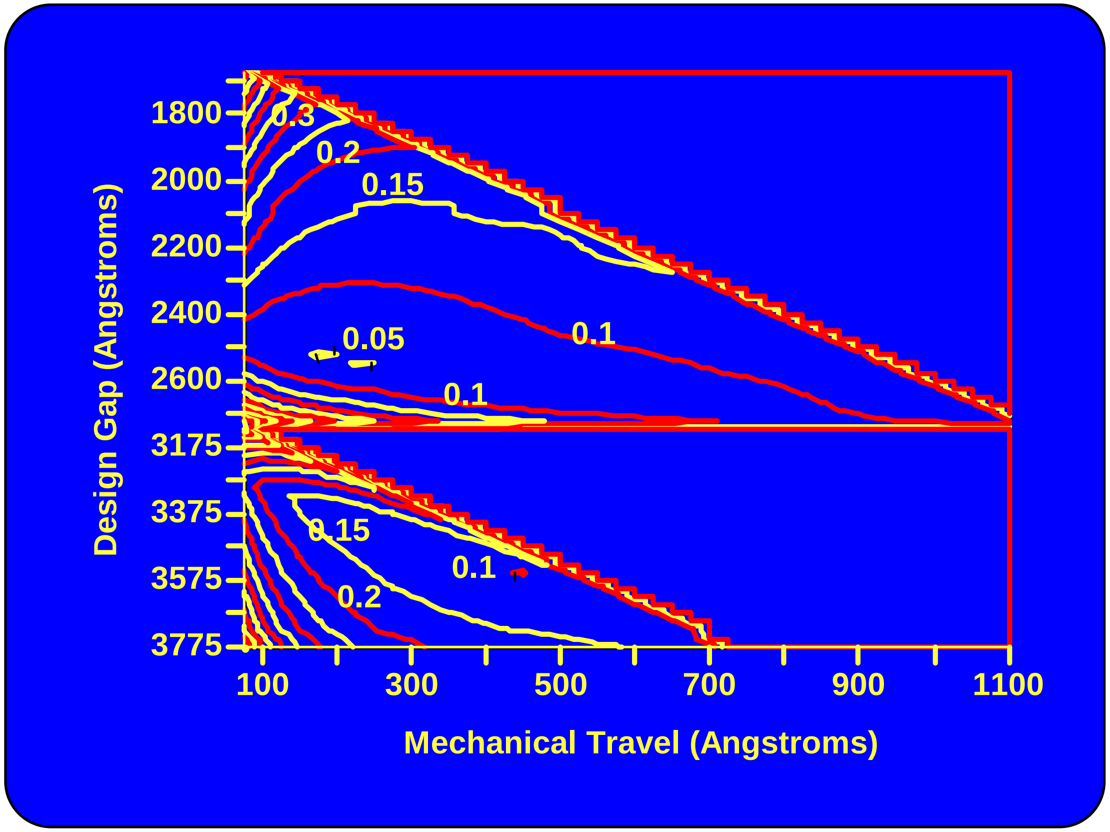
Single wavelength detection

- simple example:
  - thin metallic mirrors, nominal thickness fixed
  - plane wave model, including loss
- reflected intensity periodic in l/2
- gap uncertainty due to 3 Å uncertainty in 70 Å thick metallic mirrors
- note problem: how do you tell the difference between change in “interconnect loss” and change in pressure??



Error contours for single wavelength detection

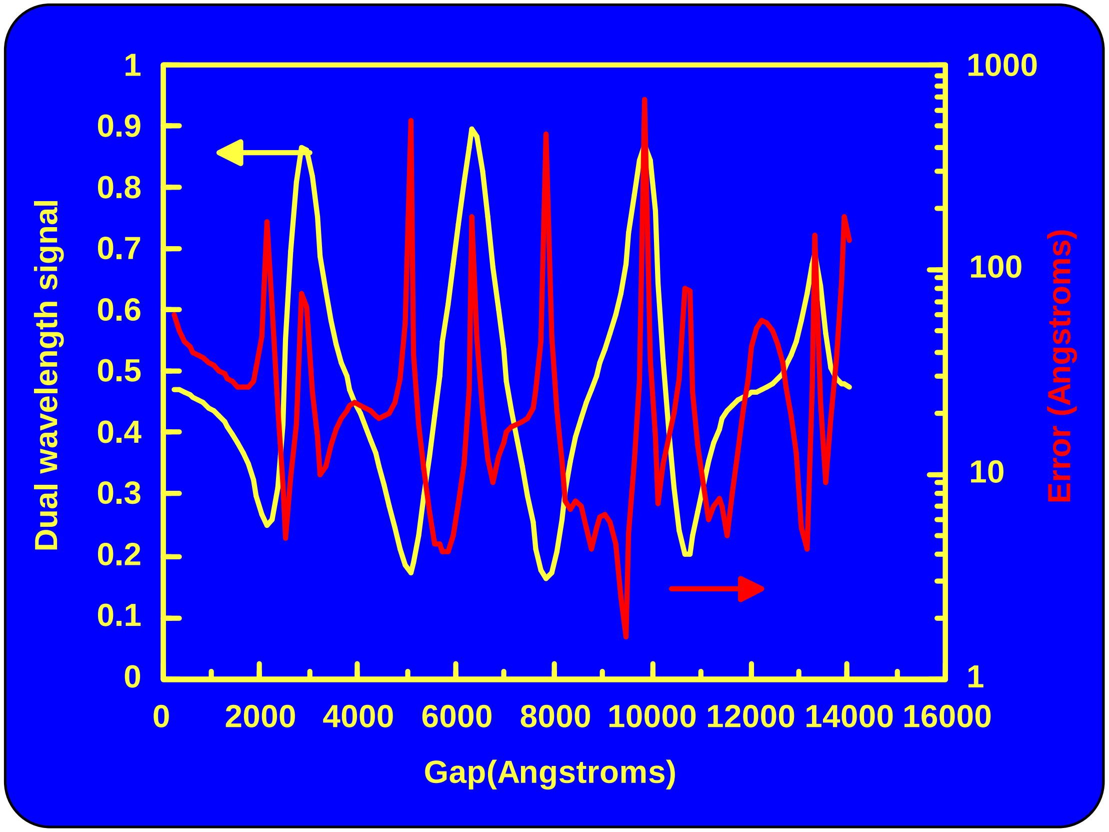
- 3 % (3 s) variation in all layer thicknesses
- functional dependence:
  - nominal gap (sacrificial poly thickness)
  - maximum mechanical travel of moving mirror
- yield contours: 97% have accuracy better than contour value
  - includes linearity error
  - clear superiority of first response branch



Dual wavelength detection

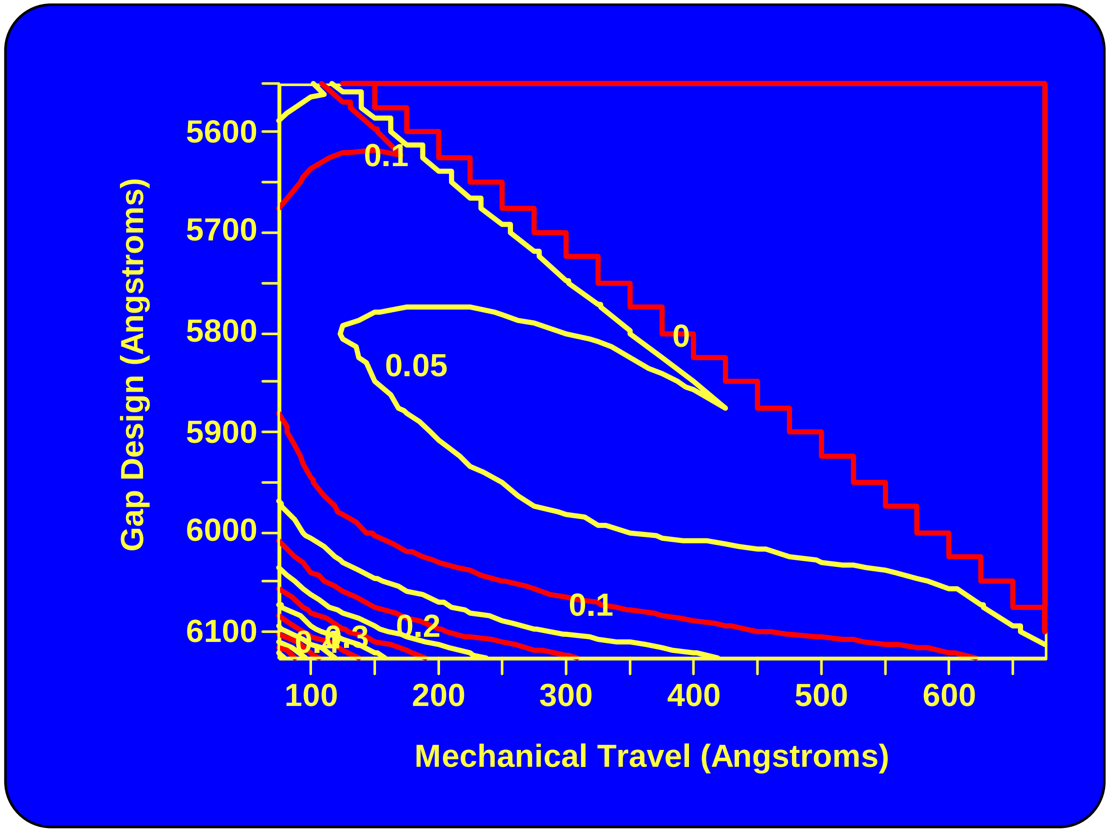
- need to eliminate "interconnect" loss errors
- measure relative reflectivity at two different wavelengths
  - measurand

    I(l1) / [I(l1) + I(l2)]
  - periodic in lowest common multiple of wavelengths
  - nine distinct response branches
- increases "linear" response travel



Dual wavelength error contours

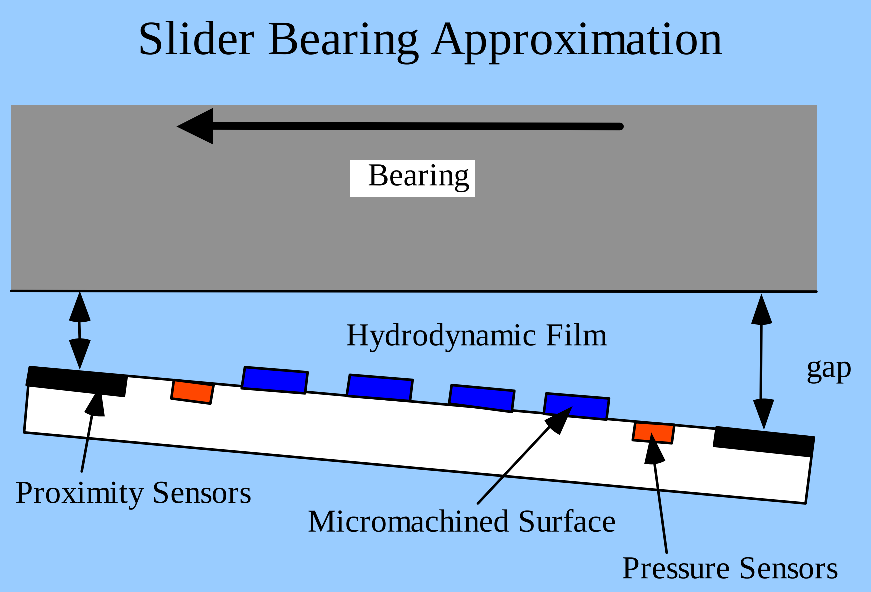
- **97% yield contours**
- **clear optimum design**
  - **nominal initial gap (sacrificial layer thickness): 6000 Å**
  - **compliance should be set for 600 Å mechanical travel at maximum pressure**
- **design of interference-based devices has a significant impact on sensitivity to manufacturing variations**



Another critical measurement: gap between surfaces

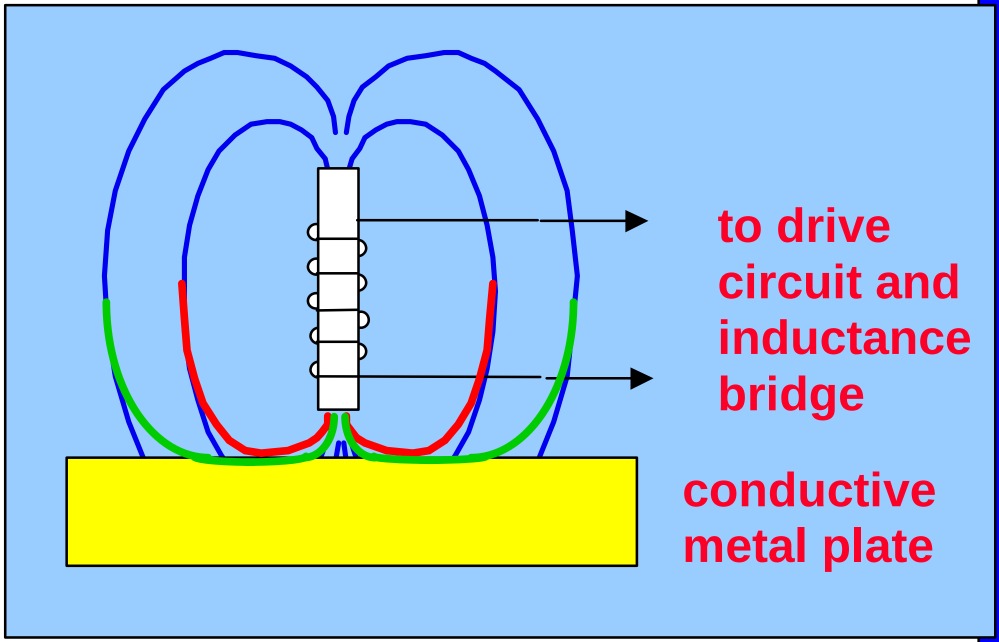
- should be non-contact
- medium between surfaces not in your control
  - may be hostile/corrosive
- cannot guarantee electrical connection to "remote" surface
- absolute distance desired
  - for many applications range is tens to hundreds of microns
- inductive proximity sensors
  - eddy current sensors widely used for distance to metal surfaces

Example: mechanical bearings

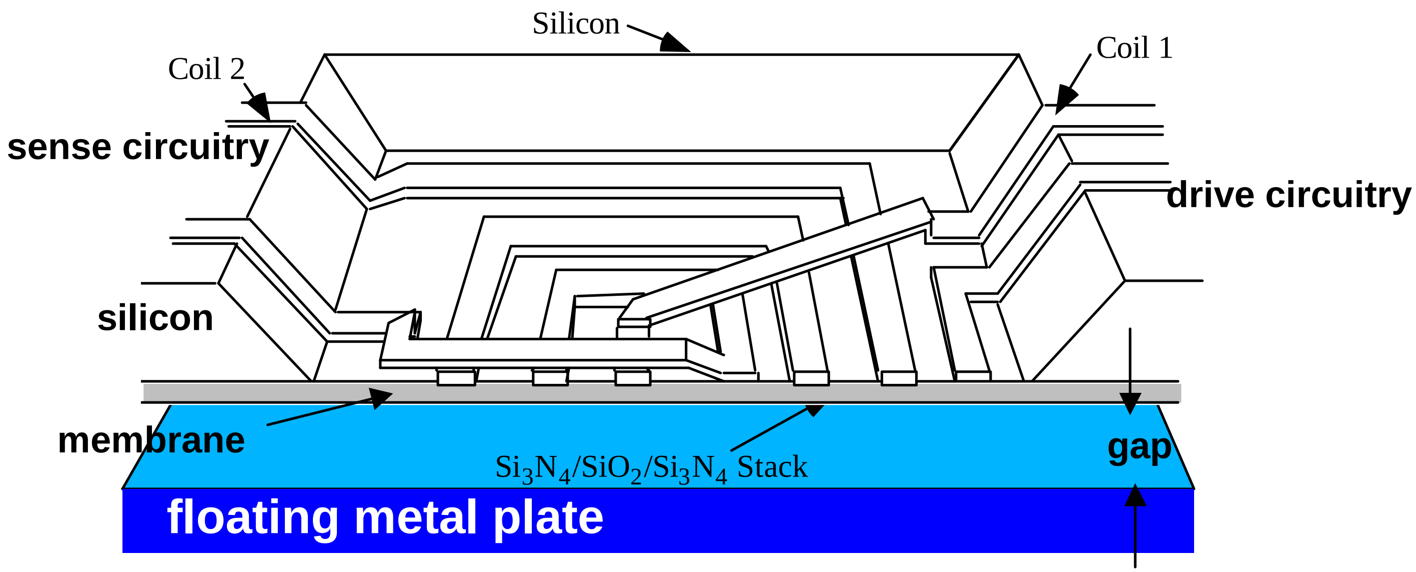


Conventional eddy current sensors

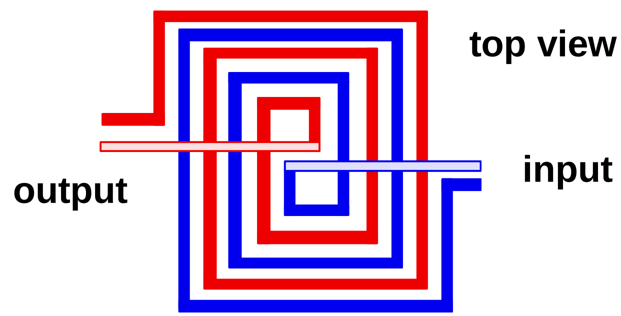
- solenoid-produced magnetic field
- eddy currents induced in plate
  - "expels" magnetic fields
    - changes coil inductance
  - must be "high" frequency
    - coil inductance must dominate resistance
    - skin depth should be small
- scaling to smaller size
  - planar coils have less "end" flux
  - resistance much higher
- solution: use dual coil "transformer"



Miniaturized planar proximity sensor

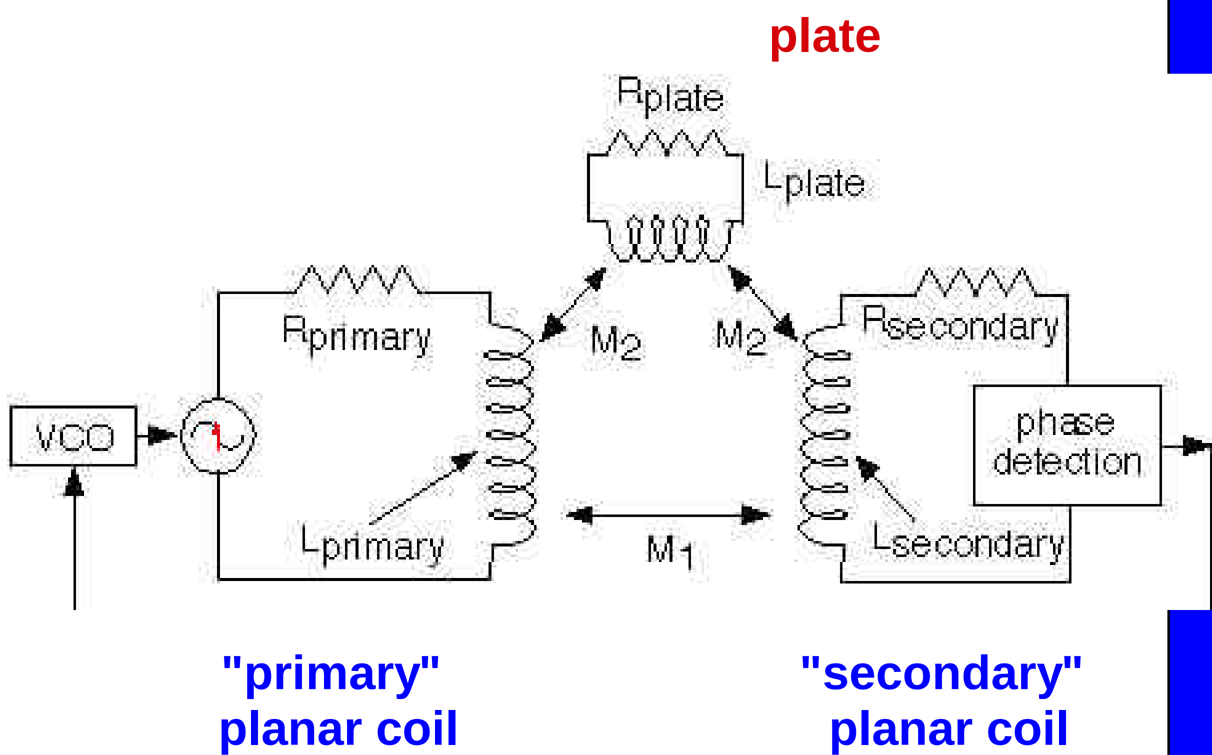


- coils made on "back" of membrane
    - -removes conducting silicon from magnetic path
    - -protects coil/circuitry from environment



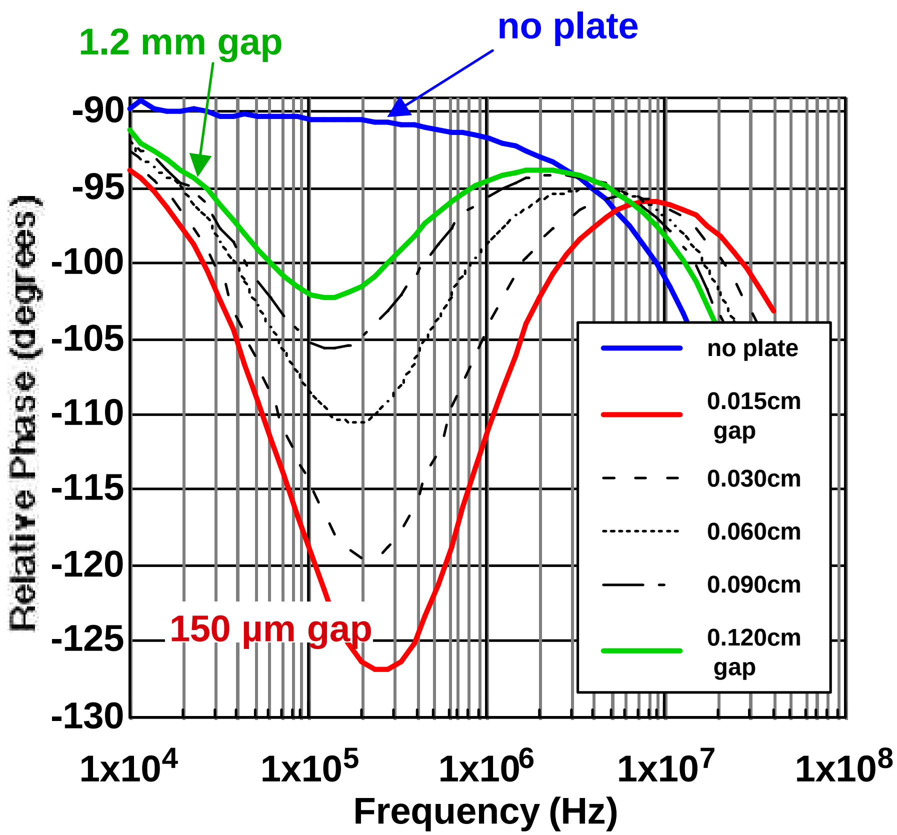
Dual coil equivalent circuit

- three branch transformer model
- "floating" metal plate acts like a shorted secondary
  - -mutual inductance and resistance depend on gap, conductivity of metal
- significant sensitivity to gap seen in relative phase of secondary signal

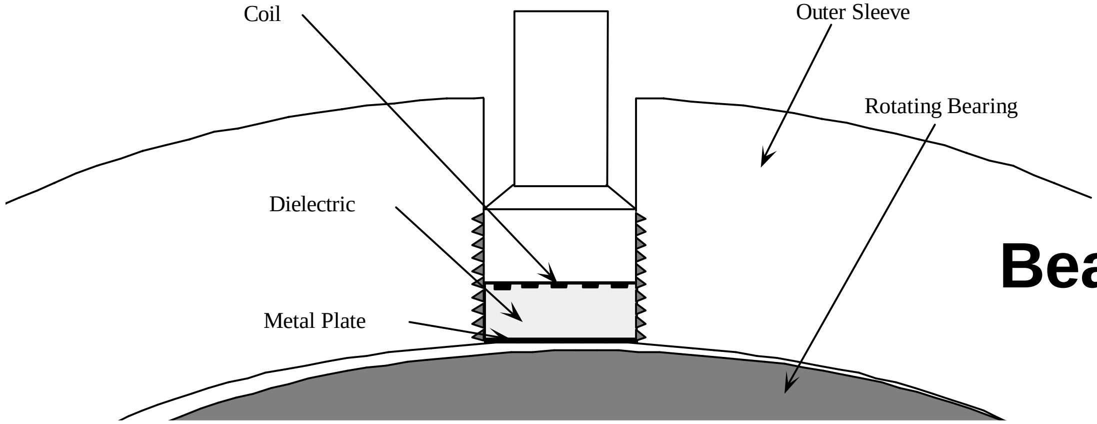


Dual coil inductive sensor measurement

- "large scale" PCB mock-up
  - -excellent agreement between model calculations and measurements
- model predictions for scaled sensor:
  - -frequency and phase change insensitive to increases in coil resistance
  - -should operate with coil areas at least as small as 500 µm x 500 µm

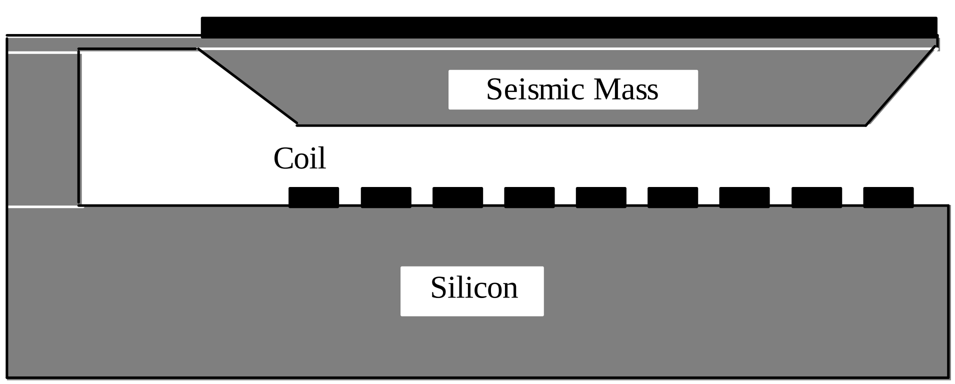


Other potential applications using inductive sensing

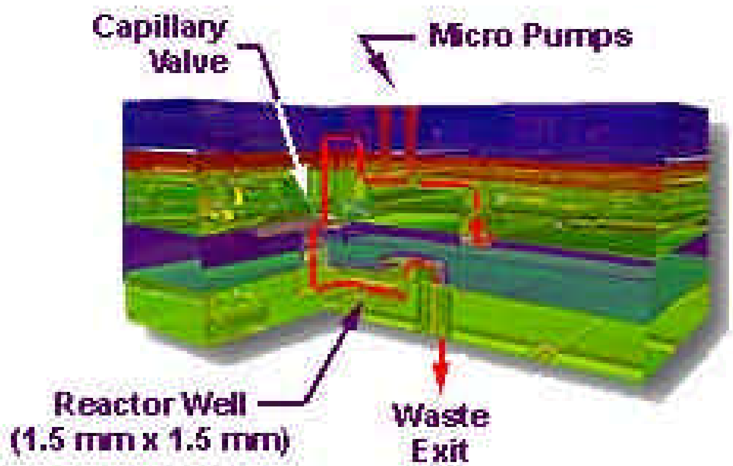


Bearing Wear Sensor

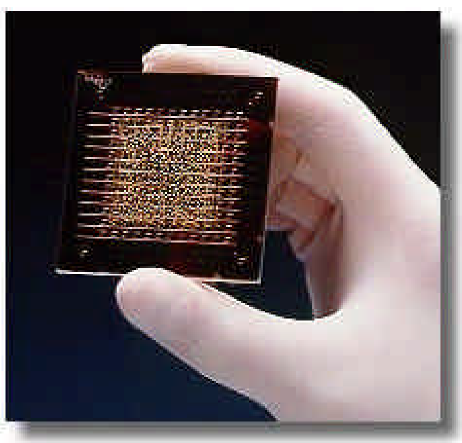
Accelerometer



"Micro-fluidics": how to make really small plumbing



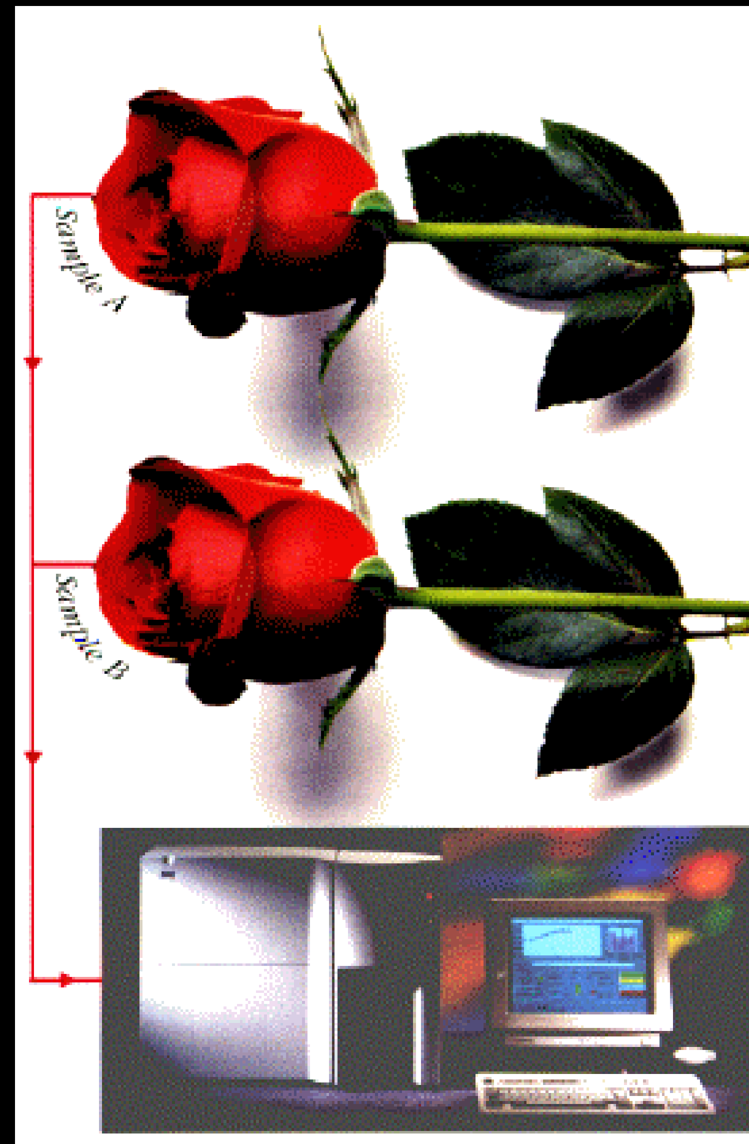
Orchid Biocomputer
(http://www.orchidbio.com)



Caliper Technologies
(http://www.calipertech.com)

You can also make an "electronic nose" using related technology

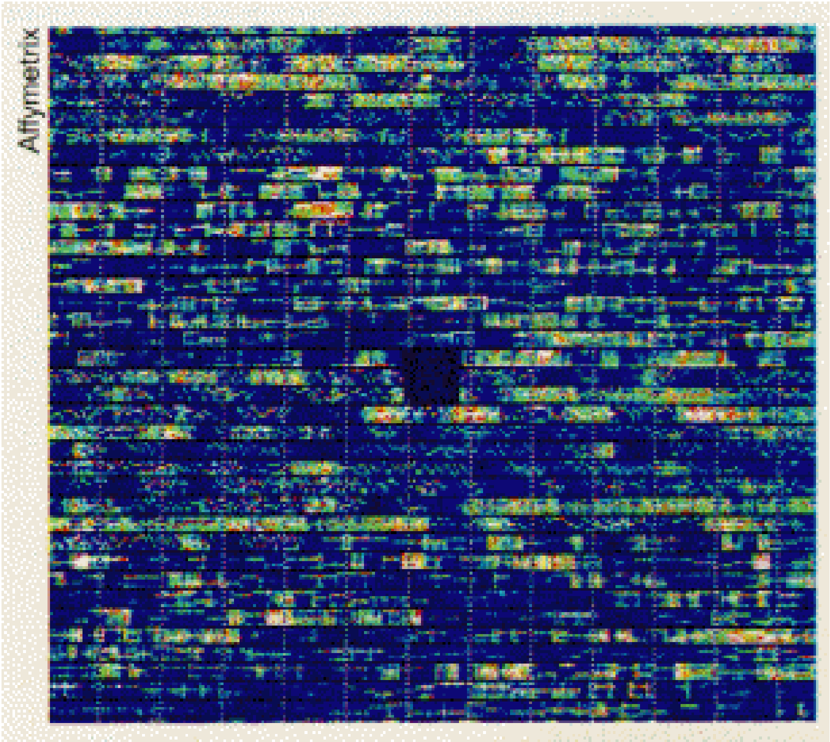
- an emerging technology area:
  - Electronic Nose by AromaScan, Cyrano, …
- applications include
  - perfume, beer, wine, food odors
  - detection of dangerous gases



from: AromaScan

What about things that come in water?

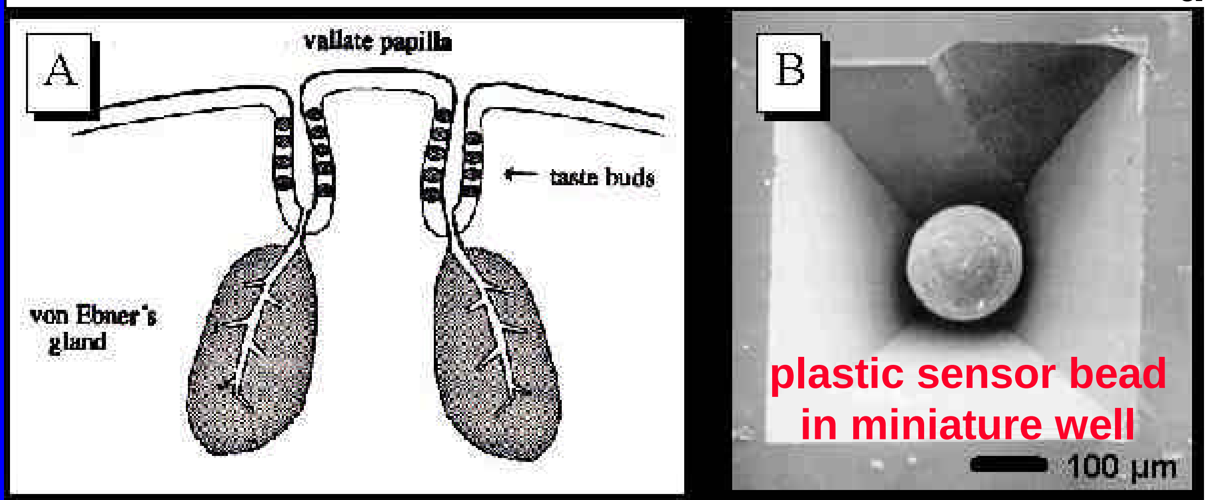
- **DNA chips**
- **label genetic material to be tested with fluorescent marker**
- **apply sample to DNA tagged chip**
- **marked DNA sticks to the device only where it hybridizes to a DNA probe with complementary sequence**
- **companies**
  - **Nanogen**
  - **Affymetrix**

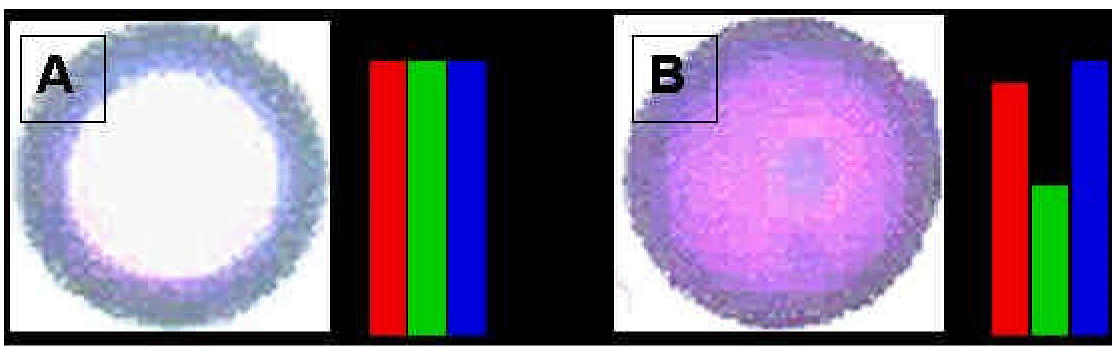


DNA sequence of the cancer gene p53

photo from John Travis, "Chips Ahoy: Microchips covered with DNA emerge as powerful research tools," in Science News, vol. 151, March 8, 1997, pp. 144-145.

Micromachines and Chemistry: Towards an "electronic tongue"





clear: no calcium

purple: calcium present

unique combination of microelectronics and chemistry faculty:

- Eric Anslyn, John McDevitt, and Jason Shear
  Department of Chemistry and Biochemistry
- Dean Neikirk, Department of Electrical and Computer Engineering

combinatorial synthesis on "bead substrates"

- many combinations of chemical reactions via "split lot" synthesis
- MEMS microfluidic devices integrated with sensing beads

Classical devices made small

- micromachined structures can produce macroscopic effects
  - applicability to "smart" bearings
- "batch" micromachined Fabry-Perot cavities can be used for accurate pressure measurement
  - complete device has been demonstrated
  - design methodology that incorporates fabrication variability must be used
- inductive proximity sensors
  - dual coil design allows scaling to IC dimensions
  - is inductive sensing a viable alternative to capacitance?