N/MEMs: Small Components Enable Powerful Microsystems

Dennis L. Polla
Program Manager
Microsystems Technology Office (MTO)
Defense Advanced Research Projects Agency (DARPA)

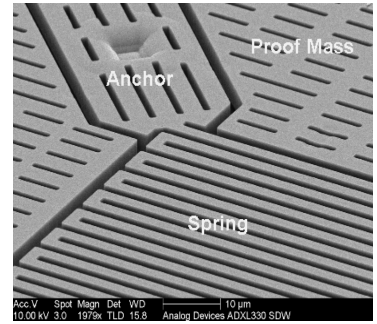
Michael B. Wolfson
Senior Scientist
System Planning Corporation

8 April 2010
SPIE Defense, Security, and Sensing

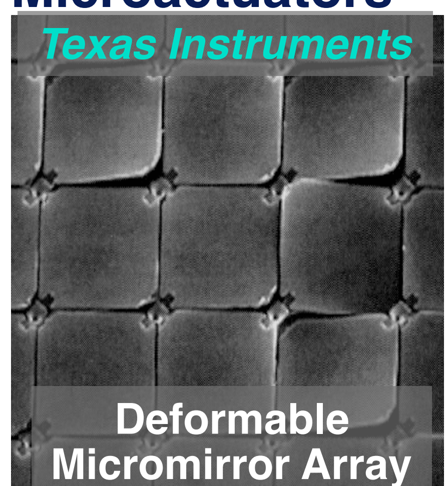
N/MEMS Are Everywhere

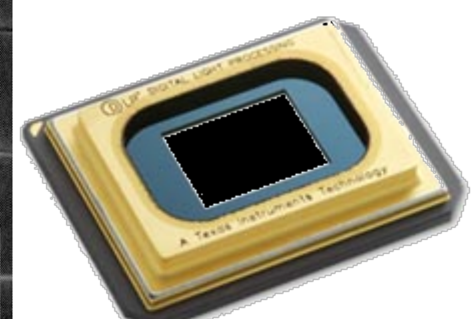
Microstructures

Microsensors



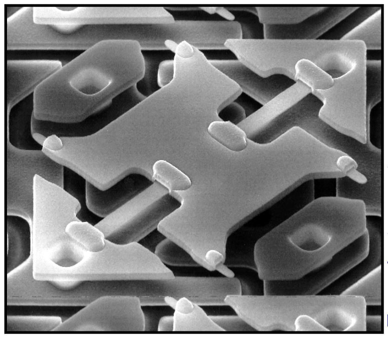
Microactuators





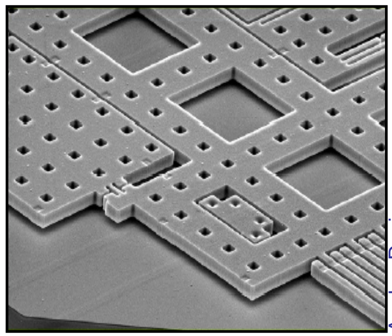
Successful Component Demonstrations

DARPA Microsystems Technology Office (MTO) MEMS program has focused on the development of enabling component capabilities for new DoD systems.



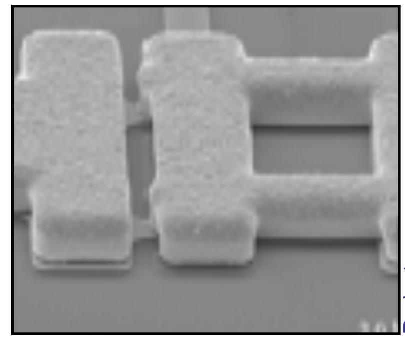
Texas Instruments

Displays



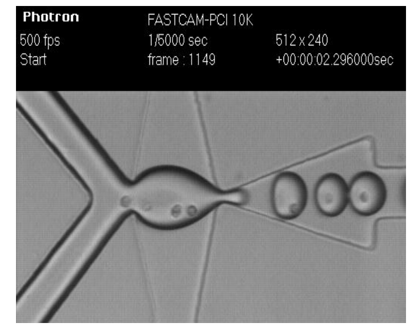
Analog Devices

Accelerometers

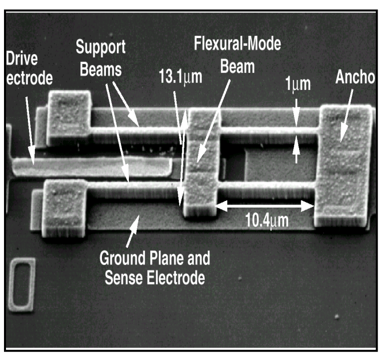


Radant

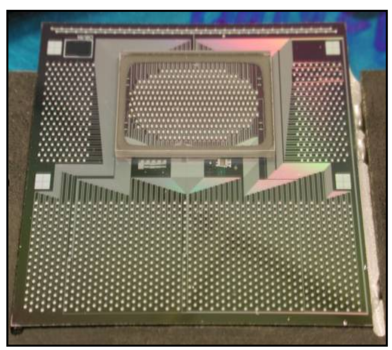
RF Switches



Bio Fluidic Processors

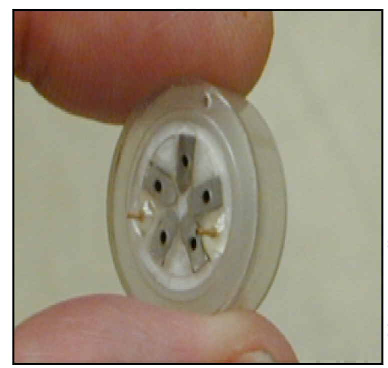


RF Resonators



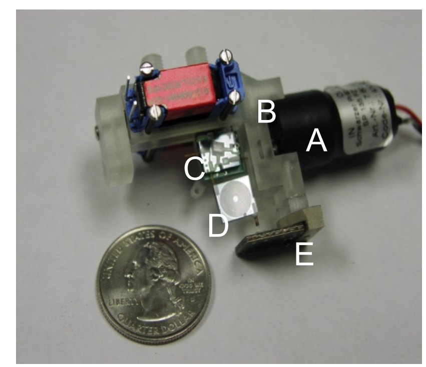
Calient

Optical switches



Honeywell

Fuel Cells



Micro Gas Analyzers

Performance	Capabilities	Size	Speed

MEMS Programs

- **DARPA played the leading role in the U.S. in the development of MEMS**
- **Component-level demonstrations and advanced capabilities important to DoD**
  - **Accelerometers/Gyroscopes**
  - **RF Switches/Resonators**
  - **Fluid processing**
  - **Digital displays**
  - **Chemical sensors**
  - **Fuel Cells**
- **Current DARPA MTO programs focus on miniaturization to drive systems performance**
  - **Fundamental Research**
  - **Specific DoD Applications**

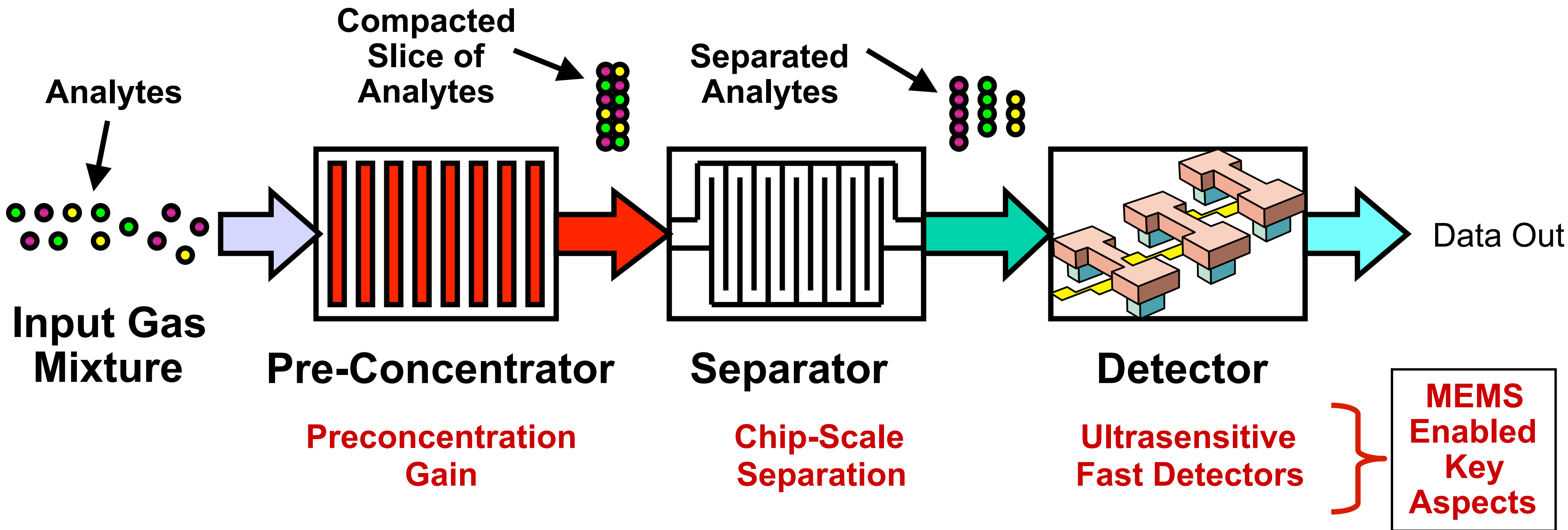
DARPA MEMS Programs

- ***MEMS (1993-2000)***
- Micro Fluidic Systems
- BioFlips
- MEMS Exchange
- Chip-Scale Atomic Clock
- Harsh Environment Robust Micromechanical Technology
- 3-D MERFS
- ***Micro Gas Analyzer***
- RF MEMS Improvement
- Micro Isotope Power Sources
- Micro Electric Propulsion
- Navigation Grade Micro Gyroscopes
- Micro Cryogenic Coolers
- ***N/MEMS S&T Fundamentals***
- Analog Signal Processors
- Hybrid Insect MEMS
- Tip-Based Nanofabrication
- Thermal Ground Plane
- ***Nano Electro Mechanical Switches***
- Micro Inertial Navigation Technology
- ***SERS S&T Fundamentals***
- ***Chip Scale Spectrum Analyzers***
- Chip Scale Vacuum Micropumps
- Active Cooling Modules
- Dynamics-Enabled Frequency Sources

Key DARPA MTO Themes

1. **N/MEMS Enables Significant New Levels of Performance**
2. Scaling – “Smaller is Better”
3. N/MEMS Integration
4. Enabling Completely New Opportunities
5. Basic Research Infrastructure is Important

Chip Scale Micro Gas Analyzers (MGA)



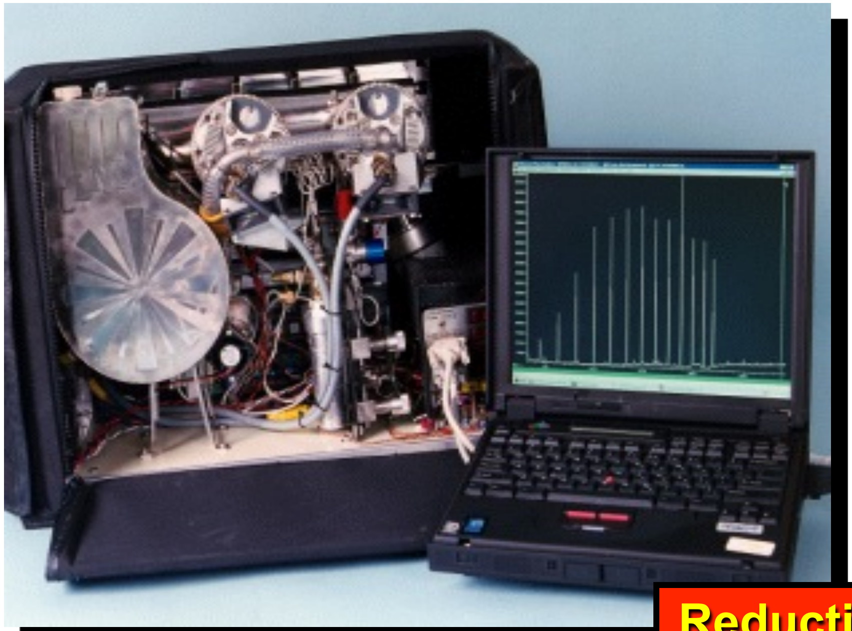
- *Objective*:
  Enable chemical detection via tiny, ultra-low power, fast, high sensitivity, chip-scale gas analyzers with low incidence of false positives.

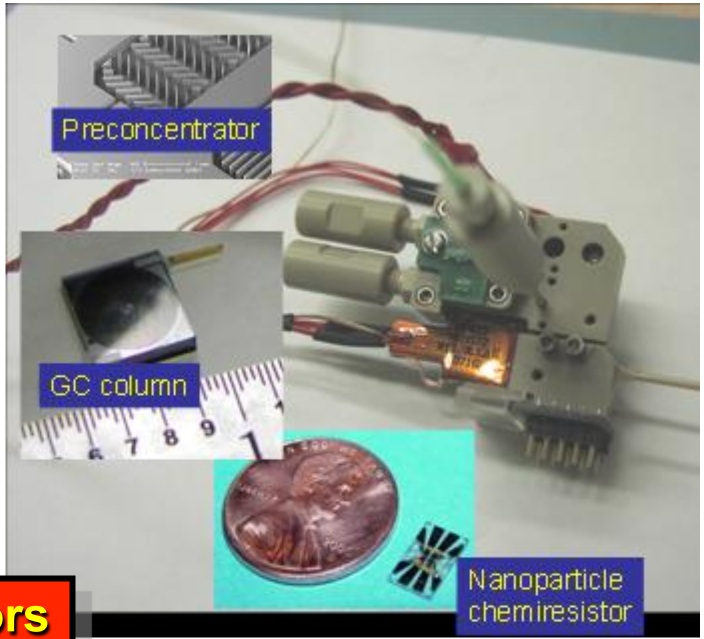
- *Approach*:
  Use MEMS and nanotechnologies to implement analyte preconcentration, separation, (e.g., gas chromatography), and detection at the micro-scale to enhance gas selectivity.

Revolutionary Devices:
DARPA MGA

MGA

Portable Gas Chromatograph	*Chip-Scale Gas Chromatograph*





Reduction Factors

		Reduction Factor		
Size	**40,500 cm^3**	**20,000X**	**Size**	**2 cm^3**
Sensitivity	**1 ppb**	**1,000X**	**Sensitivity**	**1 ppt**
Analysis Time	**15 min.**	**225X**	**Analysis Time**	**4 sec**
Energy Per Analysis	**10,000 J**	**1,000X**	**Energy Per Analysis**	**10 J**

MGA Performance Metrics Achieved

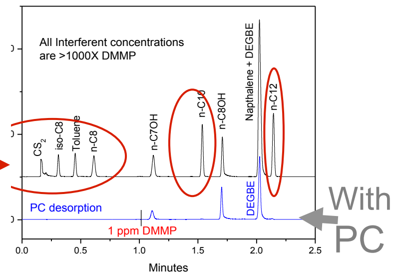
PI: Simonson (Sandia)

Preconcentration:

- Microstructures with selective coating
- High efficiency, high specificity chemical collection and release (PC Gain >1000)

Micro Preconcentrator

Selective PC does not adsorb most common interferents

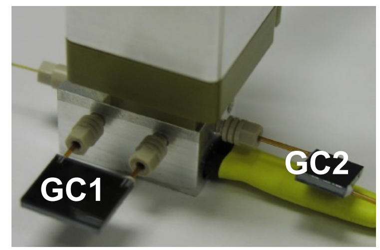


Selective Preconcention

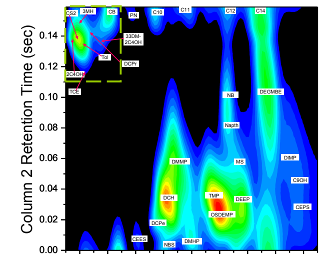
PI: Simonson (Sandia)

Separation:

- 2 column gas chromatography, GCxGC
- Extremely rapid (< 4 sec) separation of large numbers of compounds for fast analysis and low FAR



GCxGC Test Module

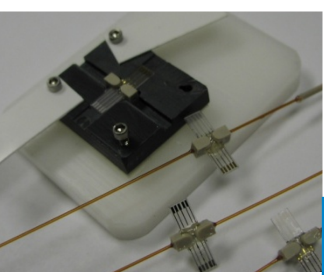


4 sec, 30 Compound GCxGC Separation

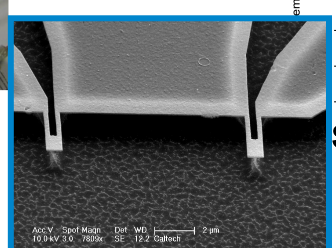
PI: Roukes (Caltech)

Detector: Nanocantilever Array

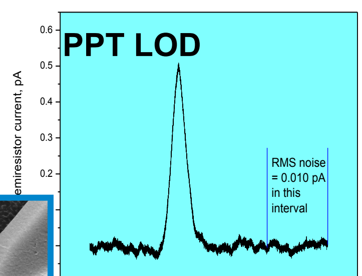
- High sensitivity sensor arrays
- Specific detection for low FAR



Chemiresistor Array



Nanocantilever Array

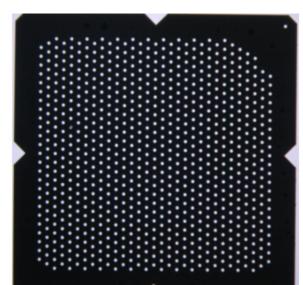


Sensitive Detection

PI: Ramsey (UNC/ORNL)

Detector: Mass Spec

- Microscale ion trap mass spectrometer.
- Operation at 1000X higher pressure than conventional MS demonstrated
- Broad chemical detection capability



Ion Trap Array

MS Test Module

Key DARPA MTO Themes

1. N/MEMS Enables Significant New Levels of Performance
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3. N/MEMS Integration
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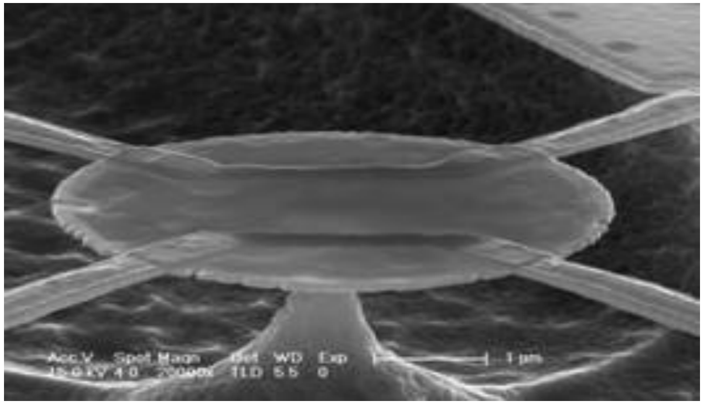
Nanoscale Resonant Detectors

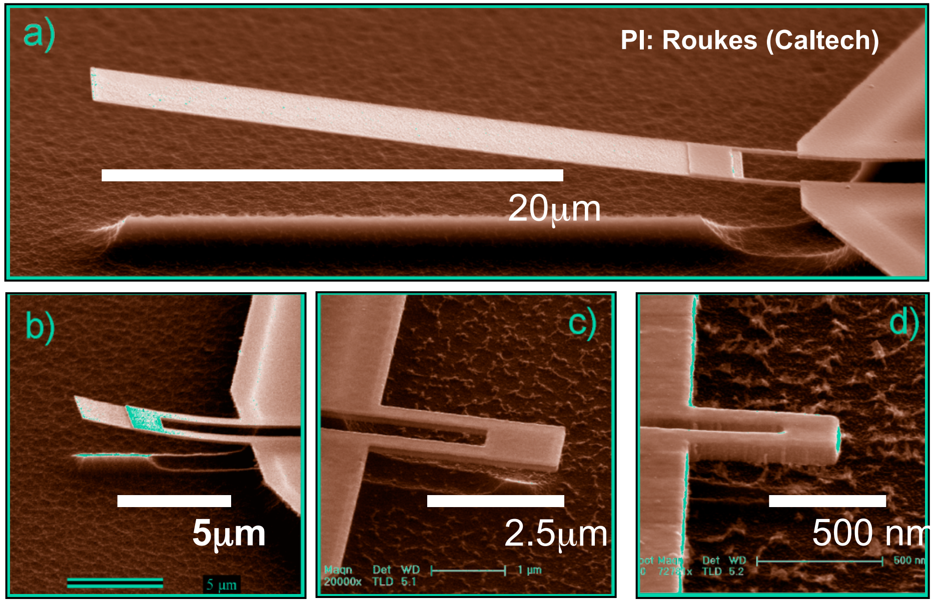
Objective

Effort in focuses on developing ultrasensitive, low power, miniaturized nanomechanical mass detectors for MGA applications.



Technical Approach

Measurement of resonant frequency shift in response to accretion of gas molecules on the surface of piezoresistive nanomechanical resonators.



Challenges

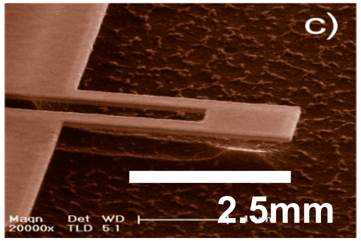
Device nanofabrication, design and realization of ultrasensitive transducer, surface functionalization at the nanoscale, and realization of ambient pressure operation.

Nano "value added": Frequency, Compliance Scaling

With uniform scaling of all dimensions, $w = a\ell, t = b\ell, L = c\ell$

- **Scaling of frequency**

$$f_0 \approx \alpha\sqrt{E/\rho}\,\frac{t}{L} \propto \frac{1}{\ell}$$



↑ with decreasing ℓ

- **Scaling of compliance (force responsivity)**

$$k_{eff} \approx \beta E w\left(\frac{t}{L}\right)^3 \propto \ell$$

↓ with decreasing ℓ

- **Scaling of thermomechanical noise**

$$S_F^{\frac{1}{2}} = \left(\frac{4k_B T k_{eff}}{\omega Q}\right)^{\frac{1}{2}} \propto \ell$$

↓ with decreasing ℓ

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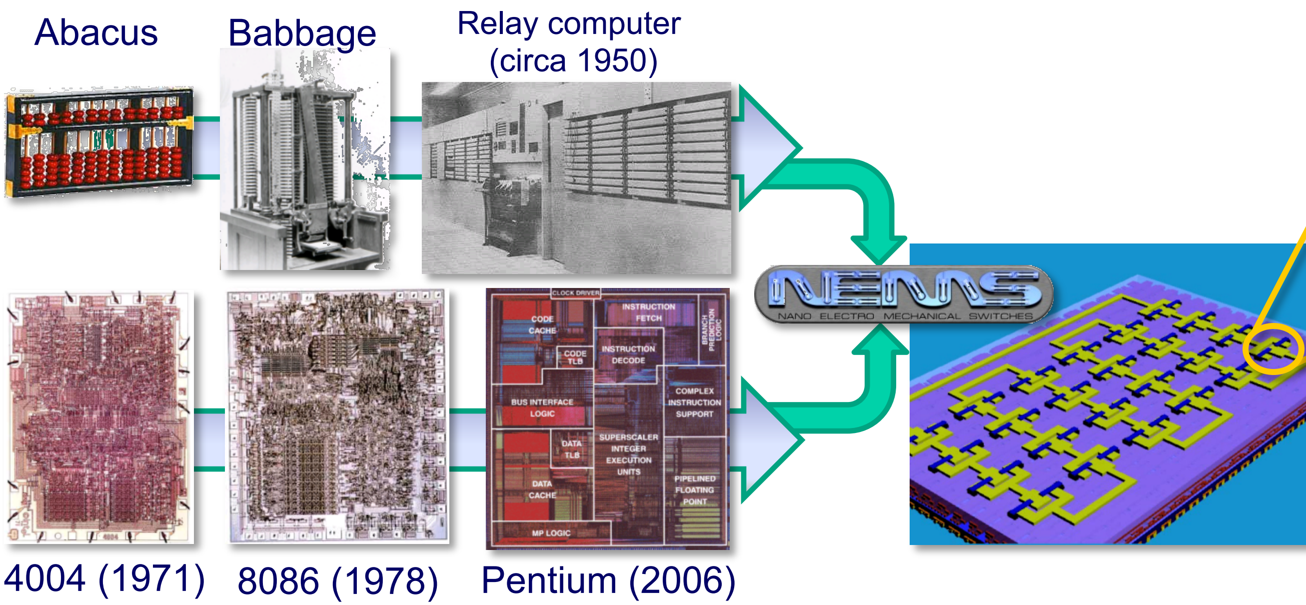
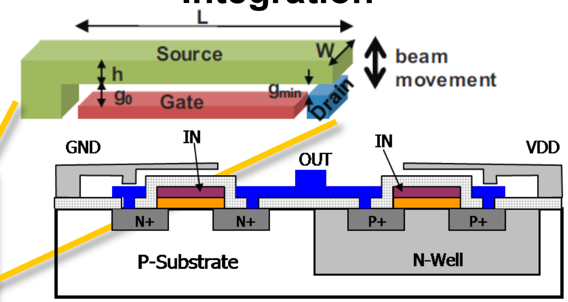
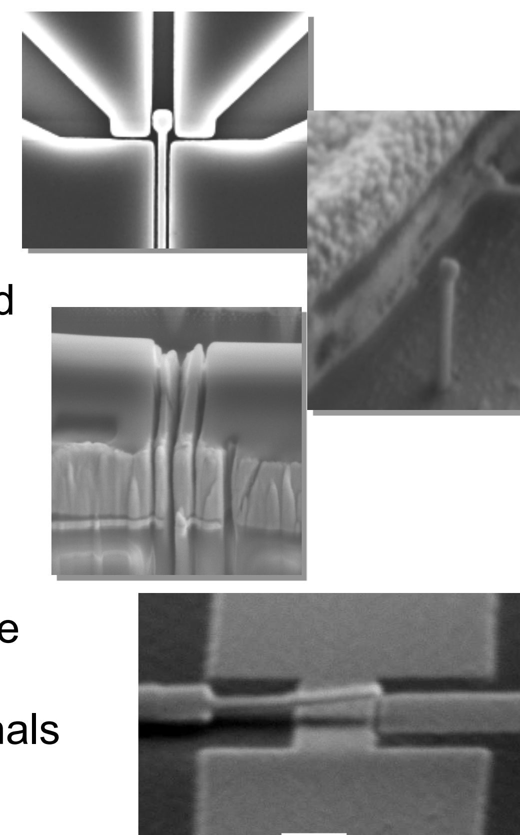
Nano Electro Mechanical Switches (NEMS) Overview

PM: T. Akinwande



Hybrid NEMS/CMOS Device Integration





Objectives

- Eliminate leakage power in electronics to enable longer battery life and lower power required for computing
- Enable high temperature operation (Carnot efficient hot computing)
- Push scaling limits with all-mechanical/hybridization computing

Technical Challenges/Approach

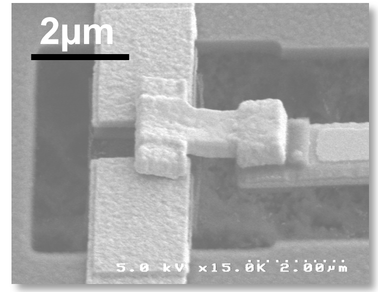
- 1 Volt, 1 nanosecond operation : sub-50nm dimensions
- Reliable nanoscale contacts & stiction : ALD materials, AFM resistance measuring techniques, etc.
- Gate dielectric charging : High K, body biasing, modulated timing signals

Significant NEMS Achievements

PM: T. Akinwande

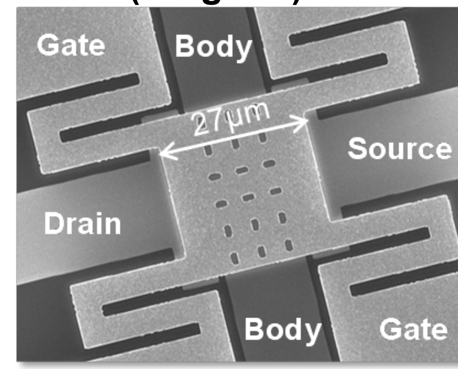
Phase I Accomplishments:

- Demonstrated pathways to CMOS-NEMS hybrid implementation of FPGAs [C. Chen et al., FPGA'10]
- Demonstration of high-temperature digital C-NEMS
- Demonstration of first-ever nanoscale mechanical relays and logic elements with manufacturability and repeatability [IEDM 2009]
- Demonstration of first body-biased mechanical logic elements and Complementary NEMS (C-NEMS) switches
- Demonstrated analog amplification using NEMS "resoswitch"
- Demonstration of CNEMS logic with >10X improvement in both static and dynamic power consumption compared to the 65nm node CMOS ICs
- Demonstration of CNEMS Digital, Mixed Signal & Analog Circuits [ISSCC 2010]
- Demonstration of new processing techniques for all-CNT switches, obviating the need for aligned CNT films, and highly reproducible & uniform layer by layer process

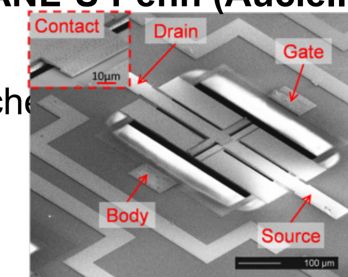


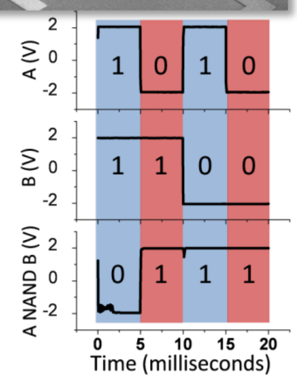
ARL (Polcawich)

UCB (King-Liu)

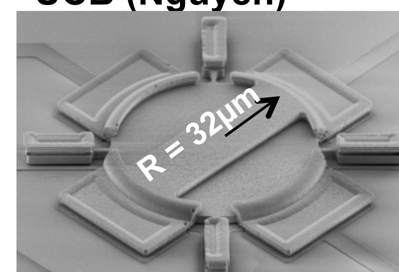


ANL-U Penn (Auciello)

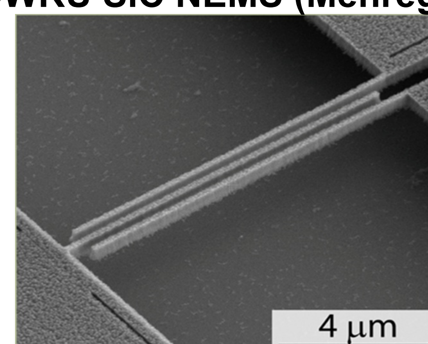




UCB (Nguyen)



CWRU SiC NEMS (Mehregany)

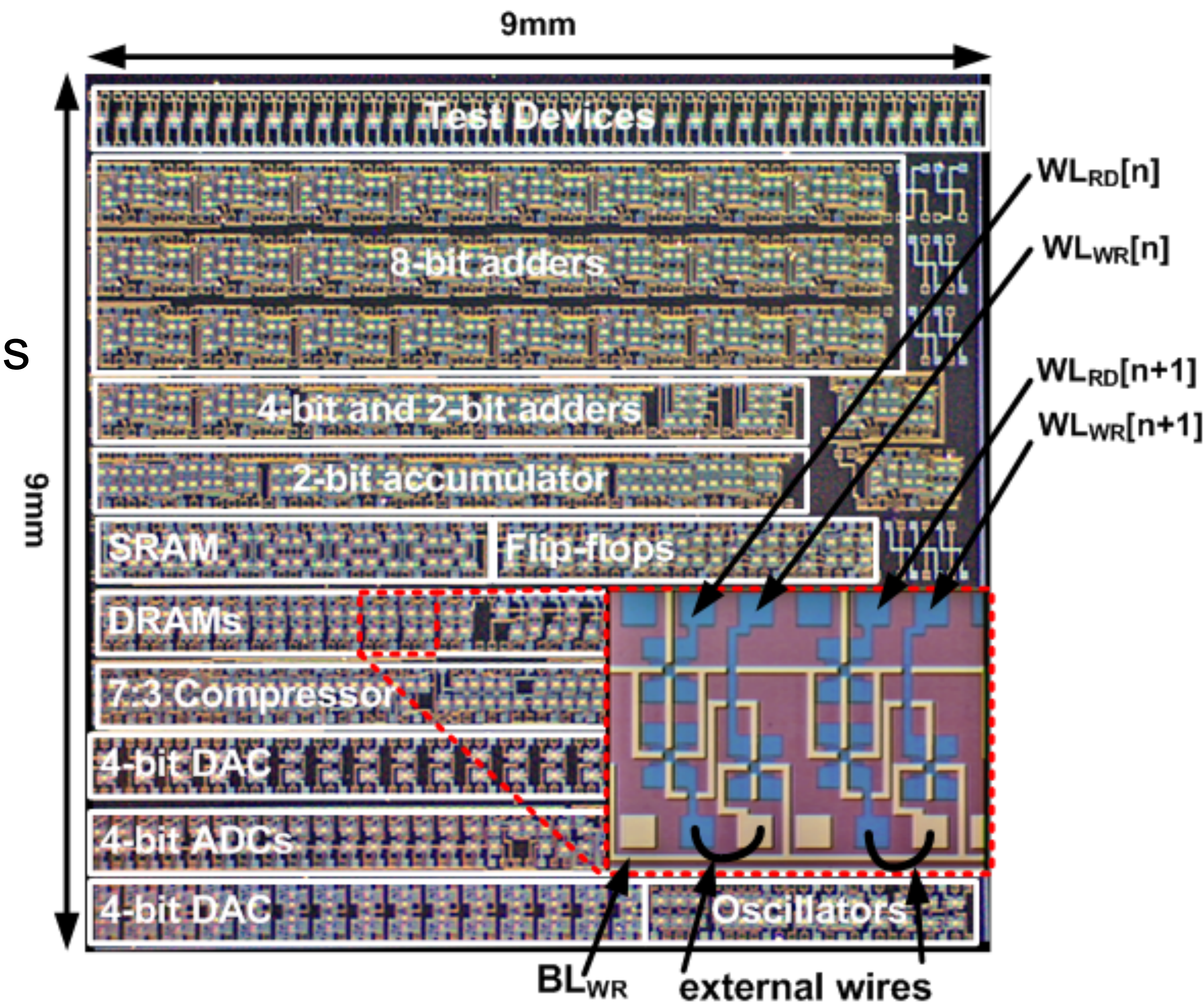


C-NEMS Circuits Test Chip UC Berkeley (King-Liu)

PM: T. Akinwande

- DAC
- ADC
- Adders
- Flip-flops/Latches
- Memories
- Oscillators

- Inverter VTC suggests composability…



F. Chen *et al.*, *2010 ISSCC*

Micro Cryogenic Coolers (MCC)

Problem

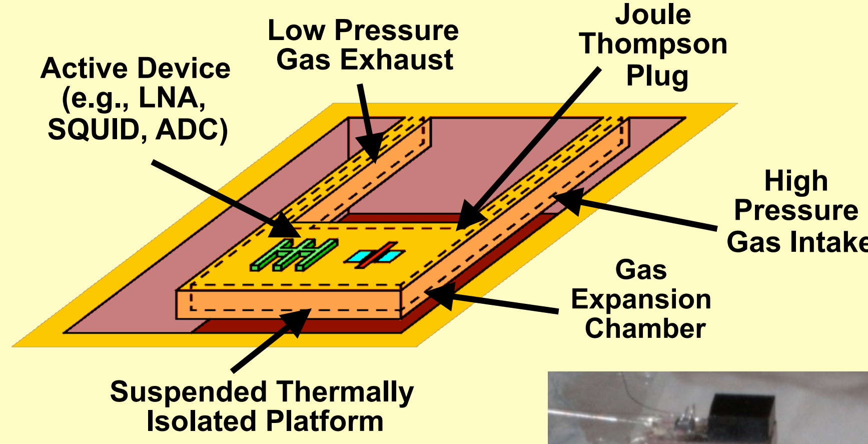
Need to reduce both size (< 4 cc) and power consumption (< 100 mW) of cyrogenic coolers by significantly increasing thermal isolation and refrigeration capability for low-power sensors

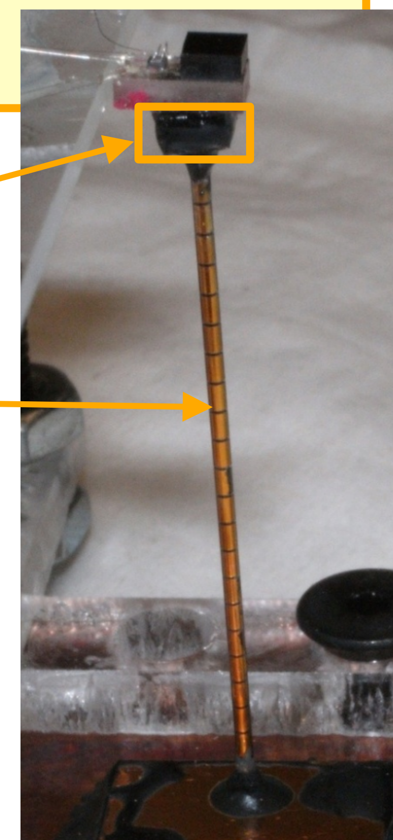
Goal: Scalable and reliable Cryo Cooling

- 3 to 50 mWatt heat lifts
- Ambient temperatures from 300 to 380 K
- Sensor platform targeting 77 to 200 K
  ΔT currently 150 K, goal is > 200 K
- Cold stage includes planar heat exchanger
- MEMS-based compressor with size and power minimized for 4:1 pressure ratio

DoD Impact

- Increase threat detection range by >2x for helicopter IR counter measure systems
- Huge reduction in SWaP for Fourier Transform Infrared Spectroscopy (FTIR) biosensors



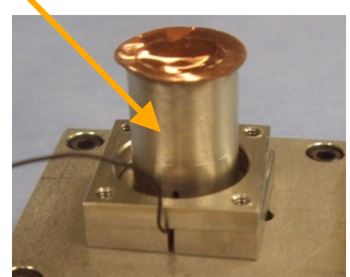


Cooler Head: < 0.1 cc

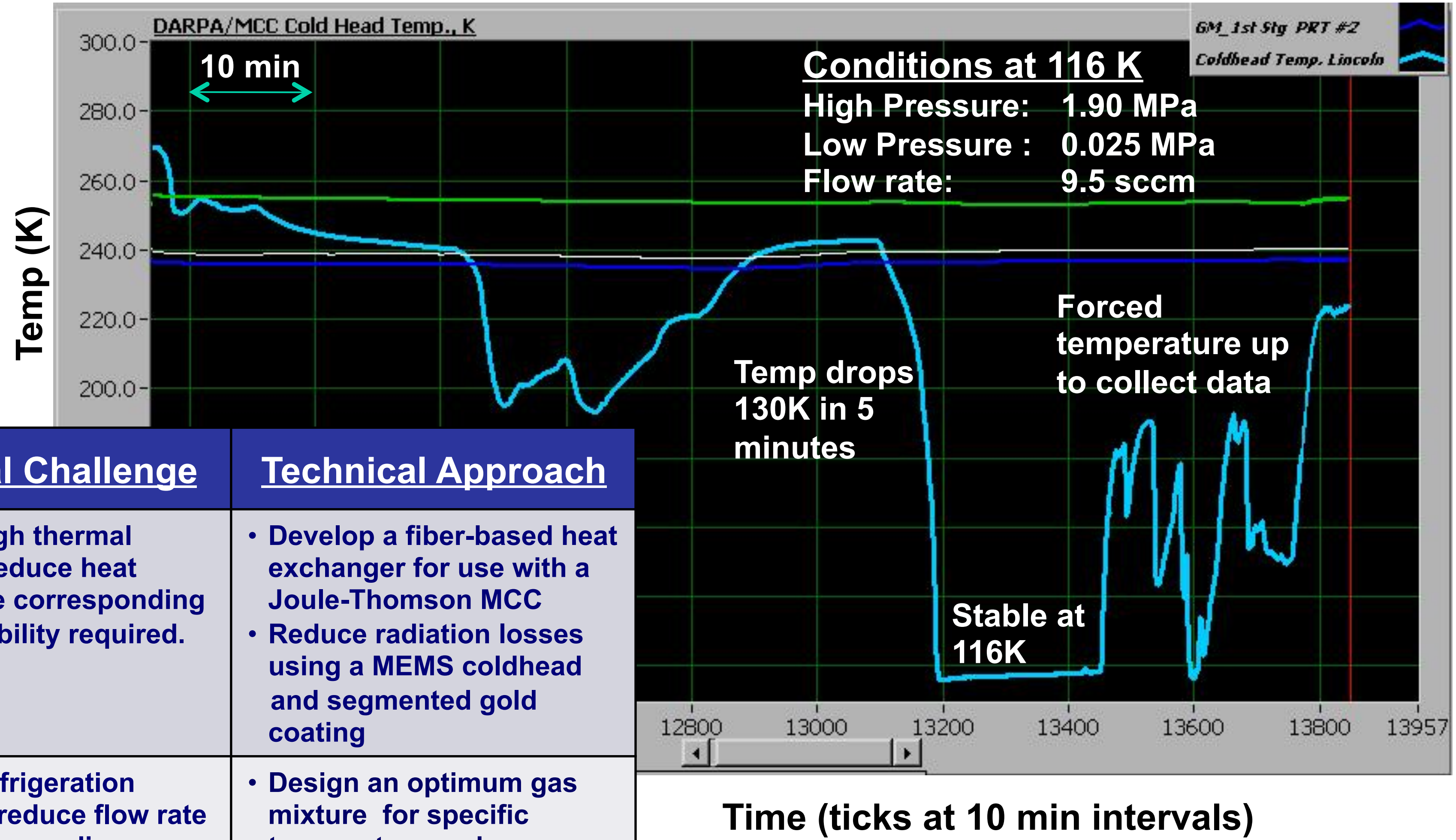
A small thermal imaging array is mounted on top of the cooler

Compressor piston inside housing under base

Thermal isolation several cm long



University of Colorado (YC Lee) Heat Lift >3mW, ΔT >150 K



Technical Challenge	Technical Approach
Achieving high thermal isolation to reduce heat loads and the corresponding cooling capability required.	• Develop a fiber-based heat exchanger for use with a Joule-Thomson MCC • Reduce radiation losses using a MEMS coldhead and segmented gold coating
Increasing refrigeration capability to reduce flow rate and the corresponding compressor size and power.	• Design an optimum gas mixture for specific temperature and pressure ranges.
Fabrication of a small and low-power compressor.	• Use a gas mixture designed for low P ratio. • Employ piezoelectric-based actuation.

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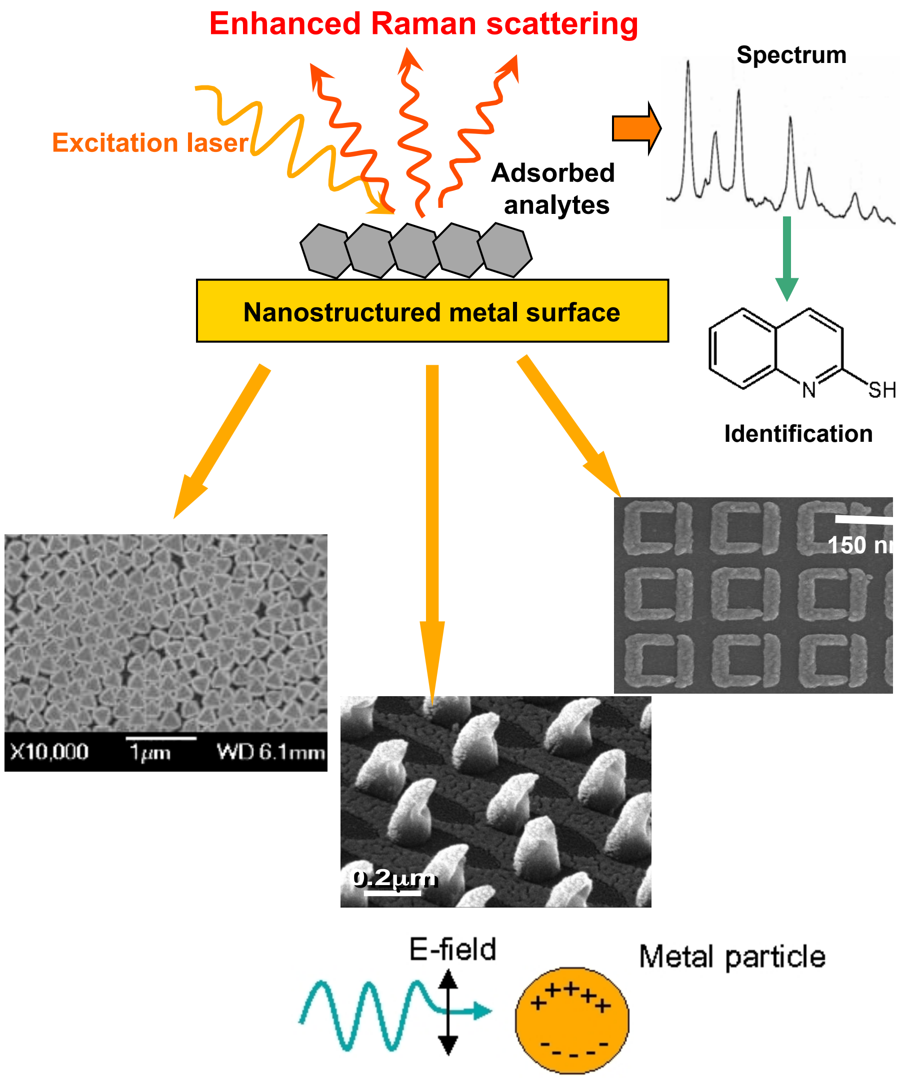
Surface-Enhanced Raman Spectroscopy Science & Technology Fundamentals (SERS S&T)



Goal:

- Enable 0.1 to 10 km stand-off detection of CWAs, BWAs, TICs, and explosives
- Decrease false alarm rates by 3-4 orders of magnitude
- To fabricate reproducible, large scale (6”) SERS materials with Enhancement Factors $>10^{12}$
- Enable handheld microsystems capable of multi-pathogen screening
- Understand the origins and mechanisms of SERS

Technical Challenges:

- Obtain theoretical and experimental data that increases Enhancement Factors
- Synthesize resonance enhanced reporters, nanoparticle attachments and encapsulants
- Determine excitation wavelength dependence

Key Accomplishments:

- Through nano-antenna design based on theoretical modeling, reproducible EFs of 10^9 have been achieved

Impact:

- Ultra-bright nanoparticles and nanostructures with SERS Enhancement Factors $>10^{12}$ will lead to a new generation of highly sensitive, low-FAR nanosensors

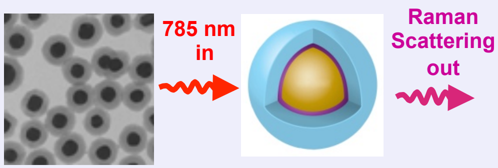
Novel SERS Substrates Will Revolutionize Chem/Bio Detection for DoD

Six Unique SERS S&T Approaches

PI: R. Van Duyne

Northwestern University

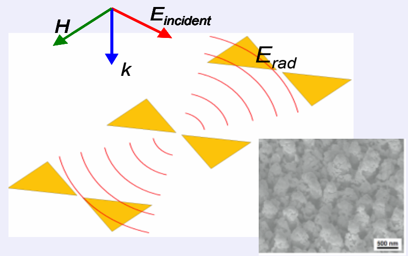
Controlled synthesis of unit cell nanoantenna structures; EM theory; precision molecule placement



PI: K. Crozier

Harvard University

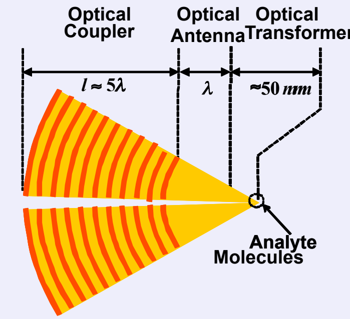
Radio engineering of periodic optical antennas, laser nanostructuring of surfaces



PI: Ming Wu

UC Berkeley

Gradient optical coupling; integrated optical antennas



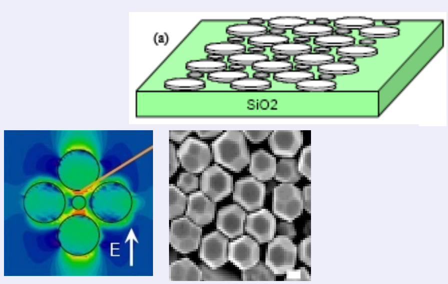
SERS S&T Fundamentals

Enhancement Factor Theory / Modeling / Fabrication / Testing

PI: Zhiyong Li

Hewlett Packard

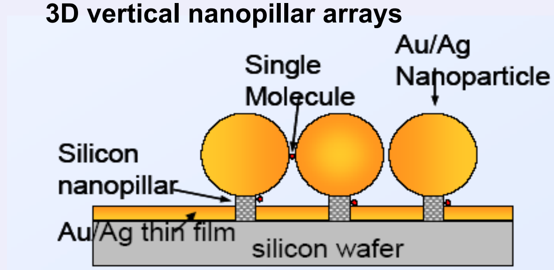
Plasmonic nanolens arrays with faceted SERS crystals



PI: T. Bond

Lawrence Livermore (LLNL)

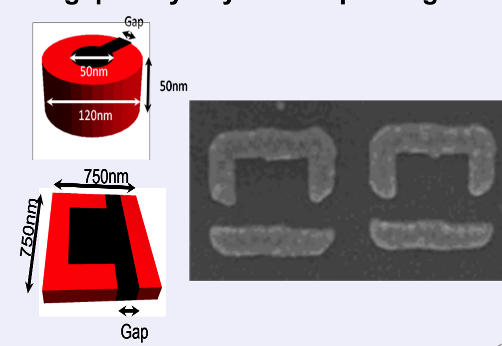
3D vertical nanopillar arrays



PI: S. Chou

Princeton University

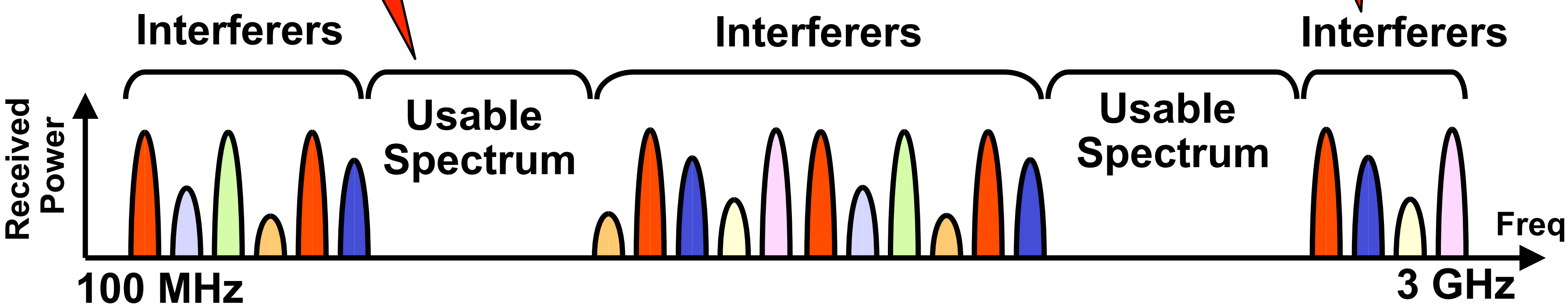
Nanogap arrays by nanoimprinting



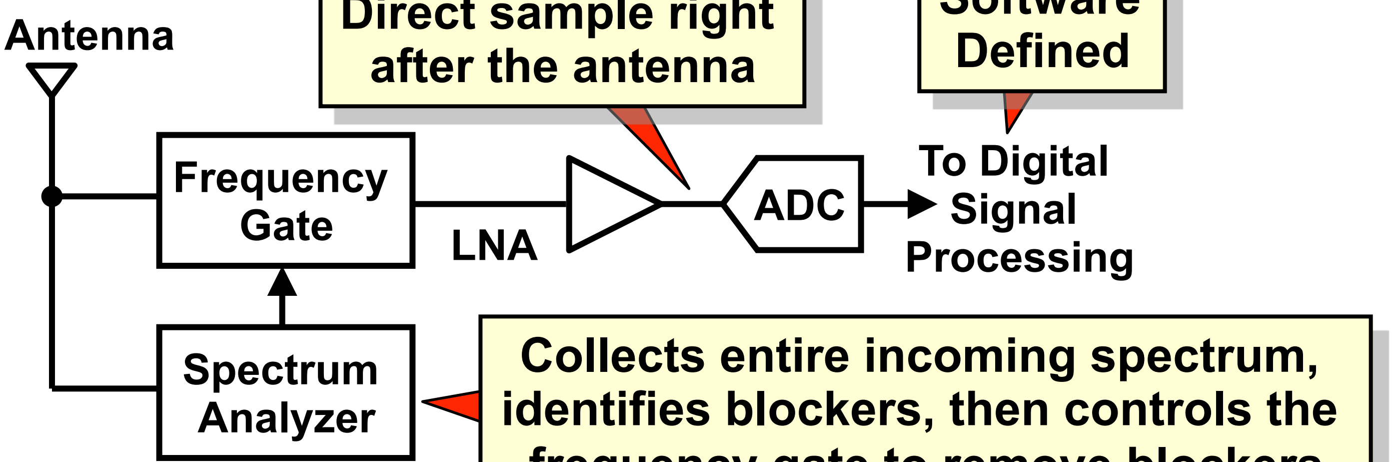
Software-Defined Cognitive Radios

Cognitive: identifies unused spectrum, then operates there → ***Need***: ultra-fast spectrum analyzer

Software-Defined: digitizes right after the antenna → must remove interferers to do this



Solution:



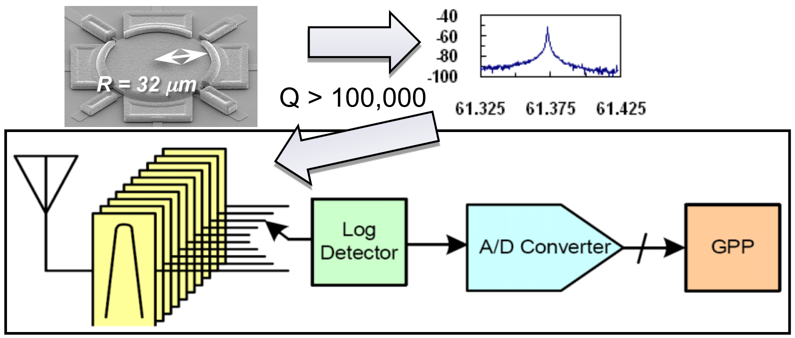
Why can't we do this today?

Today's spectrum analyzers too large, too slow, and too power hungry

Chip-Scale Spectrum Analyzers (CSSA)

Program Objective: To develop a 100-channel spectrum analyzer capable of 3 GHz operation with Q > 100,000, an input impedance < 50 Ω, resolution bandwidth < 30 kHz, and low insertion loss.
Motivation: compact, jam-resistant, low-power, intelligent radio.

One Hundred Fixed Frequency Filters

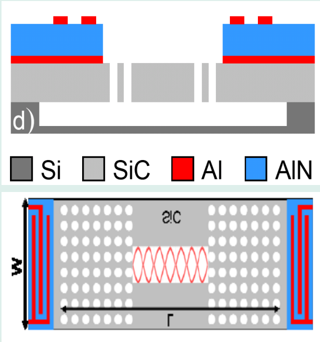


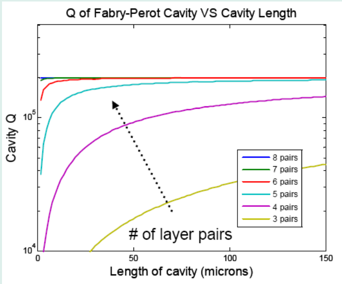
Technical Approach / Key Technical Challenges:

- Development of new anchoring technologies
- Adaptation of new materials (SiC, Al_2O_3, CNTs, AlN)
- Key challenge: Developing optimal design/material combinations that minimize energy losses required for achieving extremely high Q (> 100,000)

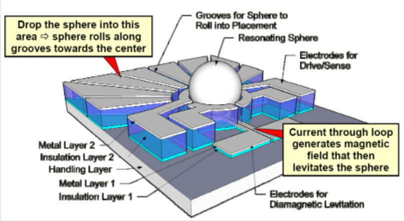
Status: Recently Started

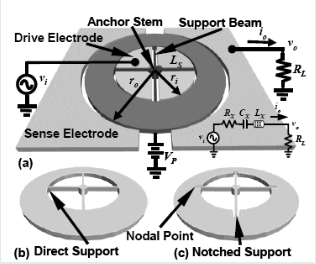
Over-moded resonators and phononic crystal interfaces

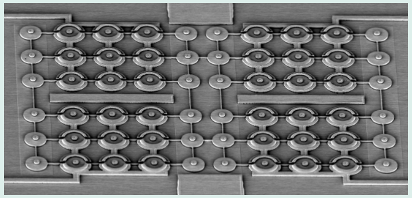




Mechanically coupled Q-boosting resonators, low-loss forms, anchors, and materials (SiC, Al_2O_3, CNTs, AlN)





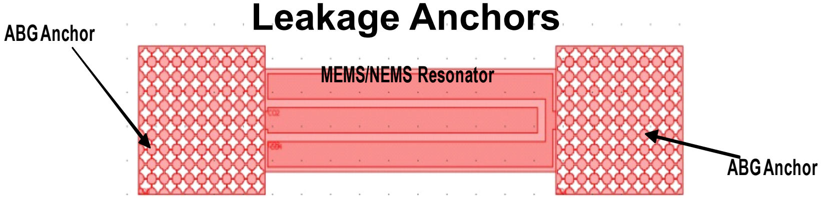


Array of coupled MEMS polysilicon resonators

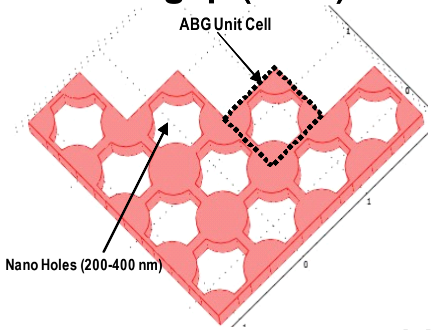
CSSA Initial Results

Northrop Grumman (D Adam)

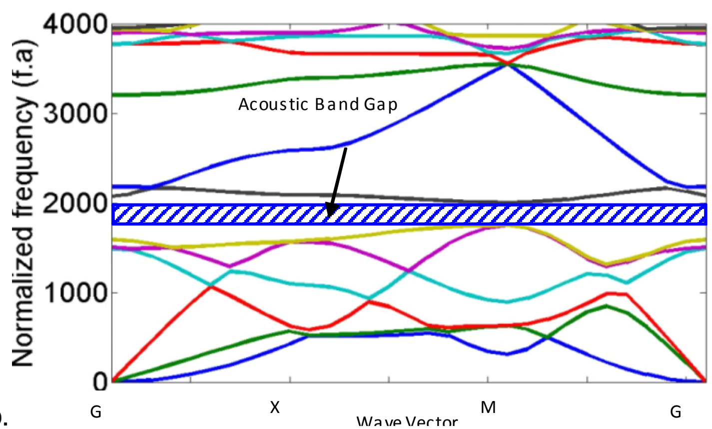
Acoustic Band-gap Structures for Low Leakage Anchors



acoustic band gap (ABG) structure

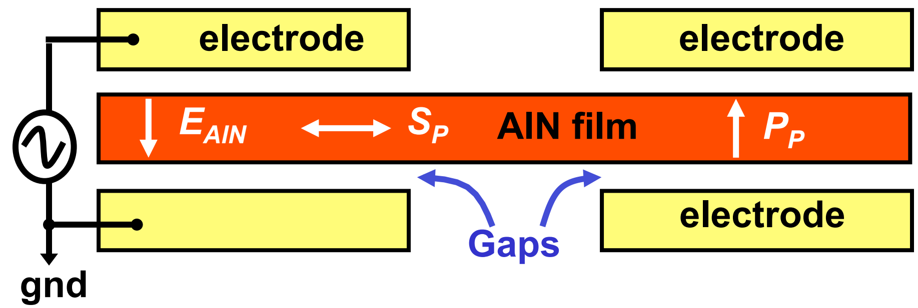


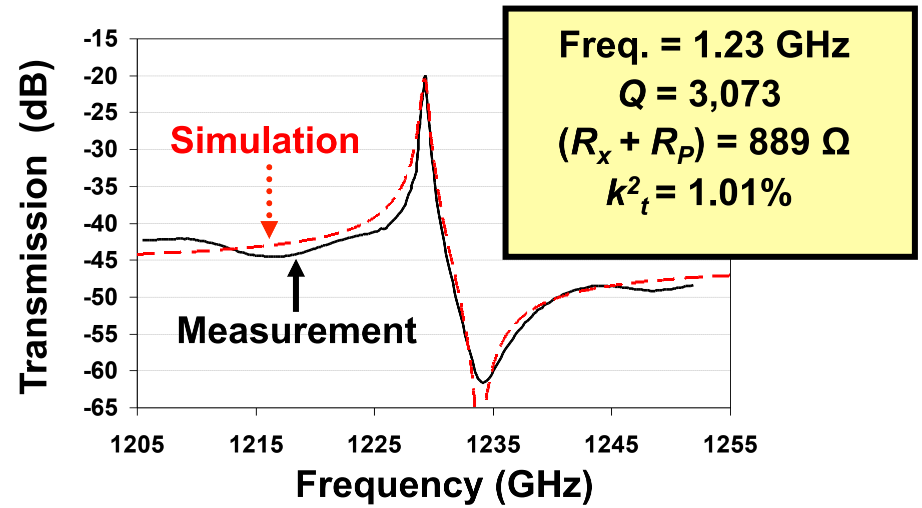
COMSOL FEM simulation shows 14% band-gap



UC Berkeley (C Nguyen)

AlN Ring Resonator Equipped w/ Capacitive-Piezo Transducers





Measured Freq. Characteristic

Key DARPA MTO Themes

1. N/MEMS Enables Significant New Levels of Performance
2. Scaling – “Smaller is Better”
3. N/MEMS Integration
4. Enabling Completely New Opportunities
5. **Basic Research Infrastructure is Important**

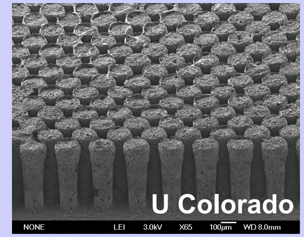
N/MEMS S&T Fundamentals

Program Objective:
To develop an advanced fundamental understanding in key technical areas important to the continuing development of N/MEMS technology and its transition into defense systems.

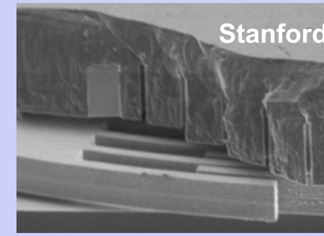
Technical Approach / Key Technical Challenges:
Basic Research: Understanding key issues involving nano/micro interfaces, scaling laws, failure mechanisms, microfulidics, photonics, N/MEMS materials and processes, et al.

Building on Strong Record of Accomplishments:
Publications and patents, transitions to new DARPA programs, industry cost-sharing, educating next-generation N/MEMS researchers

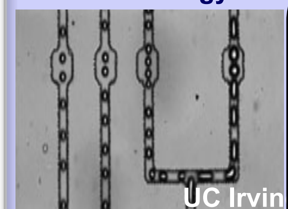
Nanowire Sensors



Interfacial Science



Microfluidics and Biotechnology

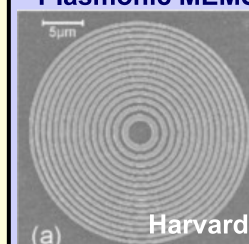


Focus Areas

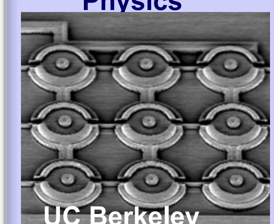
- Reliability
- Molecular Devices
- Reconfigurability
- Interfaces
- Interconnects
- Scaling Limits
- Nanostructures
- Modeling
- Power Sources
- Materials
- Self-Assembly
- Photonics

Reliability Physics

Plasmonic MEMS



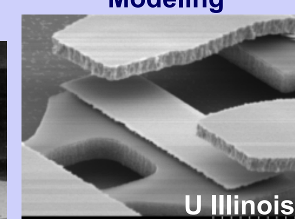
Scaling-Induced Physics



Self-Configuring ICs

Nano Probes

Multi-Physics Modeling



Strong Record of Program Accomplishment in Phase I

- More than 350 publications derived from supported research in technical journals and conference proceedings
- Approximately 200 additional conference presentations
- More than 30 patents – pending or issued
- Research is contributing to the education of ~200 graduate students; work also involves participation by 48 post-docs
- Program research oversight and guidance provided by 90 faculty
- Cost-sharing support in Phase I provided by 68 industry program partners; industry funding met DARPA expectations

Program has a profound effect establishing a broad N/MEMS community and accelerating technical progress important to transitioning emerging capabilities.

N/MEMS S&T
2006-2009

- Caltech
- Carnegie Mellon University
- Cornell University
- Harvard University
- MIT
- Stanford University
- UC Berkeley
- UC Irvine
- UC San Diego
- University of Colorado
- University of Illinois

N/MEMS S&T Fundamentals
Massachusetts Institute of Technology

Focus Center on Non-Lithographic Techniques for N/MEMS

PI: M Schmidt

Mission: To develop revolutionary methods for fabricating N/MEMS without the need for planar lithography

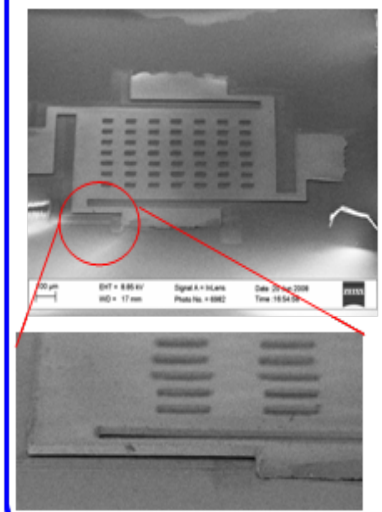
- N/MEMS technology currently constrained by the inability to prototype and manufacture products rapidly and cost-effectively in small/medium volume: A new paradigm is needed to break this log-jam
- Leverage high-resolution printing processes to deposit exotic materials at desired locations

Key Accomplishments:

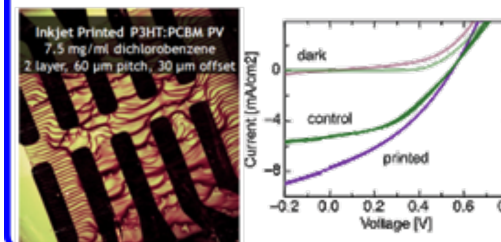
Developed a family of *fundamental process building blocks* that will enable rapid prototyping and low-cost manufacturing of microsystems by a new paradigm.

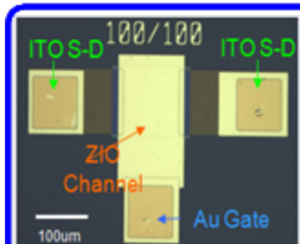
End Goal: Enable broader exploitation of N/MEMS devices in defense systems by overcoming current cost and turnaround time challenges associated with meeting low-volume DoD needs

Printed MEMS



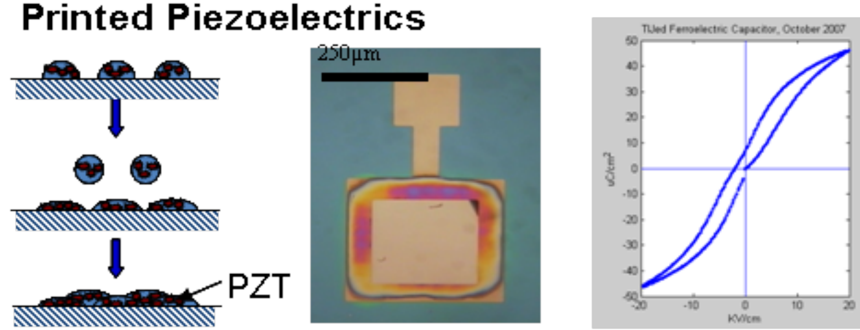
Printed Solar Cell





100°C Transistor Process

Printed Piezoelectrics



Center for RF MEMS Reliability and Design Fundamentals

PI: G Rebeiz

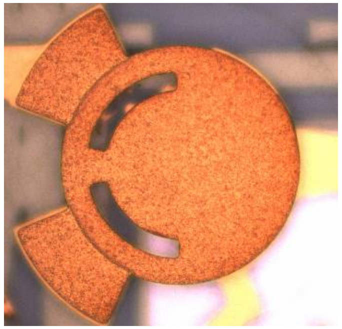
Mission: To develop fundamental understanding of microscale actuators, metal contacts, and dielectrics pertinent to high-power, high-reliability RF MEMS switches.

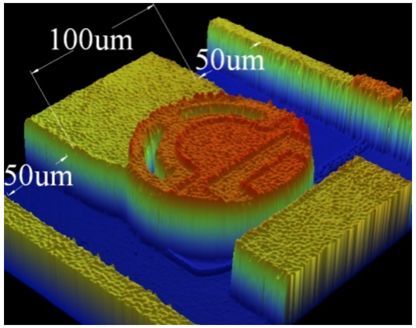
- RF MEMS actuators are sensitive to residual stress and stress gradients, resulting in low yields
- Angular design exhibits high tolerance to biaxial and stress gradients; exceptional flatness demonstrated, increasing yield
- Better insight into contact properties at high RF power for metal-contact switches
- Clear understanding of dielectric breakdown at high RF voltages for capacitive switches

Key Accomplishments:

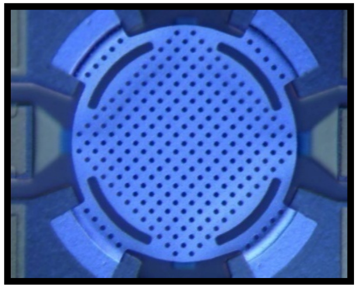
Demonstrated robust stress-tolerant RF MEMS actuator designs for enhanced reliability. Have transferred designs to industry (RFMD, Agilent, Raytheon); yield now > 94% on 6-inch wafers

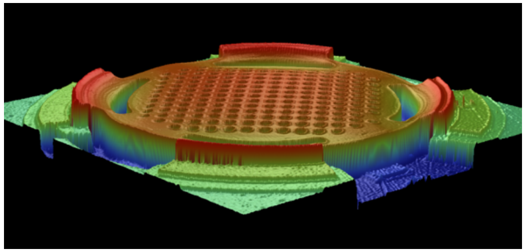
End Goal: RF MEMS switches and circuits with high power handling capabilities (10-50W) at 0.1-30 GHz for radar and tunable radio.





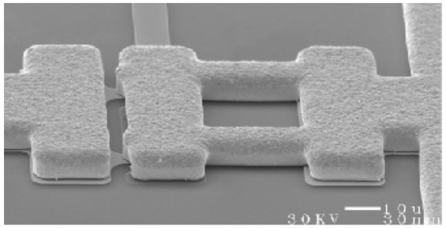
Metal-contact stress tolerant actuator (photograph and 3-D profilometer image)





Capacitive stress-tolerant actuator (photograph and 3-D profilometer image)

Prior state-of-the-art rectangular MEMS actuator



N/MEMS S&T Fundamentals
California Institute of Technology

Focus Center for NEMS-Based SPM, Sensing, & Microfluidics

PI: M Roukes

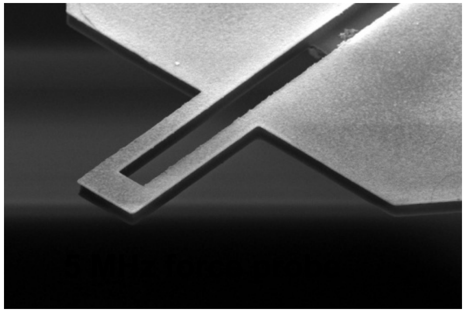
Mission: To develop high speed, high force sensitivity, self-sensing (no external optics needed), integrated probe tips at wafer-scale in a foundry-compatible fabrication process

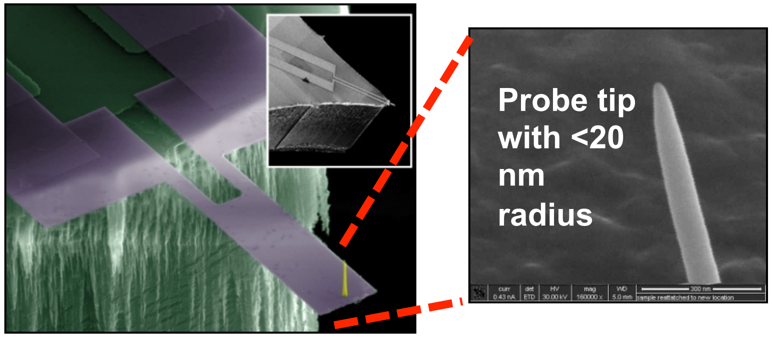
- Probes can be directly integrated into existing SPM systems, allowing the U.S. to regain the advantage in cutting-edge SPM technology by enabling the investigation of heretofore unexplored force and time regimes at the nanoscale

Key Accomplishment:

Developed SPM probes based on NEMS technology that enable major advances in the state-of-the-art with respect to speed, sensitivity, fabrication, and spatial resolution for imaging at the nanoscale

End Goal: SPM probes enabling a better understanding of the specificity and kinetics of chem/bio sensing, which are key to improved sensors for CBW agent detection





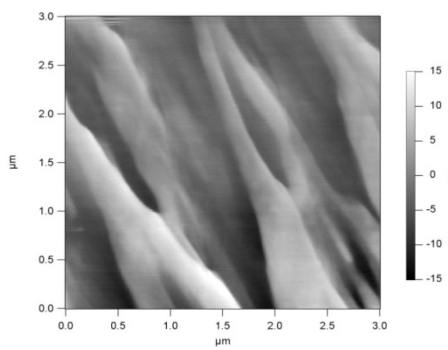


Image of calcite generated by Caltech high-speed probe in a commercial AFM system

IMPACT Center for Advancement of NEMS/MEMS VLSI

PI: A Cangellaris

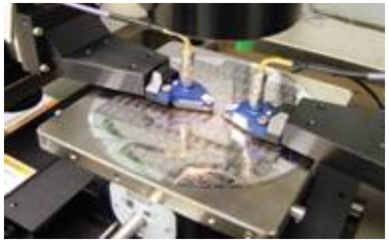
Mission: To enhance understanding of long-term survivability of MEMS through multi-scale modeling and experimentally-driven failure-rate quantification methods.

- First-principles characterization of surface and bulk dielectric charging in MEMS capacitive switches
- Electronic monitoring of packaged MEMS devices
- Scaling of device parameters and reliability Incorporated charging model into Coventor's ARCHITECT® software

Key Accomplishment:

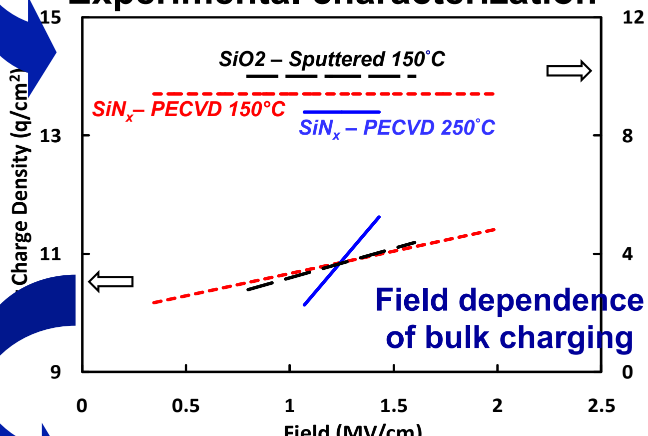
Developed validated computer models of the physical mechanisms governing MEMS performance and a stochastic MEMS CAD framework to enable fast, computer-aided, robust design of reliable MEMS devices

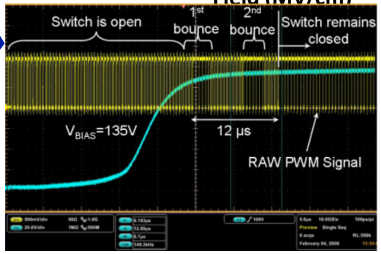
End Goal: New, advanced analytical tools and characterization techniques facilitating the design of reliable, high-performance, MEMS-based RF/microwave systems.



RF MEMS Switch

Experimental characterization





Model switch failure due to stiction

Electro-mechanical simulation predicts behavior such as stiction due to charging

Center on Interfacial Engineering for MEMS (CIEMS)

PI: R Howe

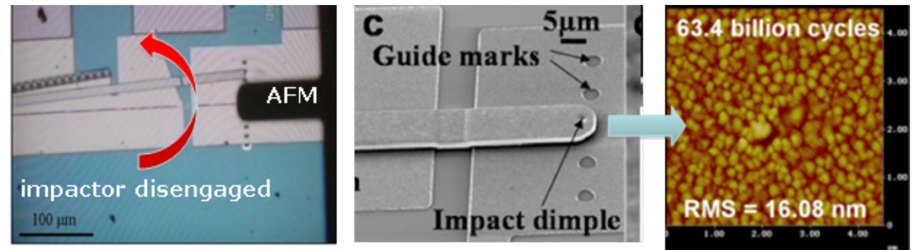
Mission: To develop high-performance photonic sensors and microsystems based on an advanced understanding of N/MEMS interfaces and interfacial engineering

- In situ micro-metrology of interfacial properties
- Fabrication of high-optical-quality microshells for visible/IR applications
- Fundamentals of waveguides and optical detectors using photonic crystals
- Flexible 3-D self-assembly for microsystems

Key Accomplishment:

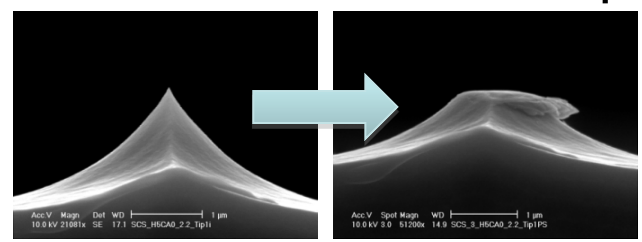
Developed materials, processes, and test structures for characterizing and enhancing N/MEMS interfaces, leading to major advances in photonic-crystal based optical sensing and communication building blocks

End Goal: Micro-encapsulated high-performance infrared sensors and optical signal-processing elements providing more reliable device functionality in N/MEMS involving contacting surfaces or cyclic operation

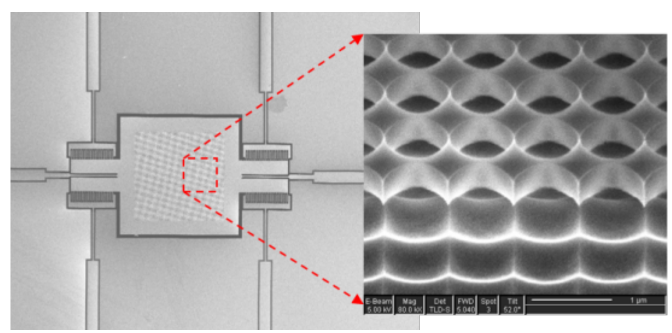


Impact wear testing

AFM image: onset of wear at impact site



Abrasion in uncoated Si probe tip



Monolithic silicon photonic crystal mirror MEMS scanner

Harvard Center for Reconfigurable Photonic MEMS

PI: K Crozier

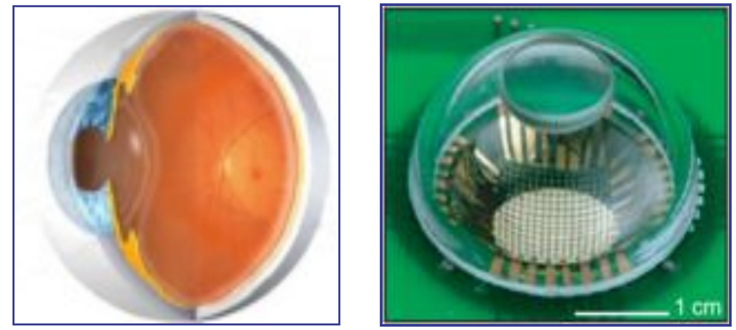
Mission: To develop a radical new class of photonic devices whose operations can be dynamically reconfigured in response to changing conditions

- Materials science: Mechanical behavior of high modulus materials on soft substrates
- Optical science: Plasmonic methods for controlling optical near- and far-fields
- Near-field optical forces: Physics of forces exerted by reconfigurable plasmonic devices

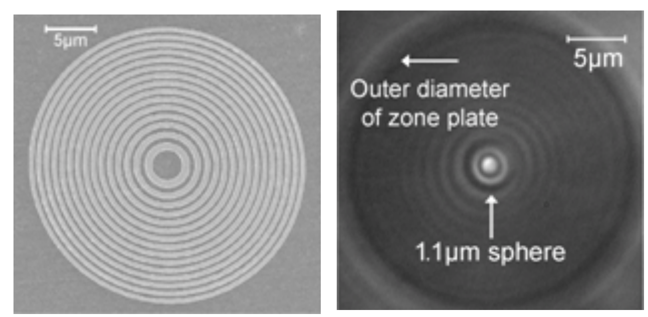
Key Accomplishment:

Demonstrated enhanced capabilities for the detection, identification, and manipulation biological materials, chemicals, and nanoparticles using surface plasmon phenomena

End Goal: Superior photonic devices for military imaging applications achieved by forming opto-electronics and plasmonics on soft elastomers incorporating actuators



Conceptual electronic eye with focal plane featuring adjustable curvature



Demonstration of microfluidic optical tweezer on-a-chip, with performance (trapping stiffness) comparable to conventional optical tweezers, but with a smaller footprint (<100 μm diameter)

N/MEMS S&T Fundamentals
University of California, Berkeley

Berkeley University of California | BSAC MiNaSIP DARPA S&T Center

Center for Micro/Nano Scaling-Induced Physics

Penn University of Pennsylvania

PI: A Pisano

Mission: To understand, control, and engineer scaling-induced physics in N/MEMS RF devices to facilitate their effective exploitation for DoD applications

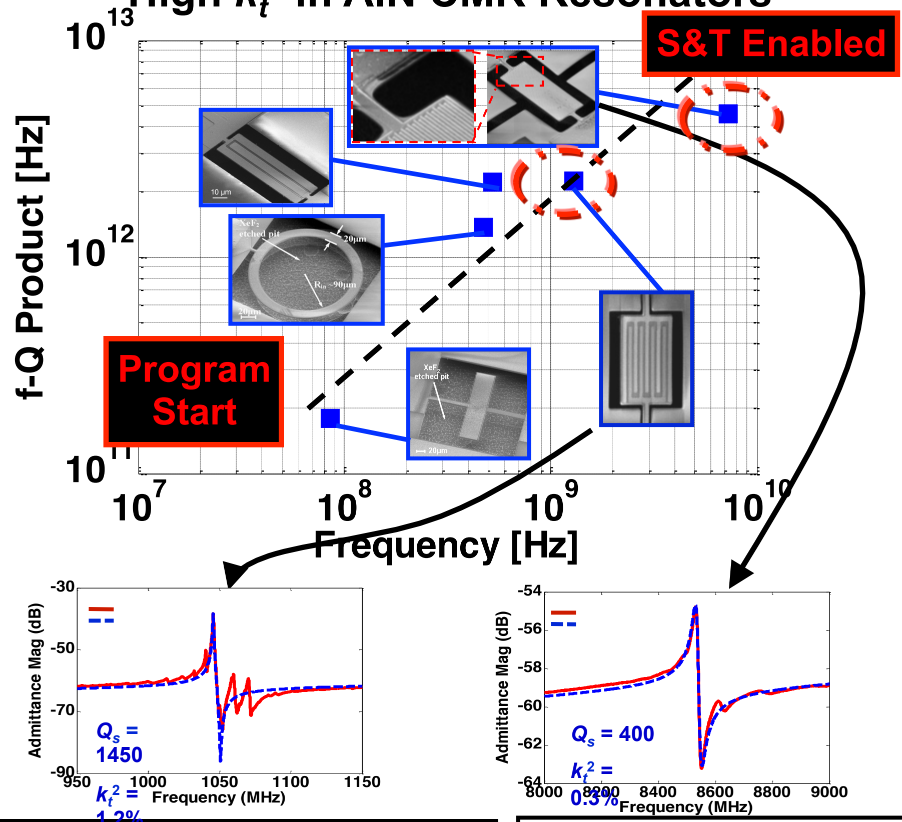
- Physical phenomena that constrain the performance of N/MEMS devices as they are scaled and arrayed to increase performance
- Effects of harsh environments on performance of N/MEMS devices (T, shock/vibration, chem)

Key Accomplishment:

Developed capabilities for controlling and manipulating micro/nano interfaces and demonstrations of major advances in noise, drift, damping and impedance matching

End Goal: Established limits to performance, stability, and robustness of N/MEMS RF devices under various environments and proven methods for extending them

High Frequency (> 1 GHz), High *Q*, and High k_t^2 in AlN CMR Resonators



Highest k_t^2 achieved for LFE AlN resonators at 1.05 GHz

Highest *frequency* (8.5 GHz) ever demo'ed

N/MEMS S&T Fundamentals
Carnegie Mellon University

Carnegie Mellon

Center for Memory Intensive Self-Configuring Integrated Circuits

PI: T Schlesinger

Mission: To develop fundamental understanding of N/MEMS devices, circuits, and materials to enable and implement self-configuring integrated circuits

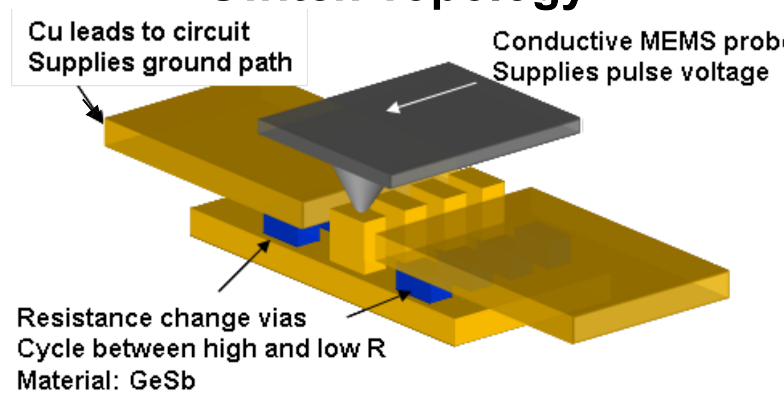
- Reliability and performance of probe sensors, actuators, and contacts; phase-change materials
- Heterogeneous integration of N/MEMS probes, nanoscale vias , and CMOS
- Switches exhibit 100X less capacitance than comparable transistors with equivalent performance
- Non-volatile/low-power devices

Key Accomplishment:

Developed advanced N/MEMS technologies involving resistance change materials, conductive probe arrays, and 3-D heterogeneous fabrication that will enable new types of reconfigurable electronic systems

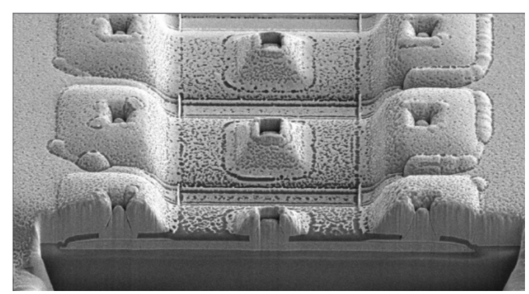
End Goal: Demonstration of integrated N/MEMS devices and phase-change material switches enabling circuit reconfiguration for modified functionality of RF circuits

Switch Topology

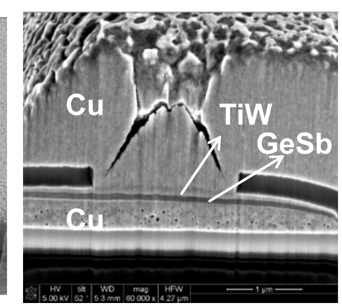


Device Performance

Probe terminal



Cross section of one via



Demonstrated:	R-on: 0.1kΩ	R-off: 8 kΩ
Extensible to:	R-on: 0.2Ω	R-off: 200 Ω

Nanoscale S&T for Integrated Micro/Nano-Electromechanical Transducers (*i*MINT)

PI: YC Lee

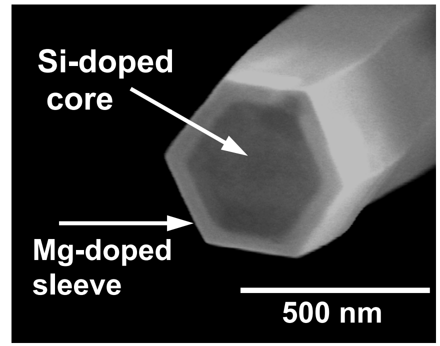
Mission: To develop S&T for repeatable, predictable, and reliable integrated N/MEMS enabled by nanostructures; to develop nanoscale building blocks for N/MEMS

- Demonstrated first *p-n* core-sleeve hetero-structure of a c-axis GaN nanowire; will lead to devices that are more efficient and reliable than a-axis GaN nanowire-based devices with intrinsic defects
- Defect-free GaN NWs enable 10X increase in Q for GaN nanowire-based resonators
- Will enable, low-power high-performance photonic and RF devices for displays, sensors, and lasers for NLOS communication

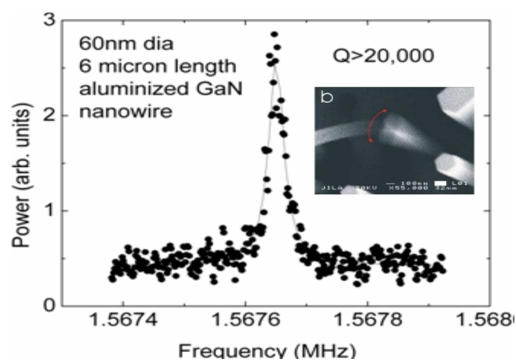
Key Accomplishment:

Developed novel experimental techniques for characterizing mechanical, optical, and RF properties of nanowire-, nanotube-, and graphene-based N/MEMS

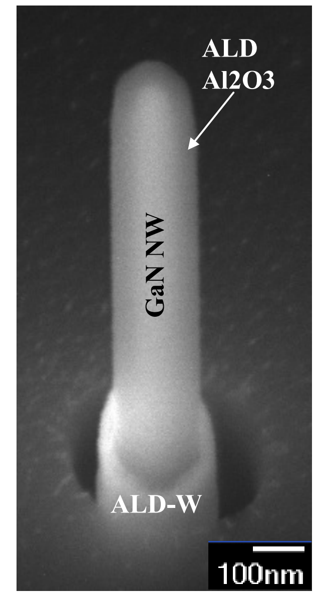
End Goal: Demonstration of a NEMS device (GaN resonator or graphene nano-switch) powered by an embedded battery in a package enabled by an ALD/MLD barrier coating: an iMINT microsystem



ALD-based W and Al_2O_3 multilayer deposited on GaN NWs for improved electrical, optical, thermal, and mechanical inter-connects



First *p-n* core-sleeve heterostructure of a c-axis GaN nanowire



Measured Q of defect-free GaN (c-axis) nanowire-based resonators; Q ~ 2800 for a-axis GaN NWs containing defects

Micro/Nano Fluidics Fundamentals Focus (MF3) Center

PI: A Lee

Mission: To develop an advanced under-standing of critical fundamental issues in microfluidics important to manufacturing and integration processes

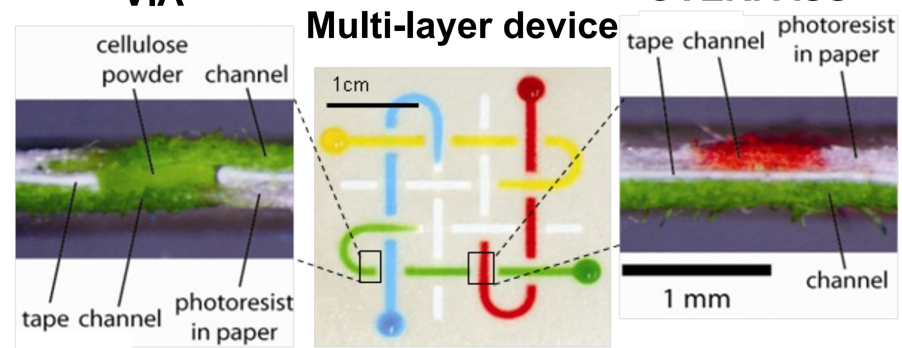
- At platform level: detection limits, material and process integration, surface science, micro-scale fluid dynamics, sort and separate constituents, reliability, and efficient transport mechanisms
- At manufacturing/integration level: material selection and material interface/surface science
- Provide small, light-weight, low-power, easy-to-use, field-deployable solider health and environmental diagnostic devices

Key Accomplishment:

Developed and demonstrated chip-scale integrated fluid processors for the rapid and high-sensitivity analysis of molecular content important to soldier health and environmental monitoring

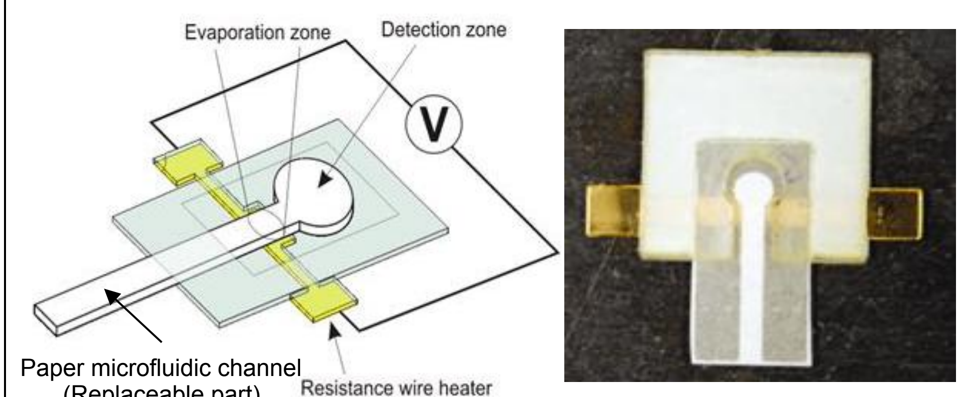
End Goal: Useful suite of microfluidics modules, established foundry process for micro/nano fluidics, and integration of multiple modules

VIA **Multi-layer device** **OVERPASS**



Complex microfluidic manifold in paper

Addition of metal traces to paper microfluidics:



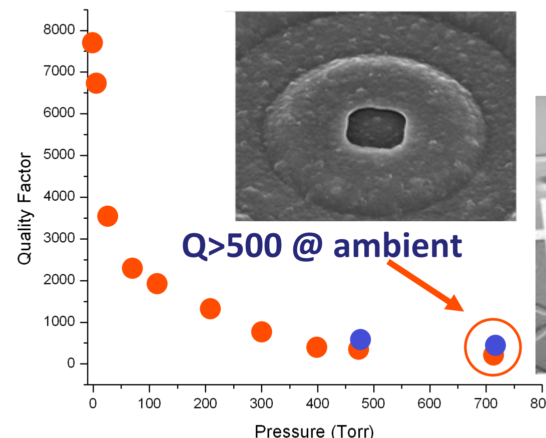
Microfluidic concentrator: Analytes are concentrated in an "evaporation zone

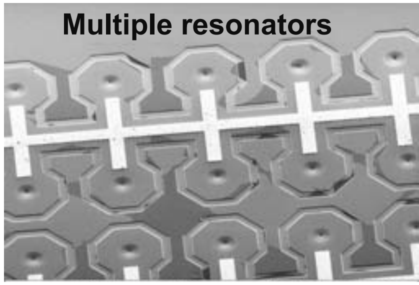
Cornell University – *HARMs*
Harnessing Active Resonant MEMS

PI: J Parpia

Mission: To develop superior high-Q MEMS resonators fabricated in CMOS technology and able to operate in fluid environments

- Resonators operating in ambient environments (air/ liquids); Q ~ 500 in air
- Resonators ready for integration with readout electronics
- CMOS integration overcomes constraints imposed by lab-specific N/EMMS fabrication requirements and associated integration challenges



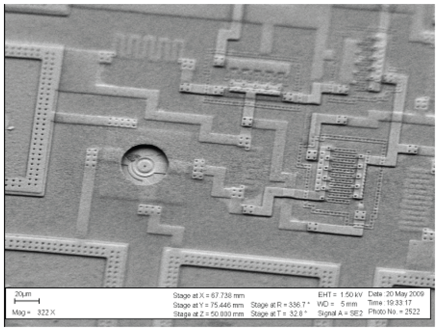


CMOS-fabricated dome resonator and measured Q vs. Pressure

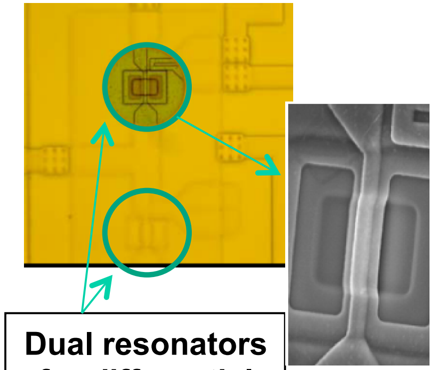
Key Accomplishment:

Demonstrated advanced physical and chemical sensing capabilities using selected MEMS and NEMS devices suitable for integration with CMOS electronics

Next-gen CMOS-MEMS



Dome resonator, resistive drive, capacitive detector

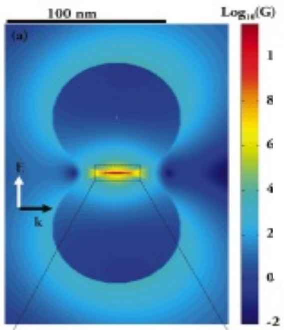


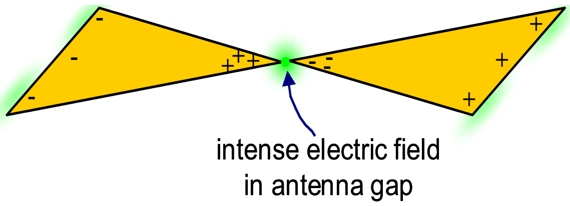
Dual resonators for differential measurements

End Goal: Fully integrated low-cost, high performance RF MEMS devices; low-mass, low-power sensors fo UAVs and miniature UGS

N/MEMS S&T Fundamentals
Successful Transitions

SERS S&T Fundamentals (PM: Polla)
Harvard University

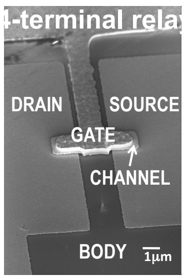


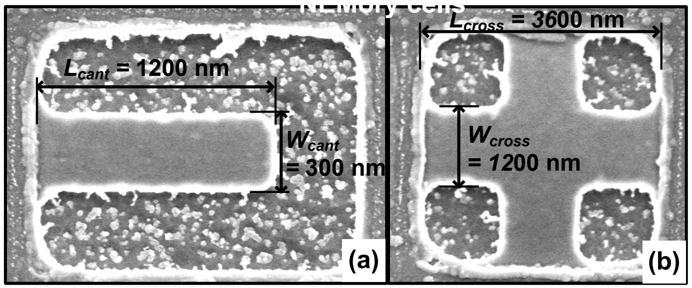


SERS Enhancement Nanoantennas

SERS nanoparticles integrated in a nanoantenna structure lead to extraordinary SERS enhancement (BAA 07-61)

NEMS (PM: Akinwande)
UC Berkeley / Stanford University

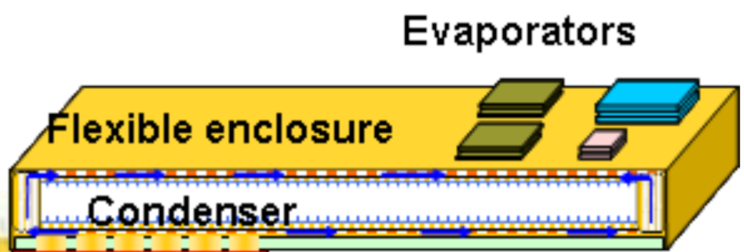


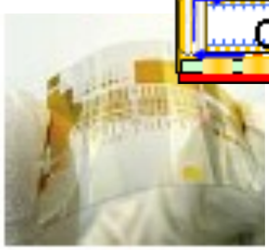


Study of micro-interconnect and interfaces between materials has led to NEMS (BAA 07-18)

Nanomechanical Switches for Digital ICs

Thermal Ground Plane (PM: Kenny)
University of Colorado

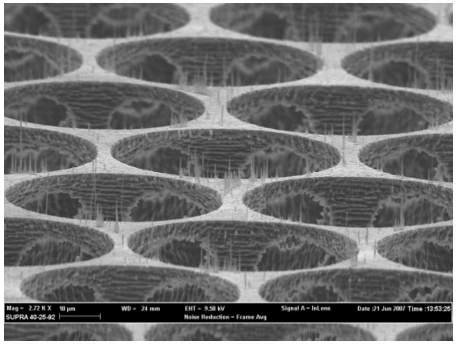


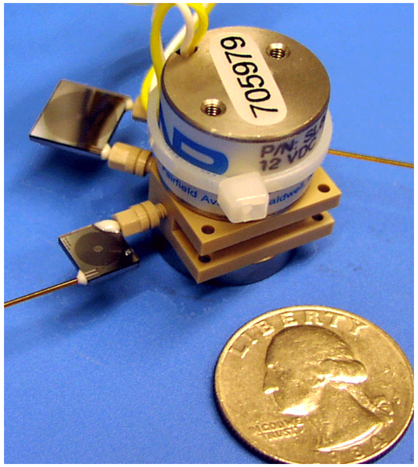


Flexible Thermal Ground Plane

i **MINT S&T enabled development of novel ALD Flexible Thermal Ground Plane (FTGP) concept (BAA 07-36)**

Micro Gas Analyzer (DTRA)





Promising technology is being transitioned to DTRA

N/MEMS S&T Fundamentals Performers

N/MEMS S&T II
2010-2012

- Carnegie Mellon University
- Harvard University
- Stanford University
- UC Berkeley
- UC Irvine
- UC San Diego
- University of Colorado

Key DARPA MTO Themes

1. N/MEMS Enables Significant New Levels of Performance
2. Scaling – “Smaller is Better”
3. N/MEMS Integration
4. Enabling Completely New Opportunities
5. Basic Research Infrastructure is Important

DARPA N/MEMS Summary

What are the opportunities for MEMS and nanotechnology?

1. Greatest opportunities for MEMS and nanotechnology (N/MEMS) are to enable new systems

2. Clear motivation for continuing development of N/MEMS technology is to enhance performance, not to drive down cost

3. Recognized needs (applications) are the most important drivers for nanotechnology development, not undirected fundamental research

4. Multi-domain scaling is the key to performance-driven nanotechnology (there remains *plenty of room at the bottom*)

5. DARPA investments in developing a N/MEMS basic science research infrastructure have produced a highly interactive community of academic, industrial, and government researchers

Thank you

Michael.Wolfson.ctr@ darpa.mil