Microsystem Capabilities for Prognostic Health Monitoring

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Microsystems Science, Technology, and Components Center

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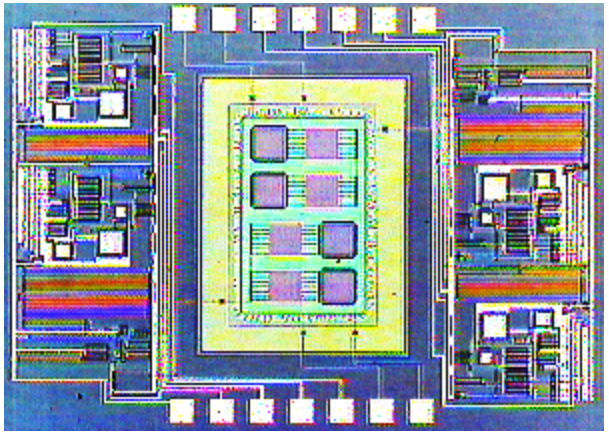
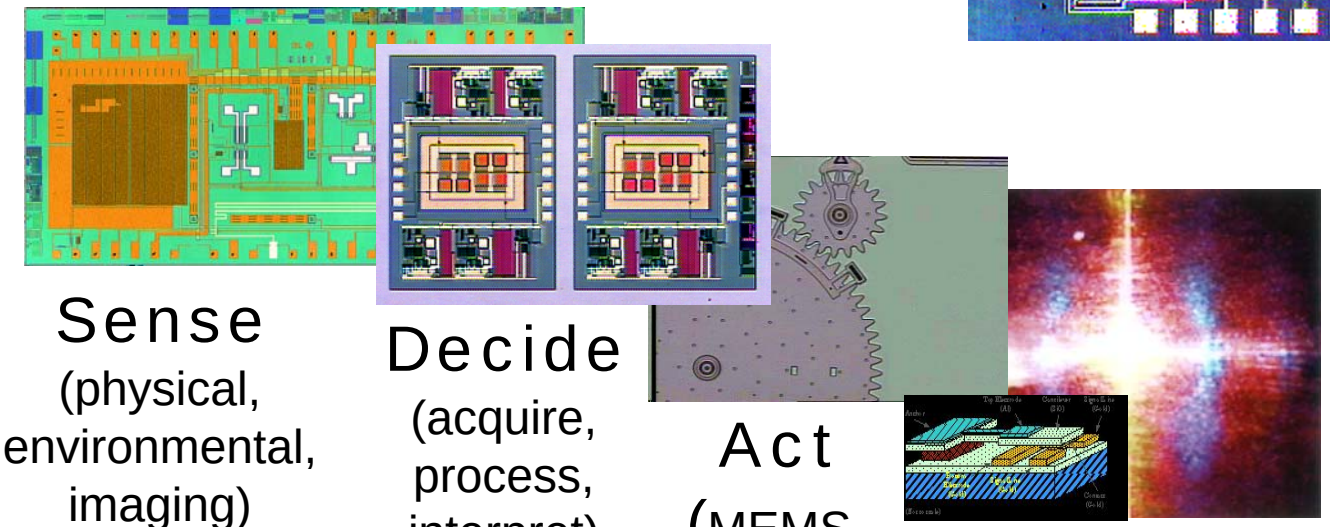
MESA Institute

Sandia National Laboratories

Integrated Microsystems: The Next Technology Revolution

- **The next leap in function of Integrated Circuits will involve more than just packing more transistors on the chip**
- **It will involve combining Si, III-V, MEMS, and advanced packaging technologies to create an integrated capability to:**





Sense
(physical, environmental, imaging)

Decide
(acquire, process, interpret)

Act
(MEMS, microfluidics)

Communicate
(optical, RF)

… affordably and reliably.

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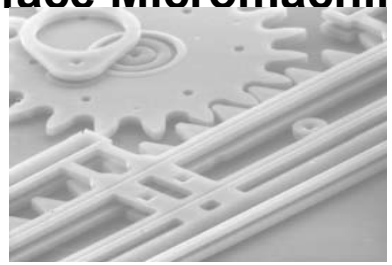
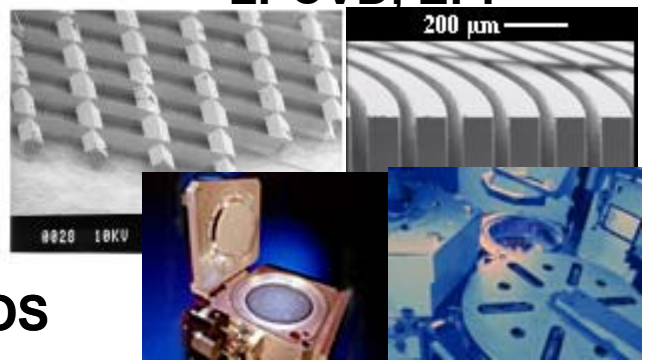
Producing Integrated Microsystems Requires a Broad Spectrum of Capabilities

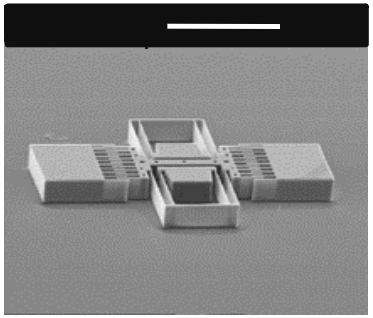
Polysilicon Surface Micromachining



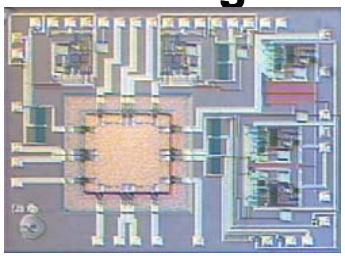
Wet Chemistry Bulk Silicon Etching LPCVD, EPI



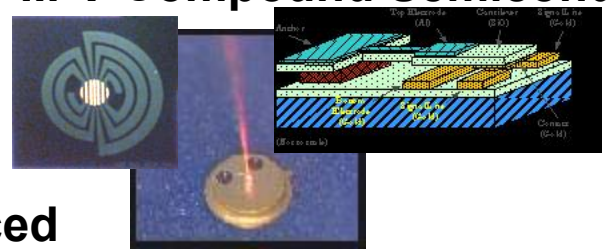
High Aspect Ratio Silicon Etching (HARSE)



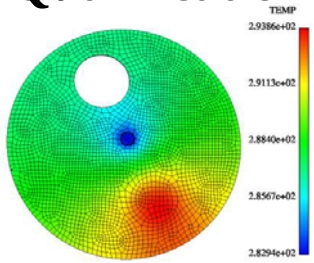
Integrated Surface Micromachining and CMOS



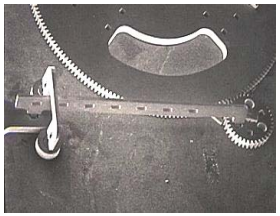
III-V Compound Semiconductors



Qualification



LIGA



Advanced Packaging

It is very difficult to obtain these capabilities *plus* the flexibility for R&D and prototyping.

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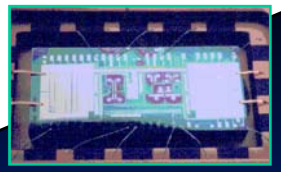
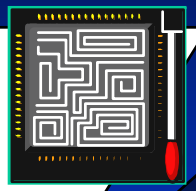
Sandia's Enabling Capabilities Produce Miniature Sensors, Processors, and Communication Systems

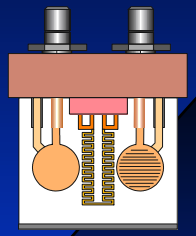
Sense, Process, Act, Communicate

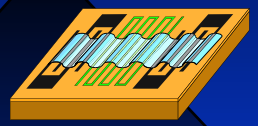


Micromachines, Microelectronics

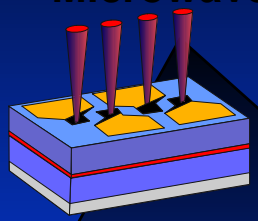


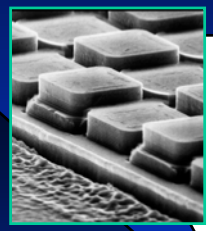
Microsensors





Photonics, Microwave Circuits

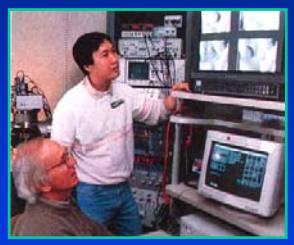




Microelectronics Development Laboratory MDL

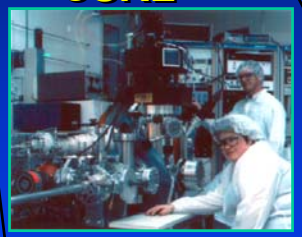
Over 30,000 ft² of clean room, 0.35 μm CMOS Fabrication Facility

Integrated Materials Research Laboratory IMRL



Materials Fabrication and Characterization, including Plasma Deposition and Surface and Interface State Characterization

Compound Semiconductor Research Laboratory CSRL



MOCVD, MBE Deposition, Electron Beam Lithography, Reactive Ion Beam Etching

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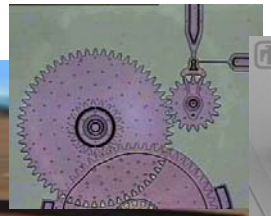
MESA provides complete facilities for microsystems design, integration, fabrication and testing

$463M including > 50% equipment and cleanrooms

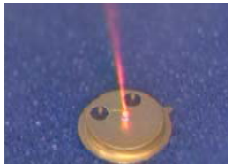
Microfabrication

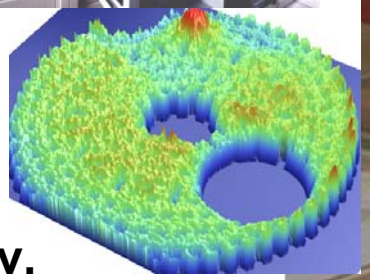
Si Micromachining



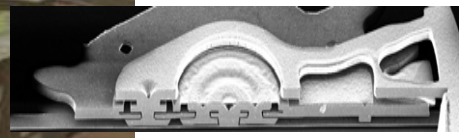
Photonics

III-V Semiconductors



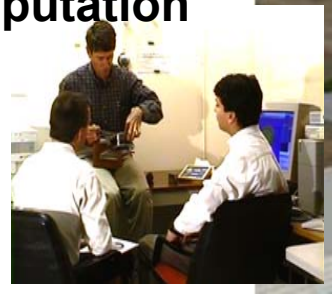


Adv. computation



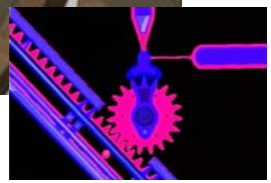
Nanotechnology

3-D design, mod/sim



Packaging and qualification

648 people
391,000 sq ft



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Microsensors for PHM Applications

Sensor:		Measures:		To Indicate:
Quartz Resonator	→	Fluid Properties (density, viscosity)	→	Fluid Degradation
MicroChem-Lab	→	Chemical Constituents	→	Chemical Degradation
Micro Resonators	→	Acoustic Spectrum	→	Onset of Failure

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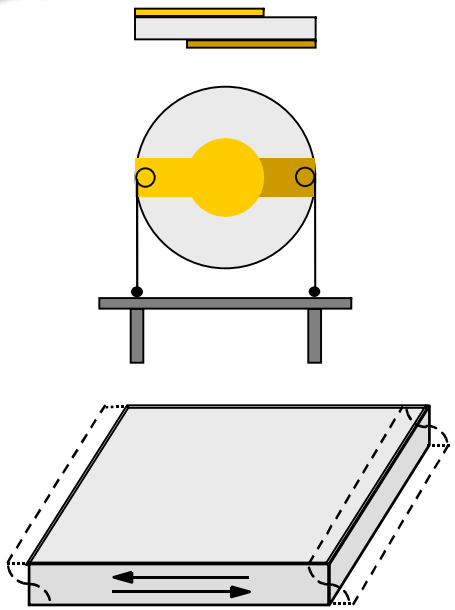
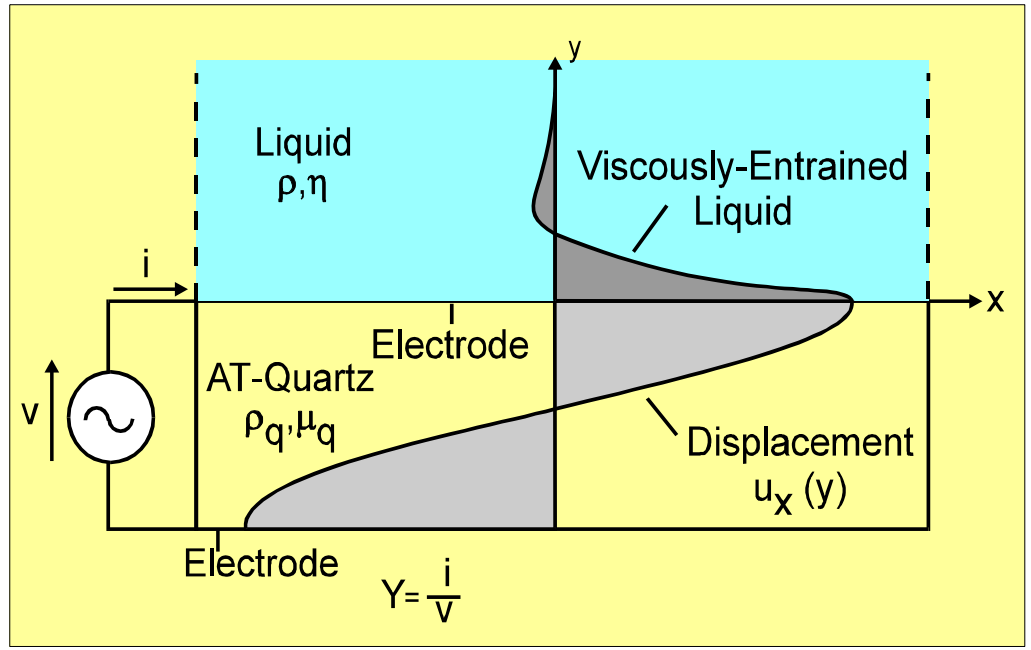
TSM Resonator Fluid Monitoring





- **AT-cut quartz crystal with gold electrodes on opposing faces**
- **Application of RF voltage produces shear mode deformation; the fundamental mechanical resonant frequencies are 5 to 6 MHz**
- **Fluids are viscously entrained at the resonator surface and create a load impedance**
- **For Newtonian fluids, frequency shift (Δf) and damping (ΔR) $\propto (\rho\eta)^{1/2}$, where ρ is fluid density and η is fluid viscosity.**

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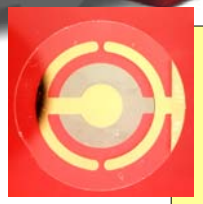
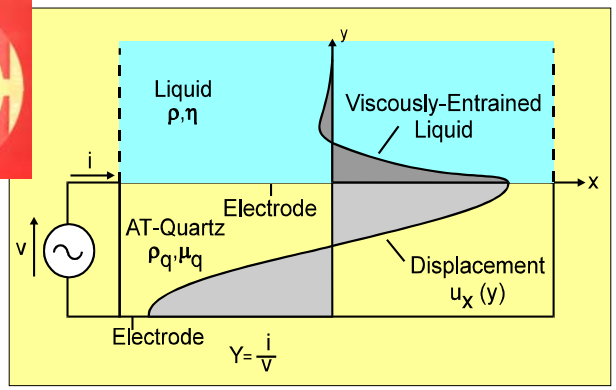
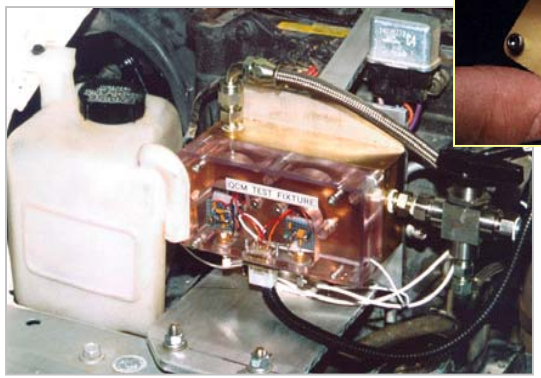
LUBRICATING OIL CONDITION MONITOR

An inexpensive *in situ* monitor that measures lubricant viscosity and indicates oil age and quality

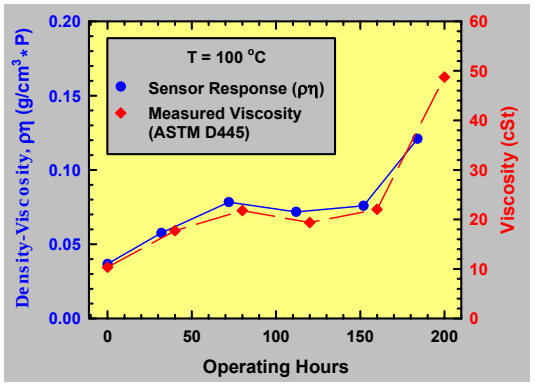




- A thickness shear mode quartz crystal resonator viscously-entrains liquid in contact with the surface
- Shifts in resonant frequency and magnitude are proportional to liquid density-viscosity



- Extracted oil samples can be placed on resonator surface
- Robustly packaged resonators can be mounted in vehicle oil pan or placed in oil flow line
- Tests conducted in laboratory, in engine dynamometers, and in operating vehicles



- Lubricant viscosity increases as oil degrades (oxidation due to high temperatures and pressures)
- Resonator response agrees well with viscosity measured using ASTM techniques (correlation > 0.9)

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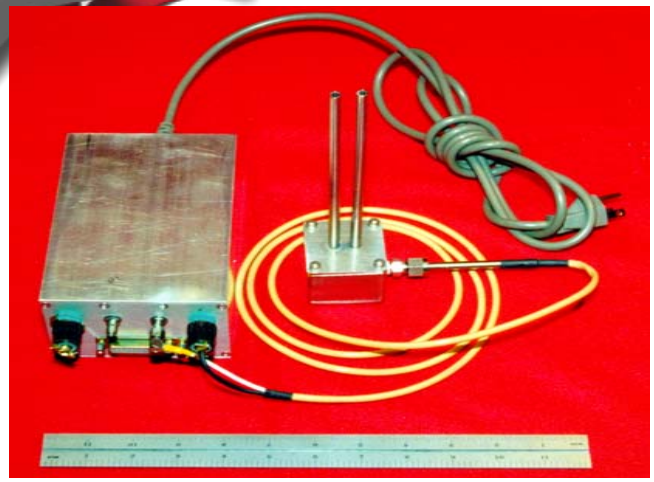
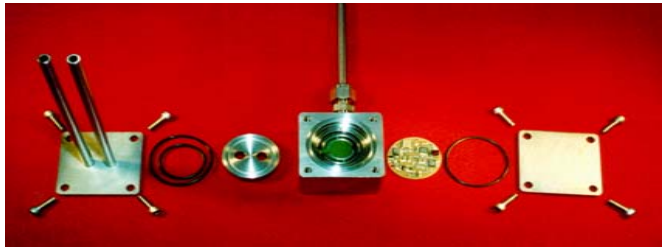
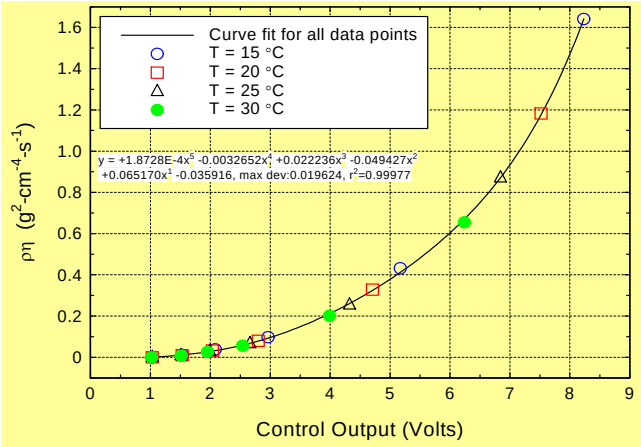
In-Line Photoresist and Spin-On-Glass Viscosity Monitor







Approach:

- Process fluids flow through cell at low pressures
- 5 MHz TSM quartz resonator measures density-viscosity of contacting fluids

System Configuration:

- Flow-through cell containing resonator, oscillator electronics, and temperature probe
- Interface electronic module with power supplies, signal conditioning, and data acquisition
- Optional notebook computer for real-time graphical display

Performance:

- Newtonian fluid calibration
- Viscosity range: 0 to 190 cP
- Accuracy: less than ± 10%
- Viscosity measurement resolution: ~ 0.1%
- Temp. range: 15 to 30 °C
- Sample interval: ≥ 5 sec.

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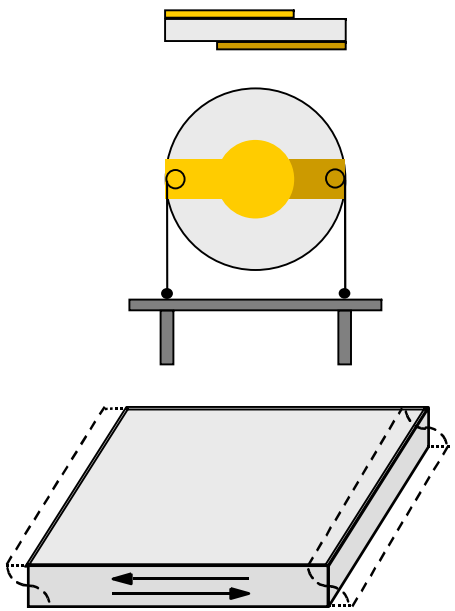
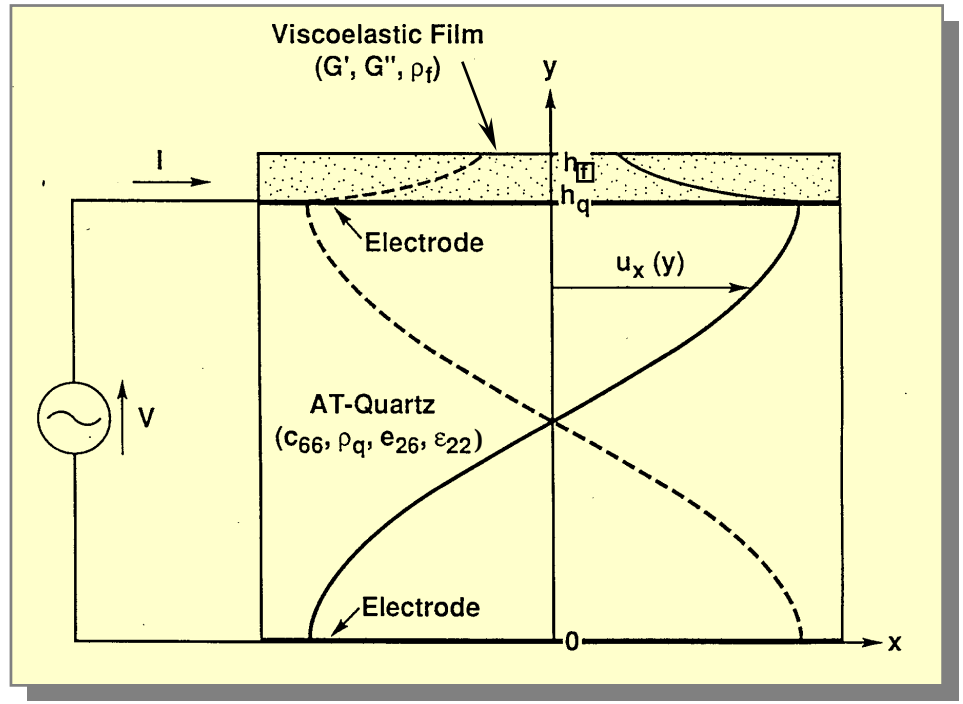
Measurement of Viscoelastic Properties of Polymer Films





- RF voltage on electrodes induces shear deformation in AT-cut quartz
- Changes in surface mechanical load shift resonant parameters
- Viscoelastic layer (chemical sensing polymer) on resonator surface produces acoustic loss and phase delay (changes the measurable operating frequency and RF amplitude)
- Layer modulus ($G = G' + jG''$), density (ρ_f), and thickness (h_f) control acoustic parameters
- Chemicals (from vapor or liquid phase) sorb into layer, creating changes in G, ρ_f, and/or h_f

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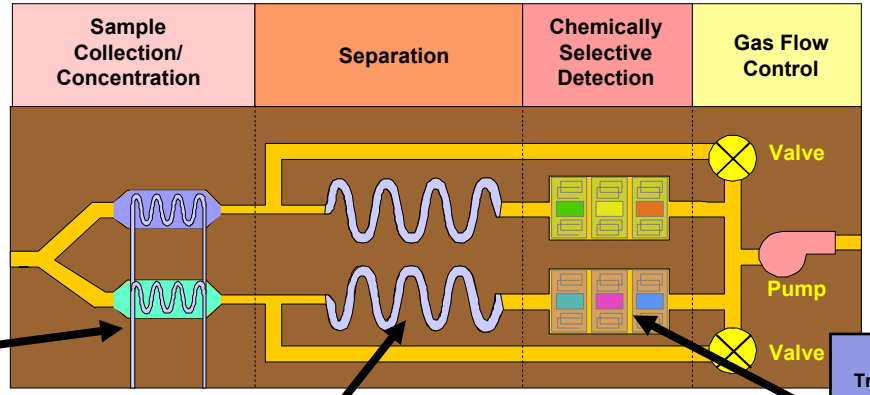
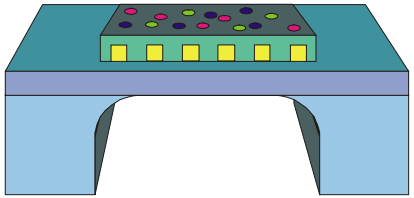
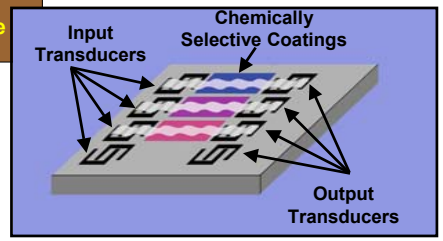
µChemLab™

A hand-held chemical analysis system that uses three microfabricated analysis stages



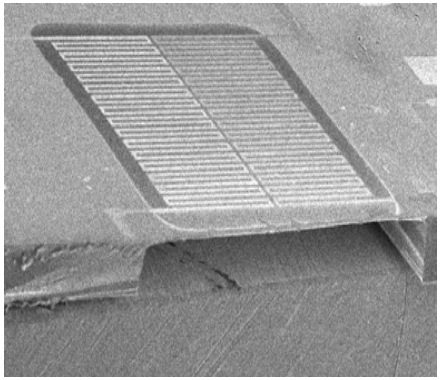


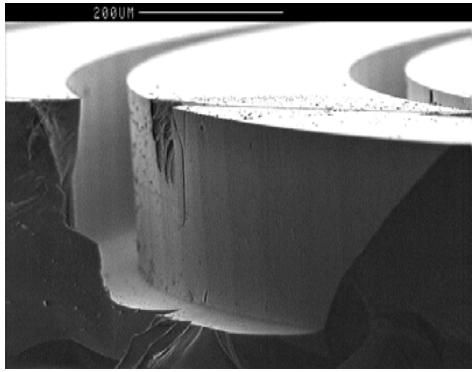


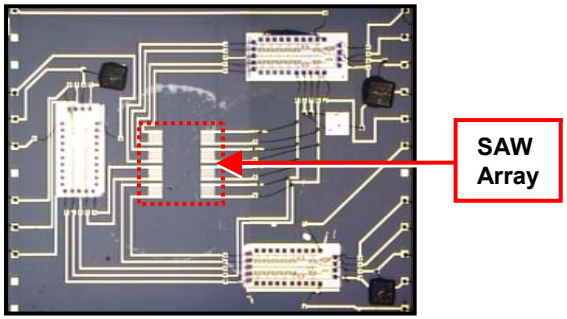
Preconcentrator accumulates species of interest

Gas Chromatograph separates species in time

Acoustic Sensors provide sensitive detection







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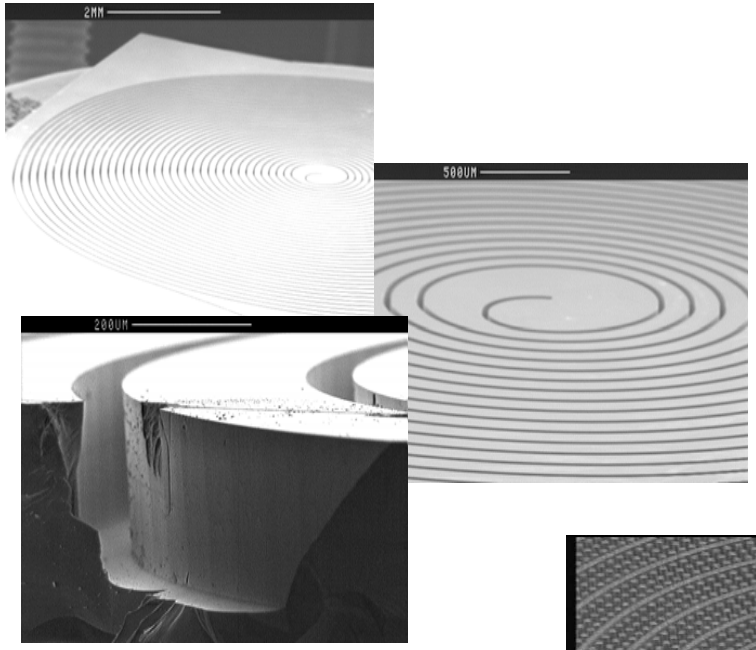
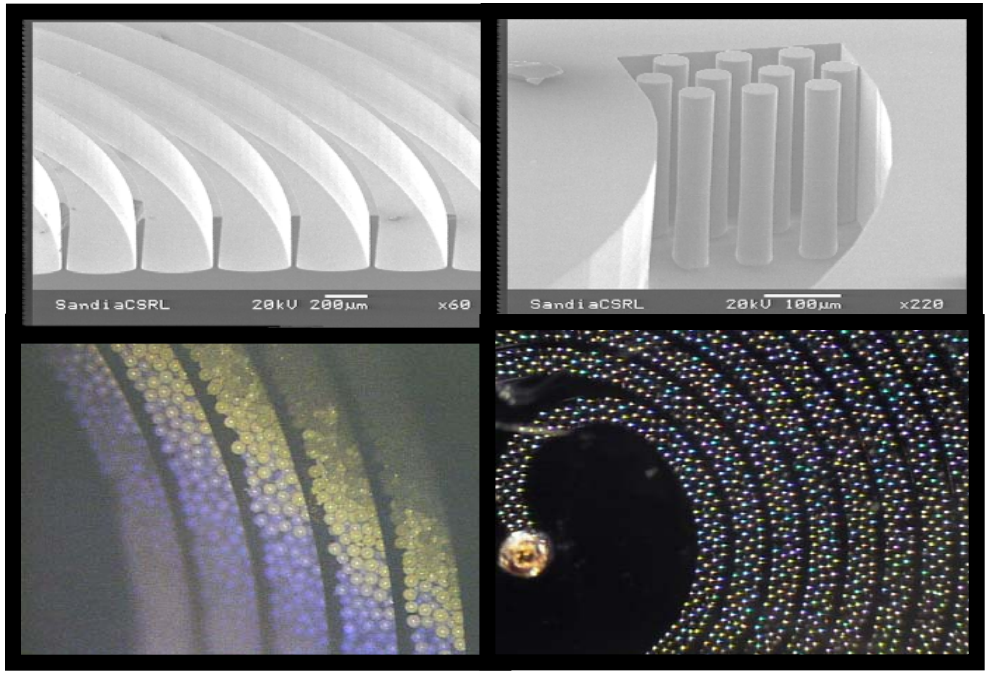
Chromatographic Column

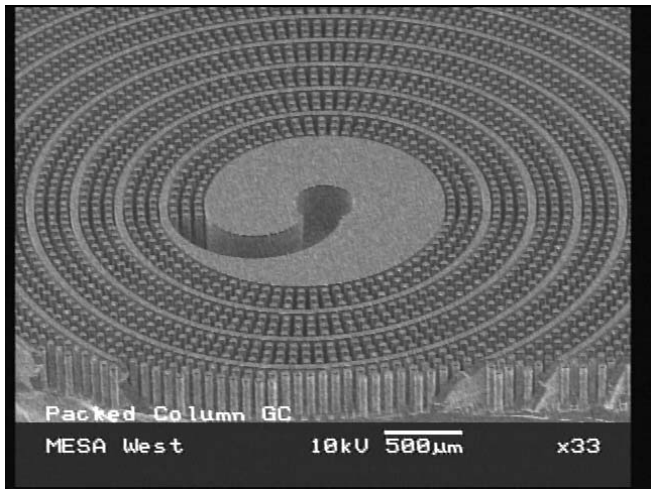
Bosch Deep Reactive Ion Etching Capability used to Fabricate World's Smallest Integrated Gas Chromatograph Column.



Fabricated On-Chip Packed Column



New GC Columns



Posts made during fabrication eliminate need to pack with beads

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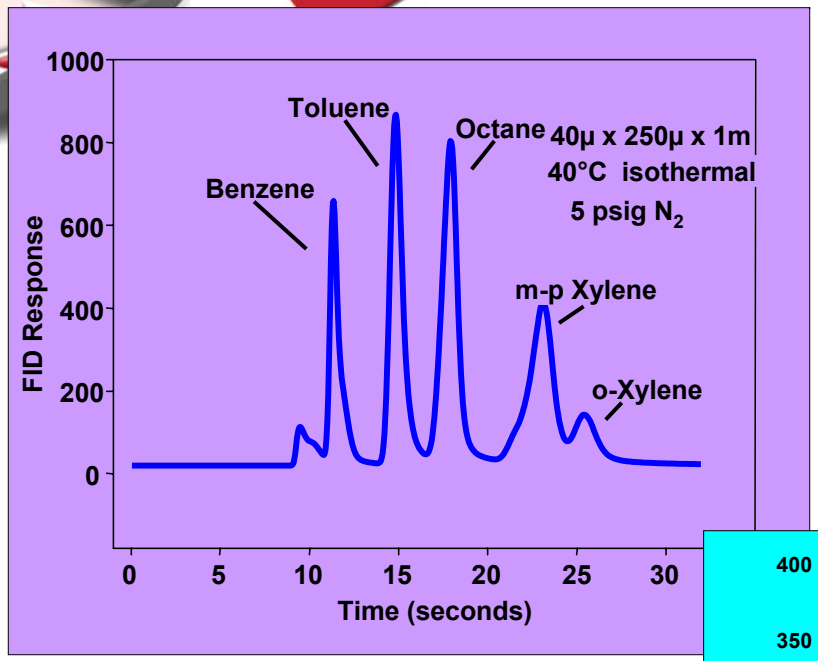
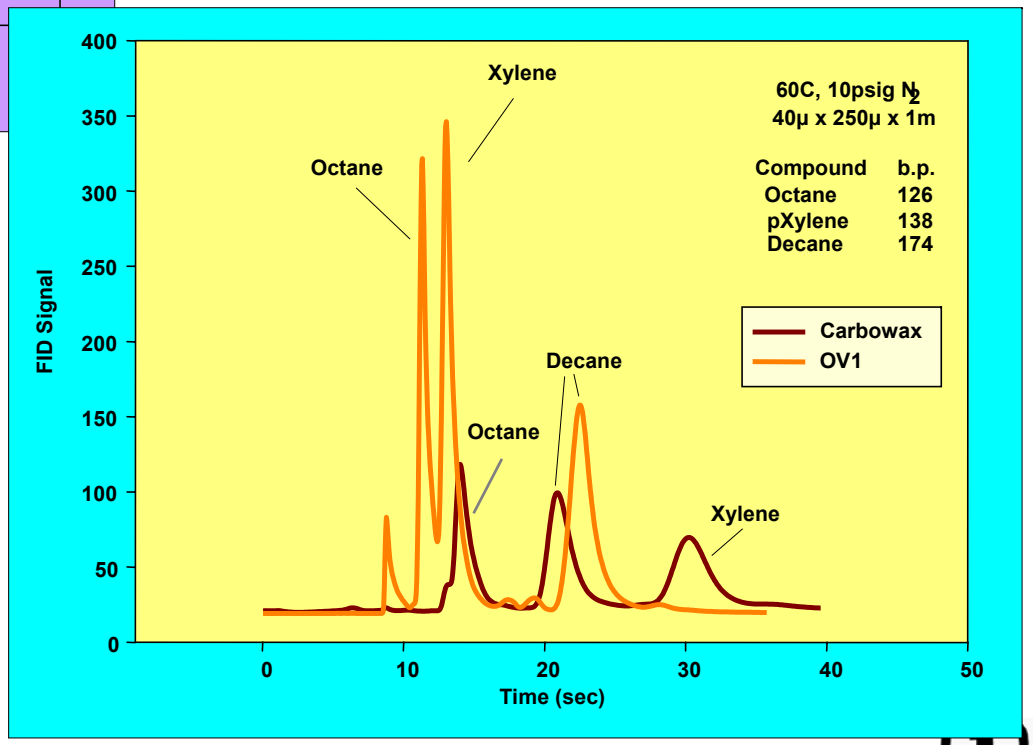
Gas Chromatograms



Selectivity Shown for Micromachined GC Column Using Two Different Coatings



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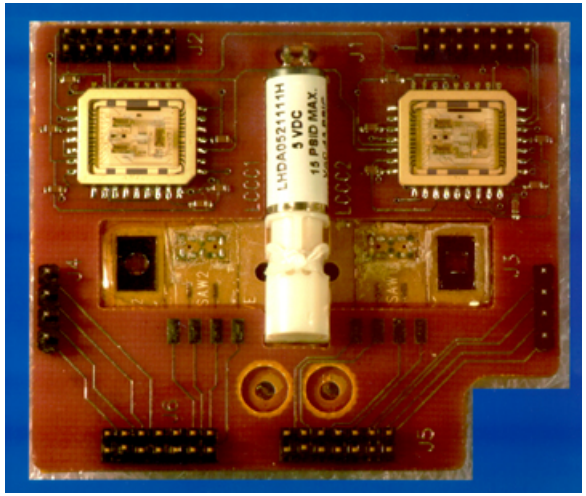
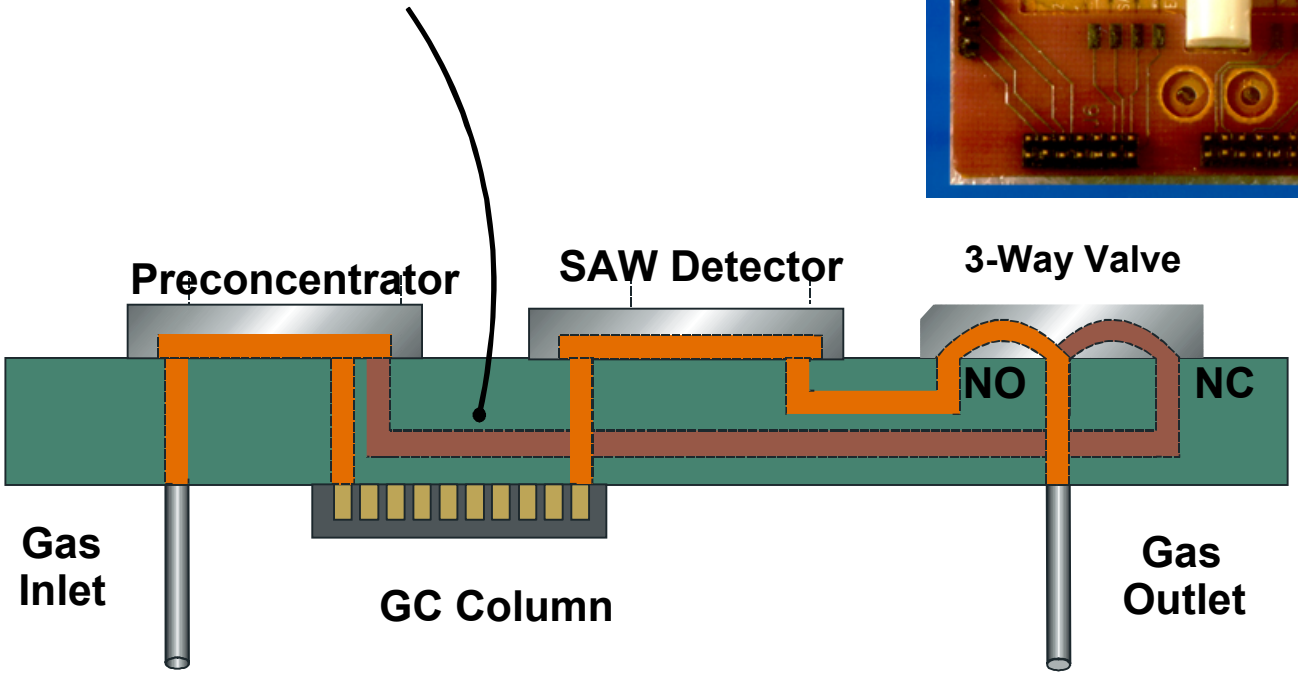
Gas analysis components are integrated on novel electrical/fluidic circuit board





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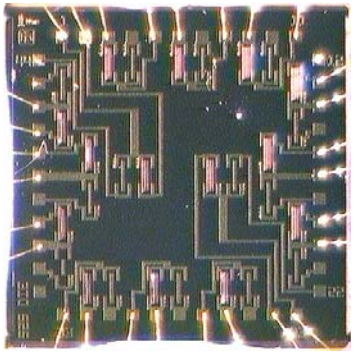
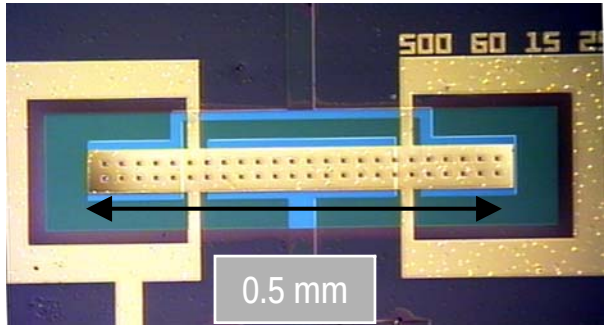
Micro Acoustic Spectrum Analyzer (MASA)

Array of Microxylophones

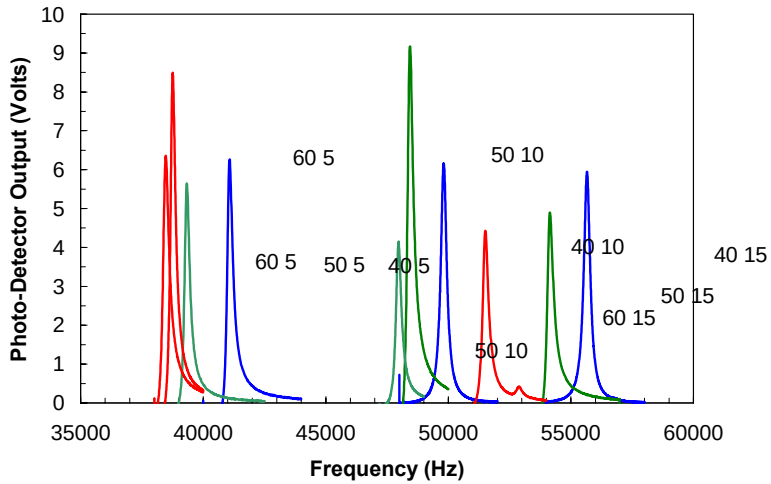


14 Microresonators/ 6 mm x 6 mm die

Microxylophone



25-50 resonators easily fit on 6-mm x 6-mm die



- **Micromachined xylophone resonates at a particular frequency**
- **Array of micro-xylophones gives frequency components of incident sound**
- **Can be used for acoustic identification of vehicles, human speech patterns, etc.**

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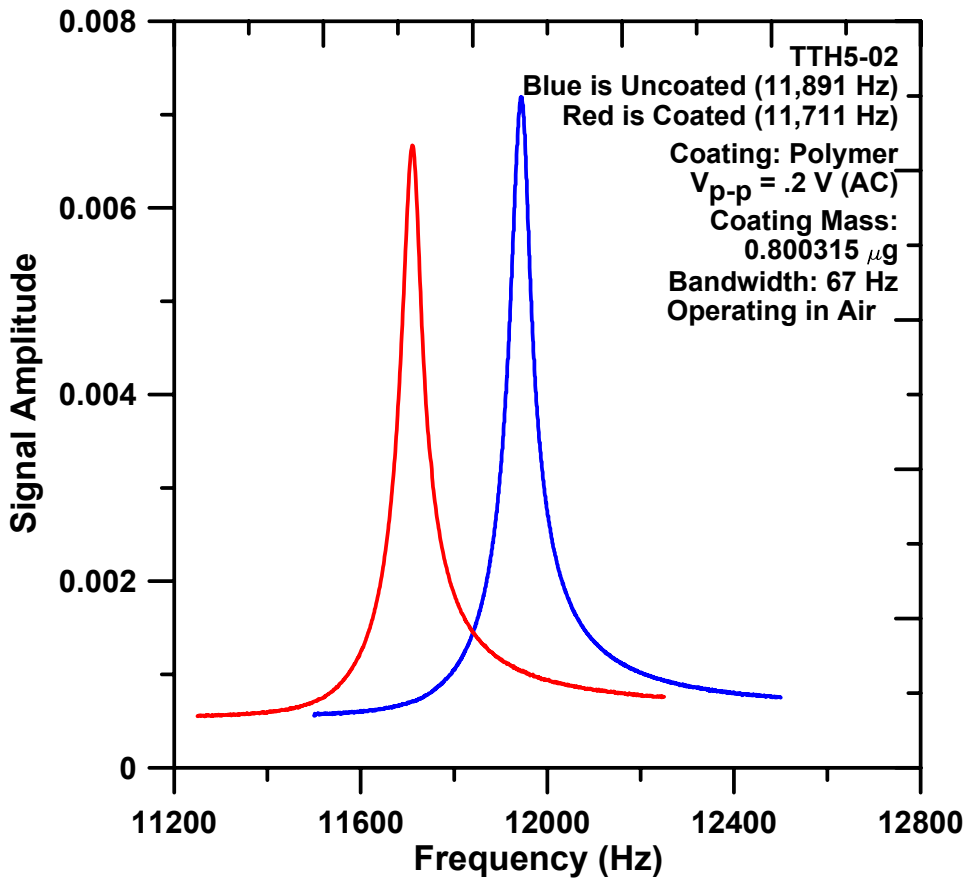
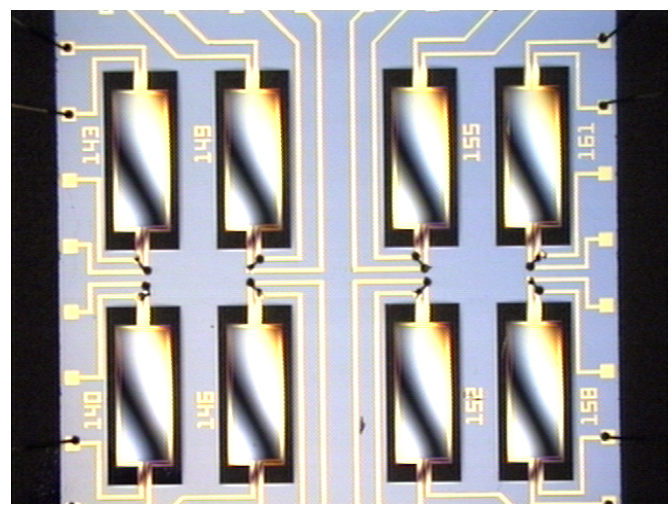
Microresonator Development

Lorentz Drive

Teeter-Totter Resonators



- Fabricated in Silicon-on-Insulator
- 5 kHz $\leq f_o \leq$ 50 kHz
- Better fabrication control of f_o
- Fine tuning of f_o through added thin films
- Reduced temperature dependence
- Single or Two-Port Devices



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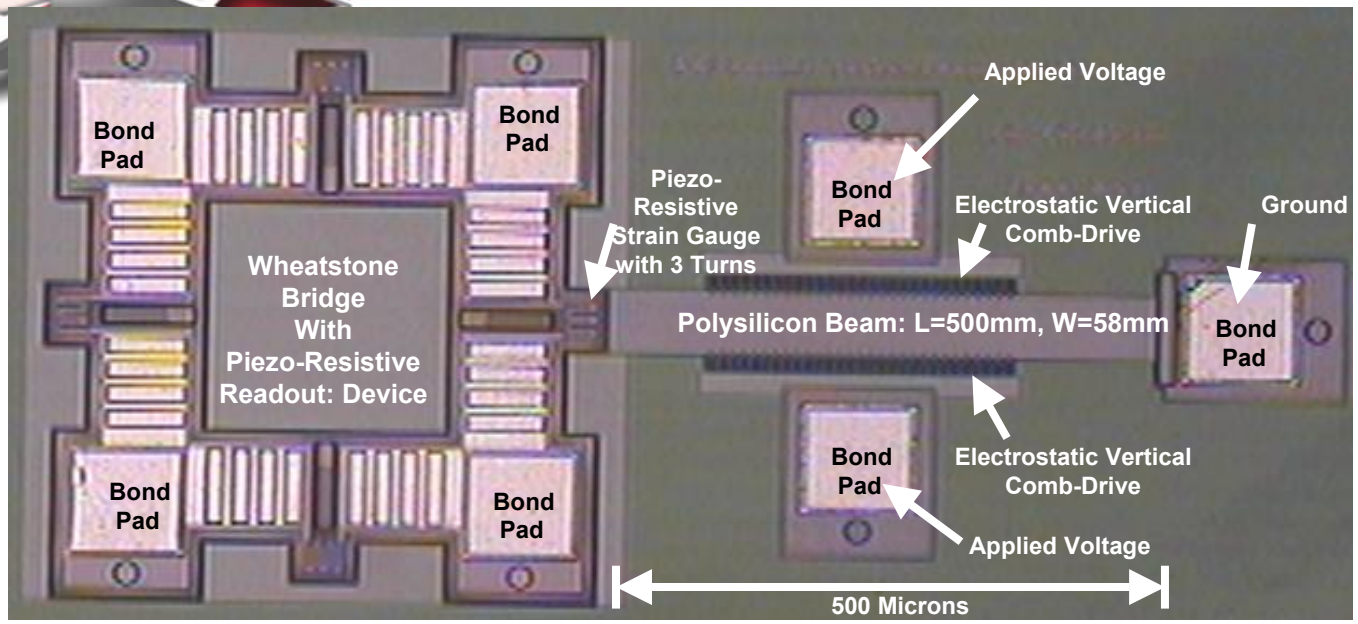
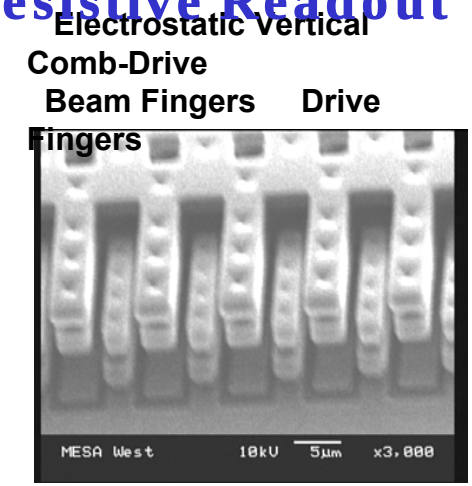
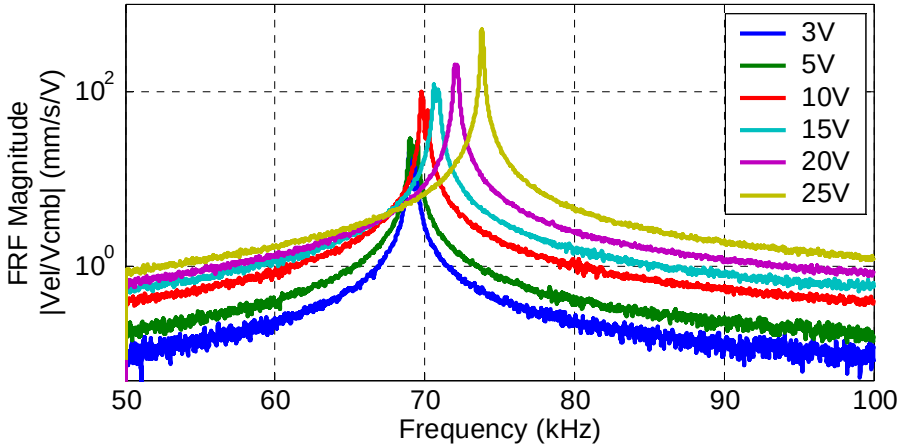
Microresonator Development

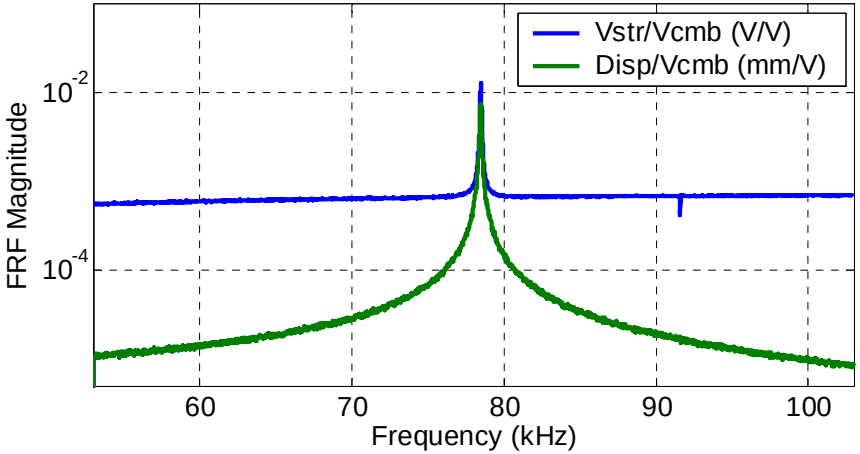
Capacitive Drive/Piezoresistive Readout





Front-Side View of Electrostatic Vertical Comb-Drive





f_0 is electrically tunable & detectable

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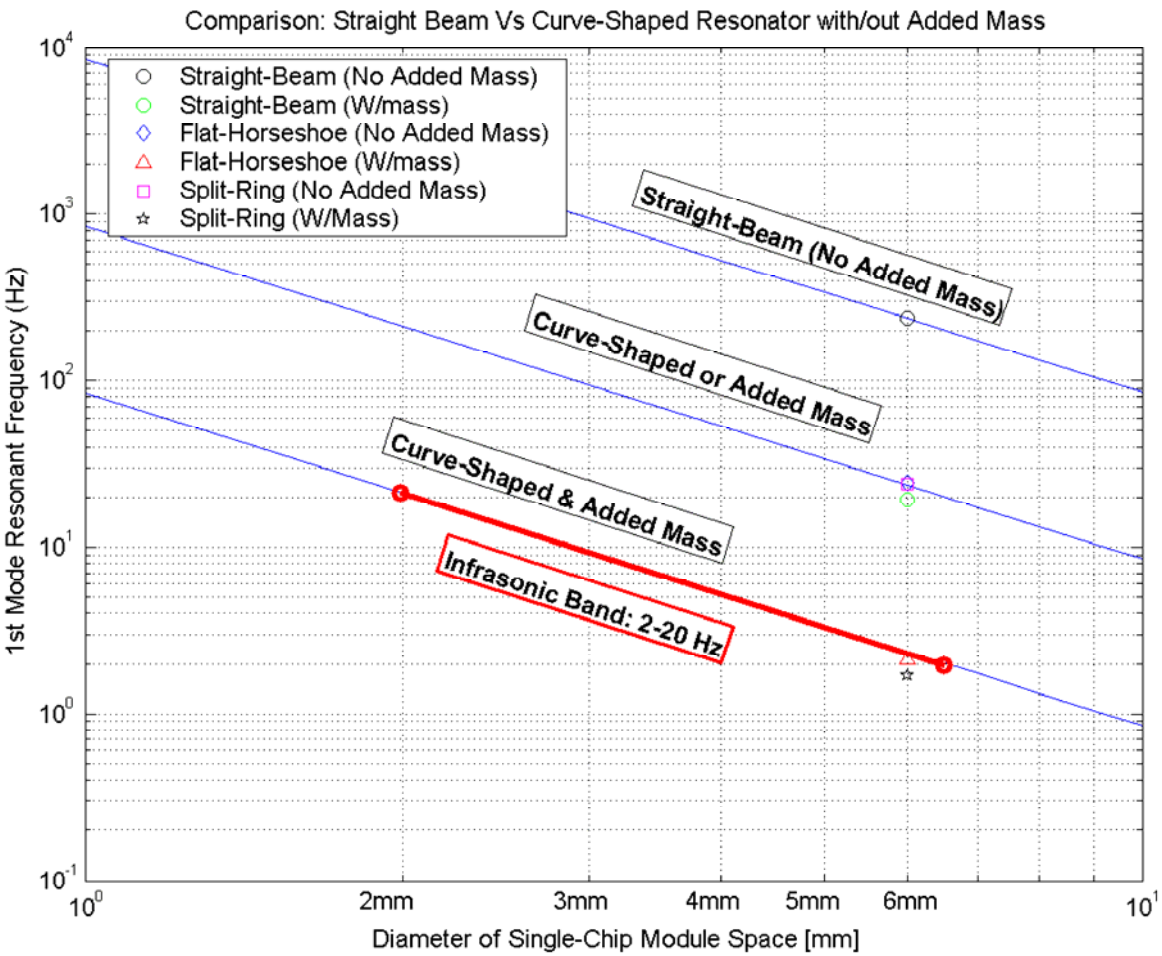
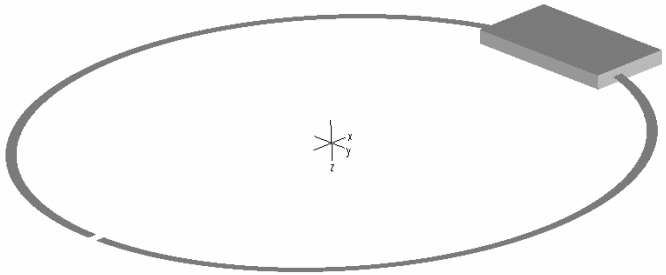
Microresonator Development

Pushing to Lower Frequencies



- Modified SUMMiT V w/SFET for integration
- Strong interest in very low frequencies
- Driven by acoustic energy in air



"Horseshoe resonator"

Modeling indicates very low frequencies are possible

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Conclusions:

- **Microsensors can be used to measure mechanical and chemical properties indicative of degradation.**
- **Their small size makes them robust, low power, and able to be used in many locations.**

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