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The History of MEMS at Sandia

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Outline

- Introduction
- Customer Pull drives Sandia's Early Microsystems
- Early learning drives technology evolution
- Capability growth expands Sandia technology into integrated microsystem solutions
- Summary

It takes time to learn the best uses for new technologies

Development of the coke furnace enabled iron cheap enough for large structures.

Image source: http://www.igreens.org.uk/canoeing_stuff.htm

The first iron bridge located on River Servern in England was built near the first coke furnace in Coalbrookdale in 1779. It used the best known wooden carpentry techniques and thus was severely over-engineered.

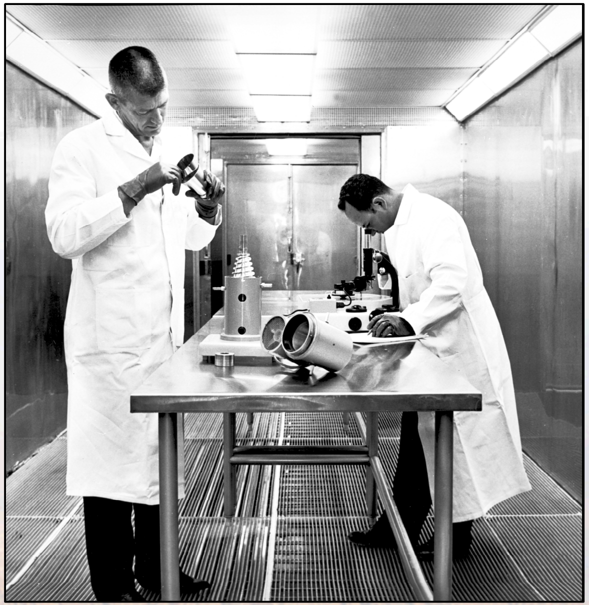
Image source: http://en.wikipedia.org/wiki/File:Coalport_br1.jpg

When an additional bridge was needed in 1818 at Coalport over the same river, it used design insights based on properties of cast iron and *required only half the cast iron as the first iron bridge!*

Sandia has long required precision mechanical components

In the 1950s, Willis Whitfield invented laminar-flow clean room technology at Sandia to enable the precision assembly of intricate and delicate mechanisms.

Those macroscopic mechanical devices of the 1950s required such extremely rigid specifications that contamination by dust particles or other contaminants rendered the mechanisms inoperable.



Micromachining appeared attractive for Sandia mission needs.

- **1964 – Harvey Nathanson produces first batch-fabricated Micro-Electro-Mechanical System ("resonating gate transistor")**
  - Device combines electrical and mechanical functions
  - Not adopted due to performance limitations; semiconductor industry focuses on transistors and integrated circuits instead
- **Early- to mid-1980s: Groups at the University of California at Berkeley and the University of Wisconsin resurrect MEMS technology**
  - Best student papers in the 1985 and 1987 International Electron Devices Meeting of the IEEE
  - University groups demonstrate integrated sensors, and electrostatic side drives motor based on movable pin joints, gears, springs, cranks, and slider structures
  - Analog Devices, Inc. and Texas Instruments begin device development (air-bag accelerometer and display device, respectively)
- **Widespread activity attracted the interest of Sandia's precision mechanical engineering community.**
  - Seminar by Prof. Mueller of University of California-Berkeley.

In the 1980s, Sandia was not ready for micromachining

Despite interest from Sandia's mechanical engineers in silicon micromachining, Sandia's semiconductor fab could not support their interest for two major reasons:

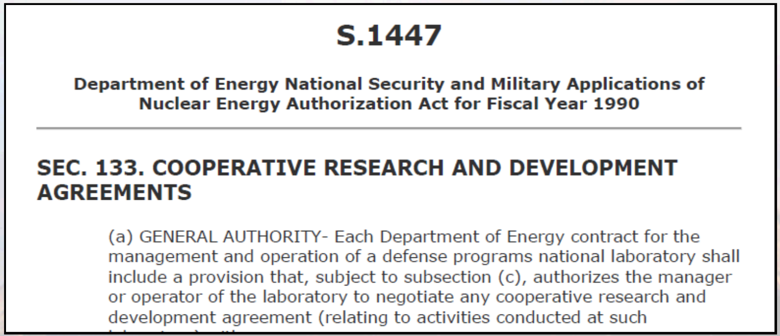
1. A ballroom-style clean room could not support alternative process chemistries that would contaminate CMOS processing.

2. The entire capacity of Sandia's fab was committed to product deliveries for Sandia systems.

Three events changed Sandia’s willingness to pursue silicon micromachining

1. The Microelectronics Development Laboratory began operations in 1989
   - Enabled new process chemistries by partitioning of cleanroom chases.

2. End of the Cold War
   - Freed Fab Capacity from Production Deliveries for R&D
   - (image from http://guides.library.msstate.edu/Berlin_Wall)



S.1447

Department of Energy National Security and Military Applications of Nuclear Energy Authorization Act for Fiscal Year 1990

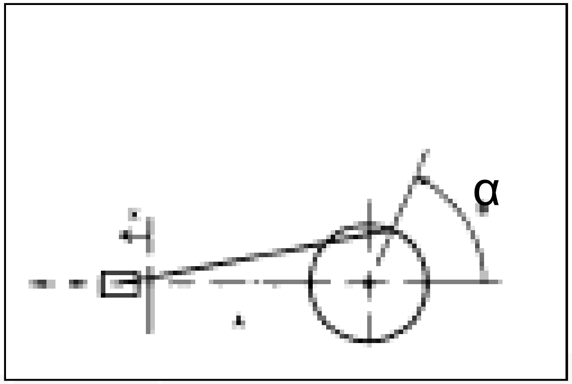
SEC. 133. COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENTS

(a) GENERAL AUTHORITY- Each Department of Energy contract for the management and operation of a defense programs national laboratory shall include a provision that, subject to subsection (c), authorizes the manager or operator of the laboratory to negotiate any cooperative research and development agreement (relating to activities conducted at such

3. Passage of the National Competitiveness Technology Transfer Act of 1989 (P.L. 101-189)
   - Allowed DOE FFRDCs to enter into Cooperative R&D Agreements

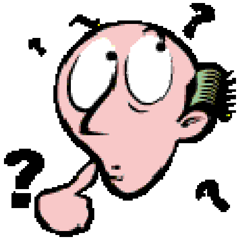
Sandia programs required micromachines that could perform useful work

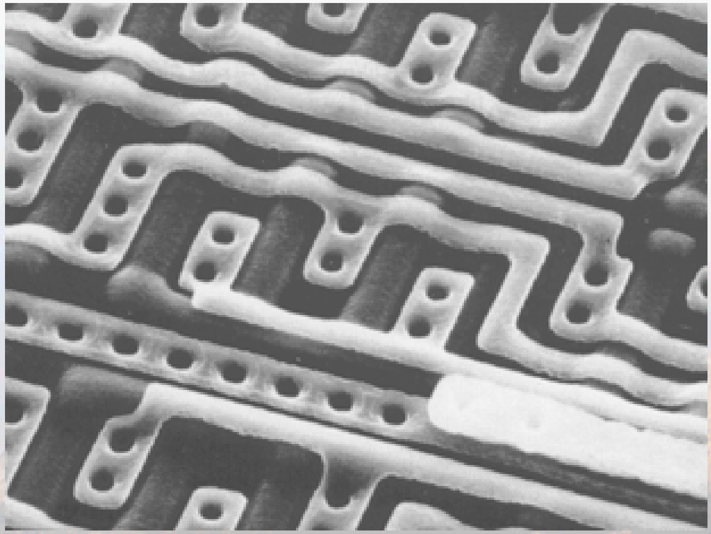
To link motors and gears into functioning actuators, Sandia engineers had to overcome two obstacles:



1. Inability to anticipate which effects would dominate at the microscale.

First microengine had only one drive motor. Oops! Gear stuck when α=0!





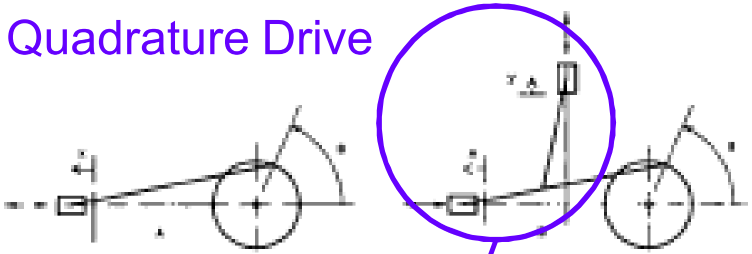
2. Conformal depositions resulted in increasingly non-planar surfaces with each additional level.

Functioning actuators required linkages between electrostatic motors and gears which had never been demonstrated.

First attempts at quick and dirty actuation were learning experiences.

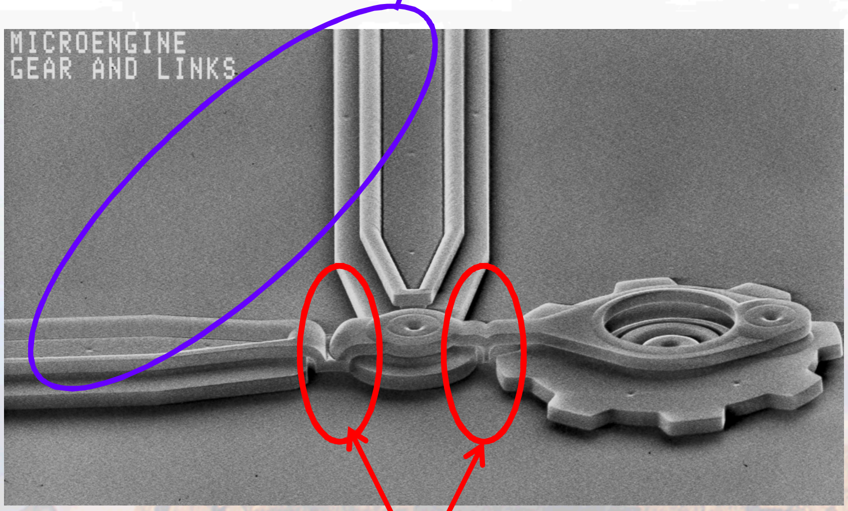
Getting support from internal customers required demonstrating proof of concept. A brute-force demonstration provided two key lessons.

Quadrature Drive



1. Stiction (sticky friction) dominated inertia in operations of microgears.

Microgears did not have enough inertia to get past dead spot when linkage aligned with radius—so use two microengines at 90°

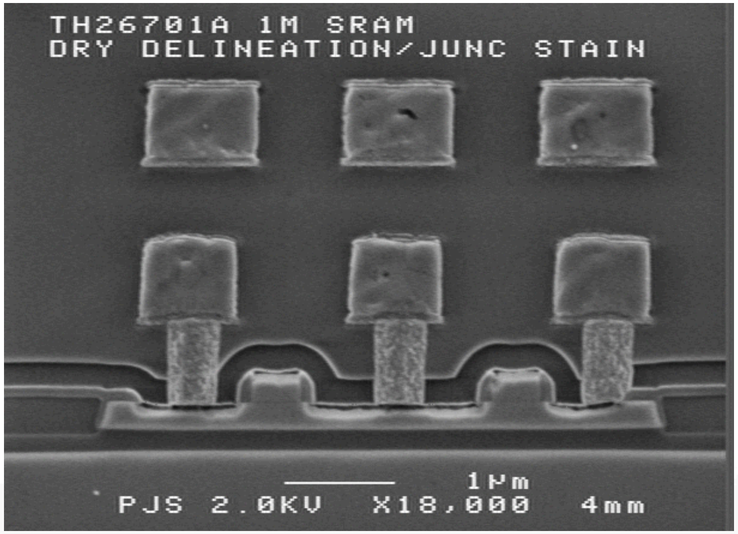


Step coverage interference

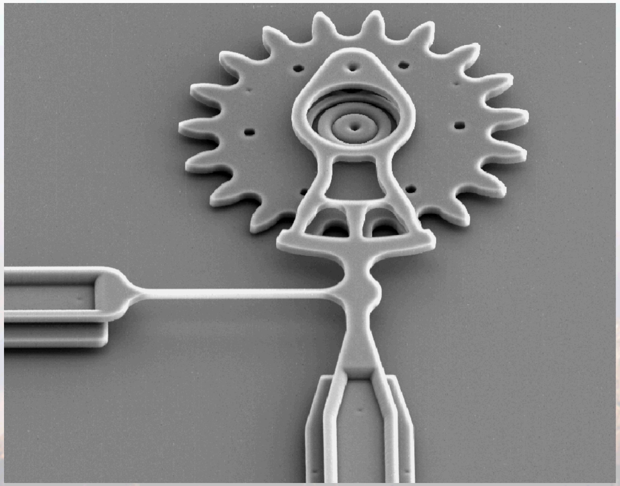
2. Non planar surfaces prevented optimal mechanical (involute) gears so first gears had square teeth.

Step coverage issues physical interference between gears and linkages—so live with suboptimal teeth for first demonstration.

The next step was to remove step-coverage interferences by Chemical-Mechanical Polishing



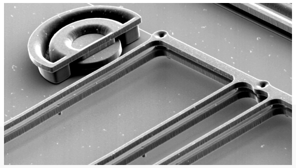
In December, 1992, a CRADA with IBM provided Sandia's Microelectronics Development Laboratory with millions of dollars worth of semiconductor fabrication equipment. Among the donation was equipment for chemical mechanical polishing (CMP). Sandia developed its own CMP process for integrated circuits.

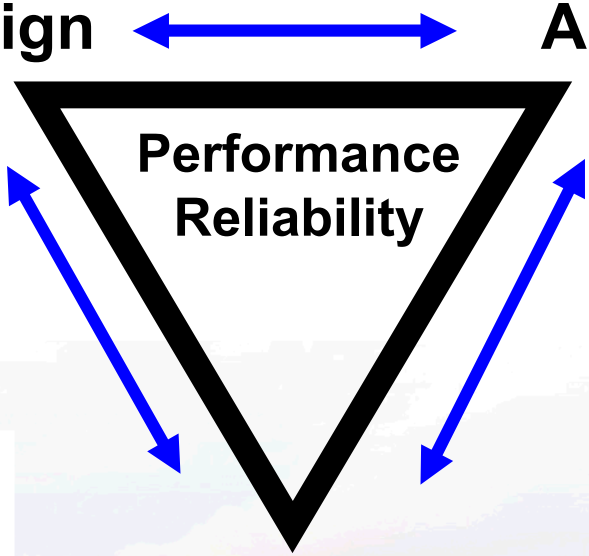


Sandia then applied chemical mechanical polishing to MEMS fabrication (U.S. Patents 5,804,084, and 5,919,548). Note the true involute gears and the planar gear linkages.

Reliability was the next concern for MEMS.

High degree of complexity in the performance/reliability tradespace as a result of materials/manufacturing, design, application/operation choices

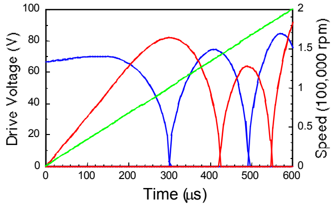


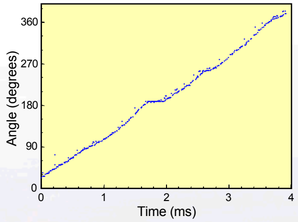


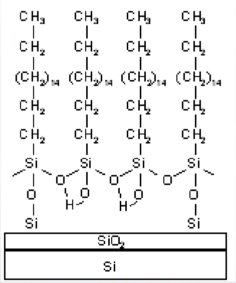
Design

Application/Operation

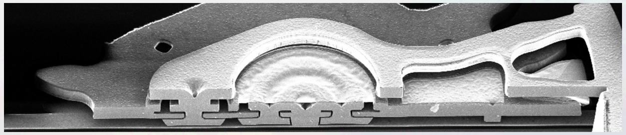
Performance Reliability





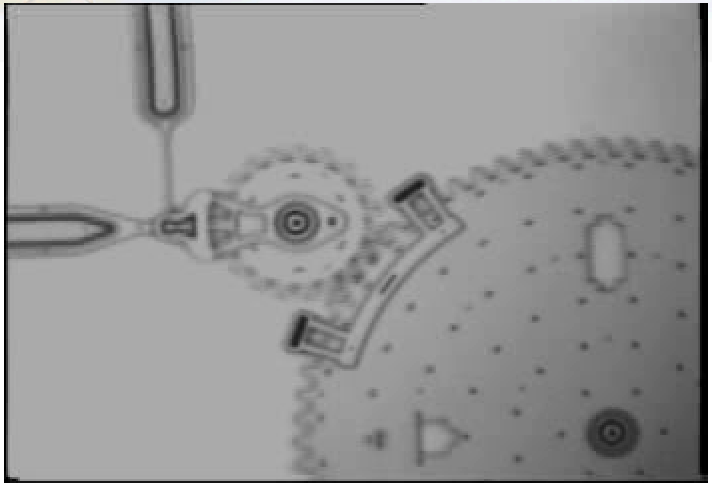


Materials / Manufacturing



- *MEMS failure mechanisms are more varied than for IC technologies*
- *Fundamental understanding of failure mechanisms is needed to develop & qualify robust MEMS devices*

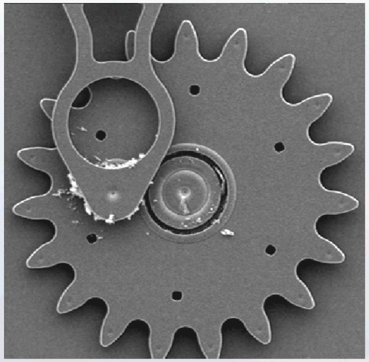
Wear and debris proved the next obstacle.



Operation to failure movie

Generating useful forces requires trading speed for torque through gear chains. At the microscale, the best involute gears on hubs suffer from stiction (sticky friction) which can cause wear and generate debris. Ultimately, a gear that started running smoothly wobbles and after enough cycles it fails.

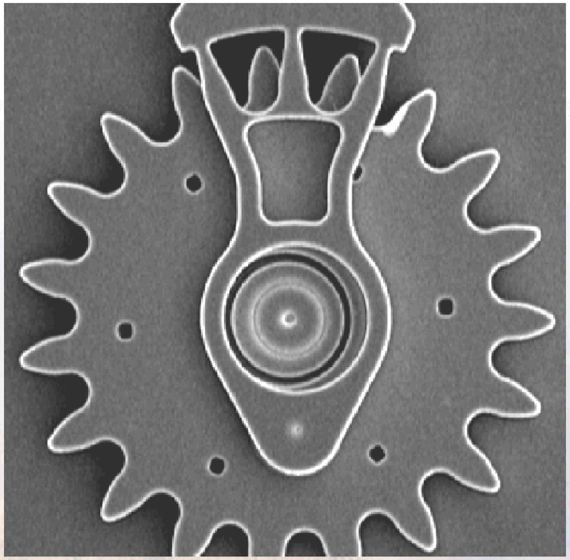
Polysilicon MEMS



1 million cycles

One fix is to change the materials and manufacturing process. By applying selective tungsten to key surfaces (white outlines) wear decreases and operating life increases.

W-coated MEMS



1 billion cycles

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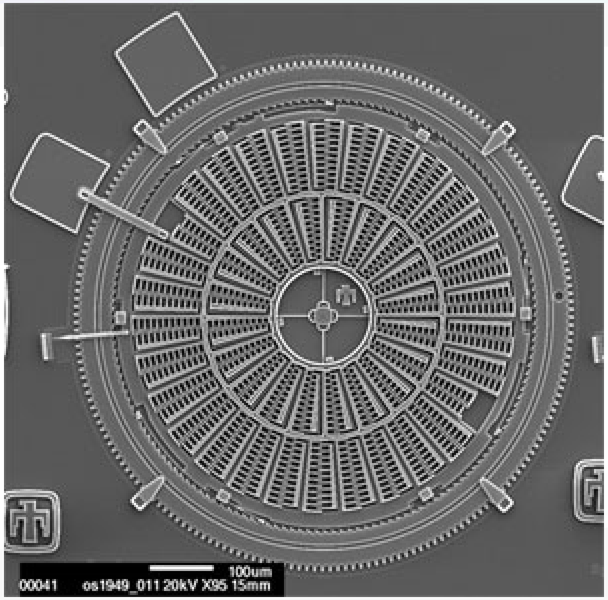
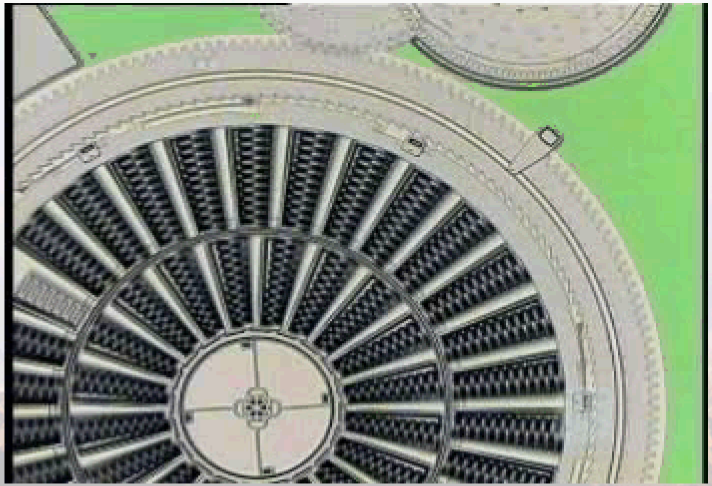
The next optimization was to minimize contacting surfaces.



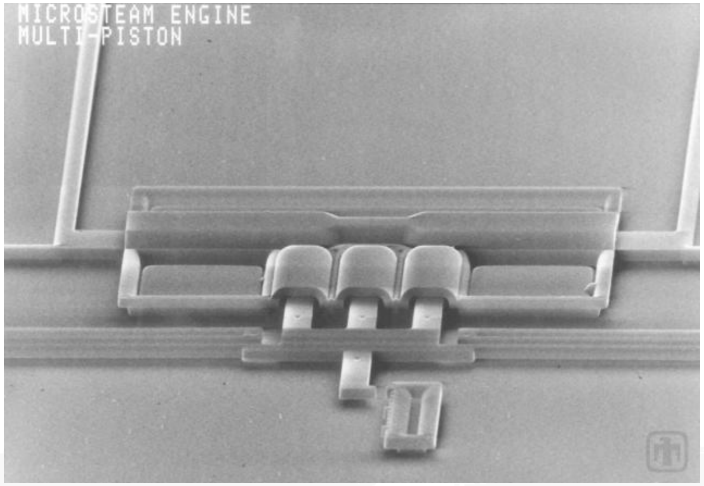
Using a ratchet and pawl mechanism, Sandia engineers implemented a tortional ratcheting actuator that greatly improved operating lifetimes. This mechanism is still used to power applications that do not require great actuation force.



Tortional ratcheting actuator movie.

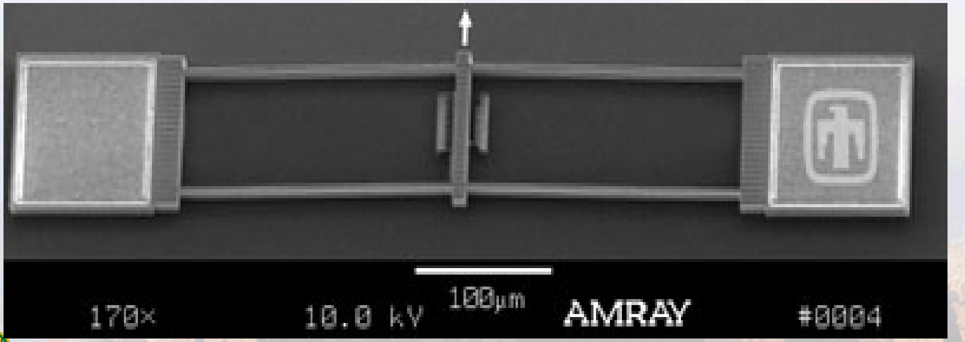
Some applications require greater force without the need for torque converters

First Attempt: Miniature steam engine.



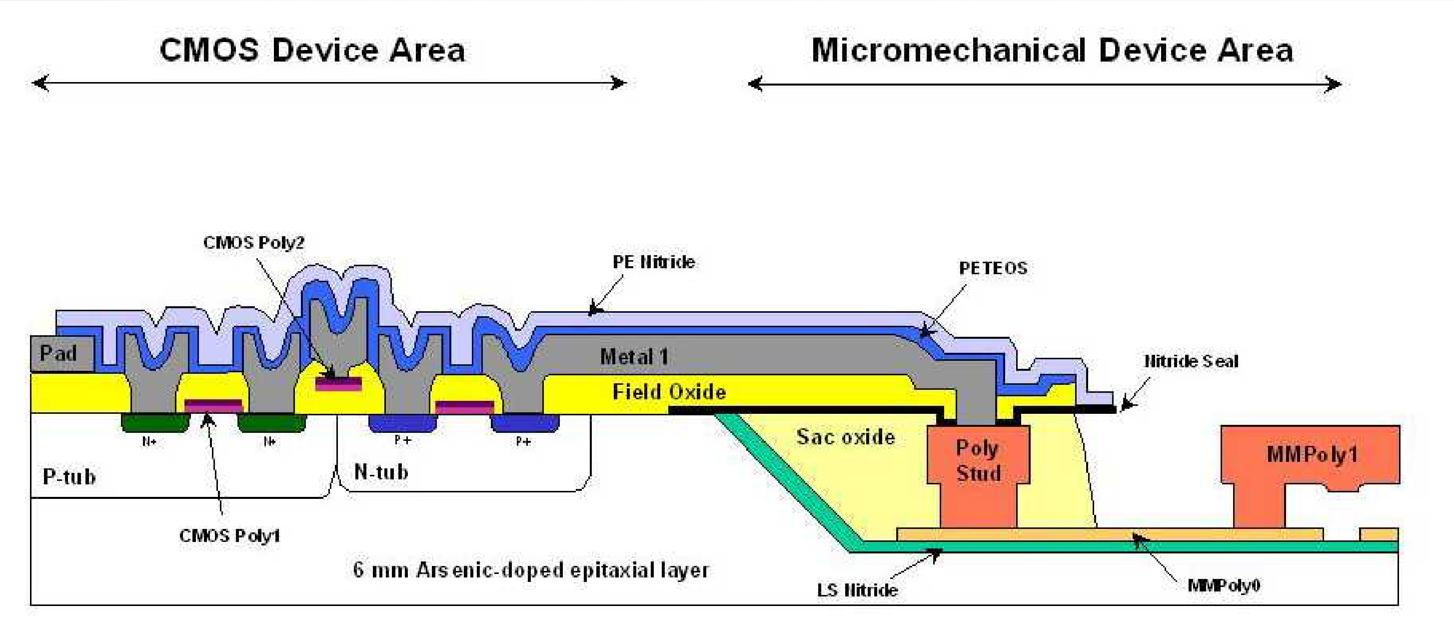
Current through a resistor located between two bond pads heats water in a reservoir to drive three pistons and linkages. Difficulties managing the working fluid made the approach impractical.

Improved Drive: Thermal Actuator



Joule heating causes the suspended polysilicon to expand. Removing current returns the actuator to the initial position due to its low thermal mass.

Technology evolves beyond components to integration. The first attempt was I-MEMS



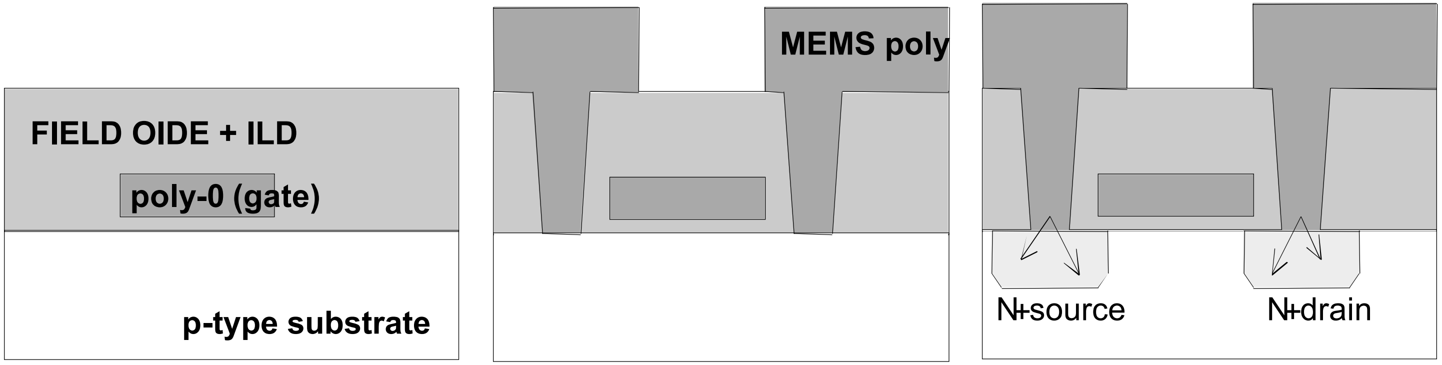
Brute force integration of CMOS circuits with MEMS. Limitations were:

1. Need for thick (6mm), non-standard epitaxial silicon
2. MEMS fabricated in a deep trench beyond depth of focus of lithography tools Manually de-focused litho tool to pattern MEMS in the trench making tool unusable for CMOS processing until refocused on wafer surface.
3. 3-μm steps to interconnect CMOS with MEMS in the trench.
4. Six-month turn time an low yield for a very complicated process.

Bottom line: NOT practical for production

A better approach is to simplify on-chip electronics and add functionality

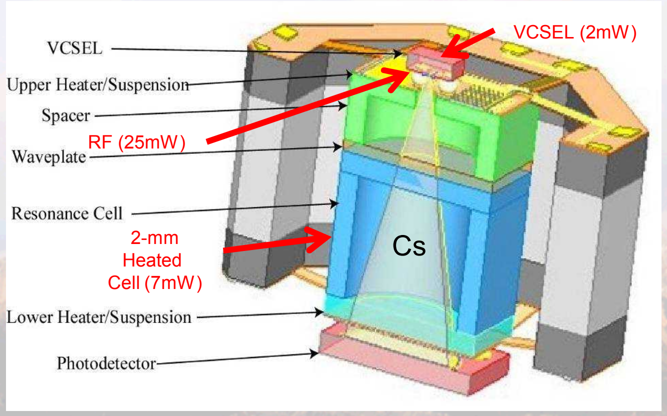
1. Use simple electronics to manager off-chip drive

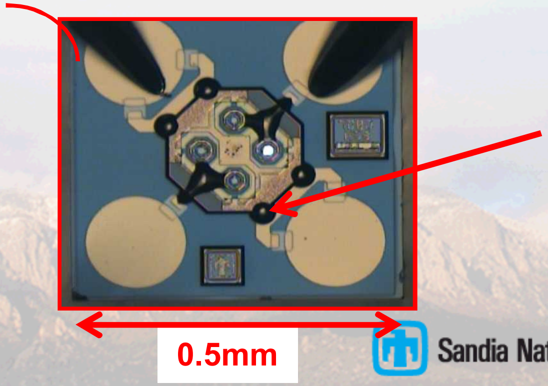


Simple fabrication using in-diffusion from doped polycrystalline silicon.

2. Add *functionality* rather than processing power by heterogeneous integration. (Multiple functions integrated into a single package.)

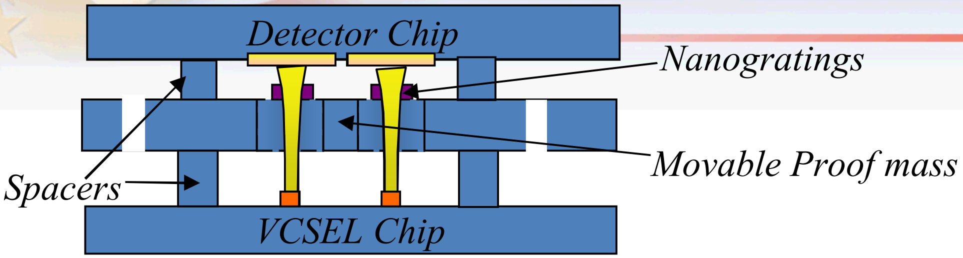
Example: Symmetricom / Draper/Sandia partnership chip-scale atomic clock



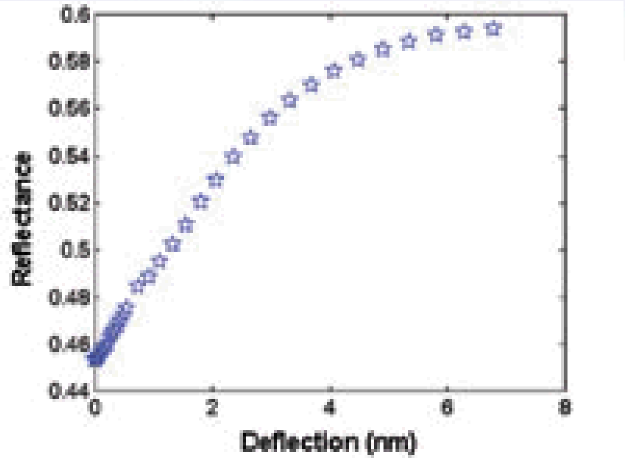


Sandia VCSEL array.

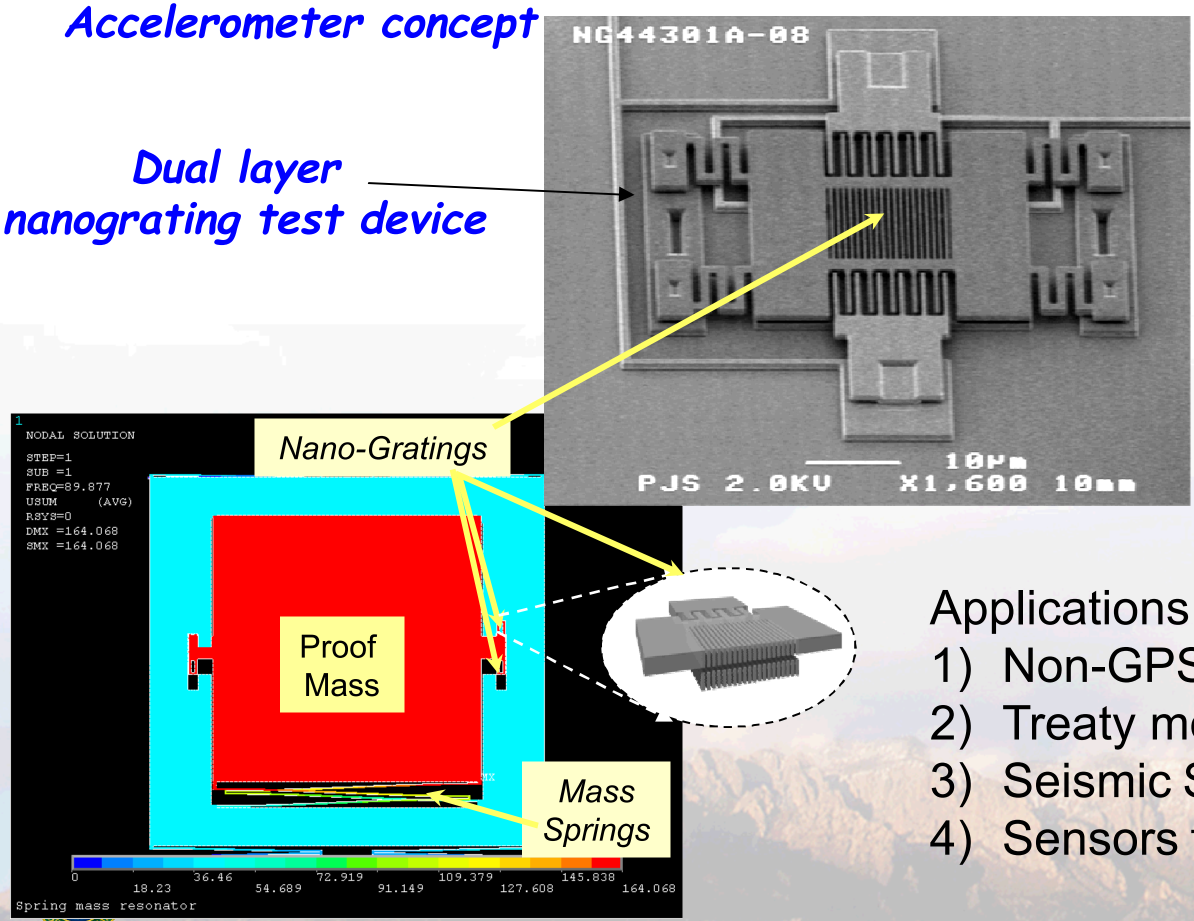
Integrating MEMS with optoelectronics in a single package: Nano-G Accelerometers Using Nanophotonic Motion Detection System



Accelerometer concept



- Displacement sensitivity **12 fm/√Hz**
- Record Mass Resonant Frequency for a MEMS device ~ **40 Hz**
- Record Thermal noise floor **~10nG/√Hz**



NanoG (10^{-8}m/s^2) Accelerometer

Applications include:

1) Non-GPS Navigation,
2) Treaty monitoring,
3) Seismic Sensing,
4) Sensors for Oil wells

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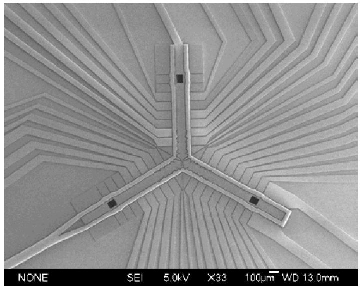
We learned from each of our false starts—a selected few examples follow

False Start	Issue	Remediation
Single electrostatic drive	Stiction and lack of inertia	Quadrature drive, planarization through chemical-mechanical polishing
Finite lifetimes from rubbing surfaces	Particle generation from wear	Minimize contacting surfaces, migrate to tortional ratcheting actuator;
Steam engine to generate more power	Source of working fluid	Evolve to thermal actuators based on heating polysilicon
Integrating CMOS circuitry with MEMS actuators	Process complexity, depth of focus issues with MEMS in trenches	Develop SFET, change strategy to integrate *functions* instead of more processing power

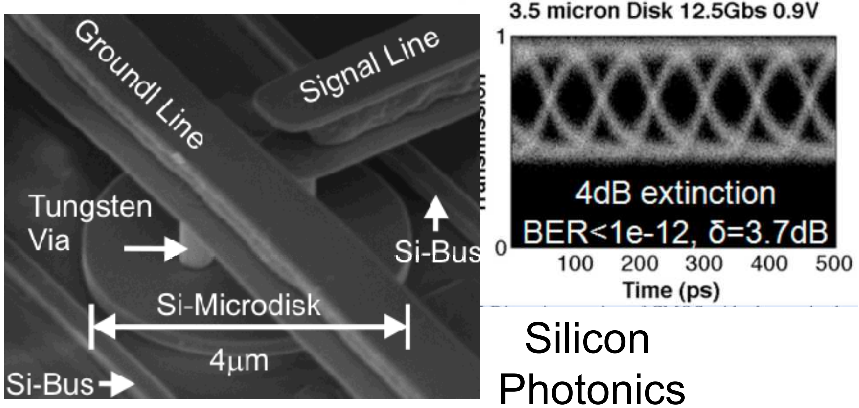
Significant advantages accrue to technology pioneers.

The applications expanded as the capability grew.

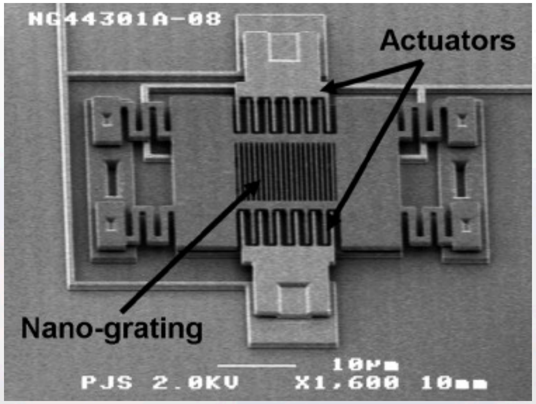
From these humble beginnings and false starts micromachines at Sandia now encompass such components and microsystems as:



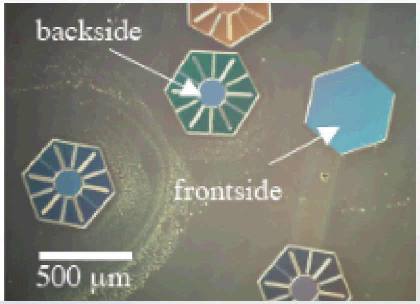
Ion Traps for Quantum Information Processing.



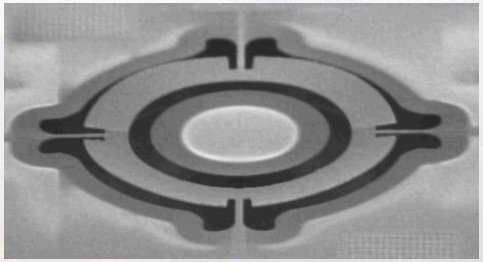
Silicon Photonics



Nano-g accelerometer with micromachined gratings.



Solar Glitter for low-cost power

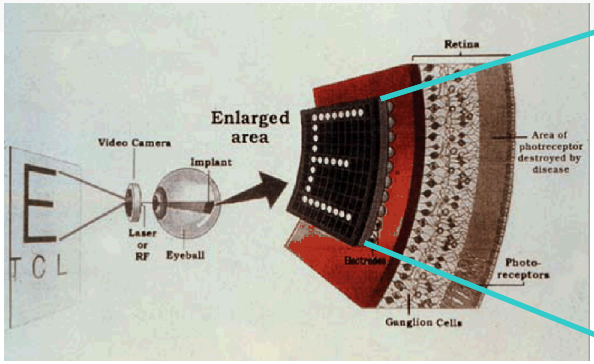


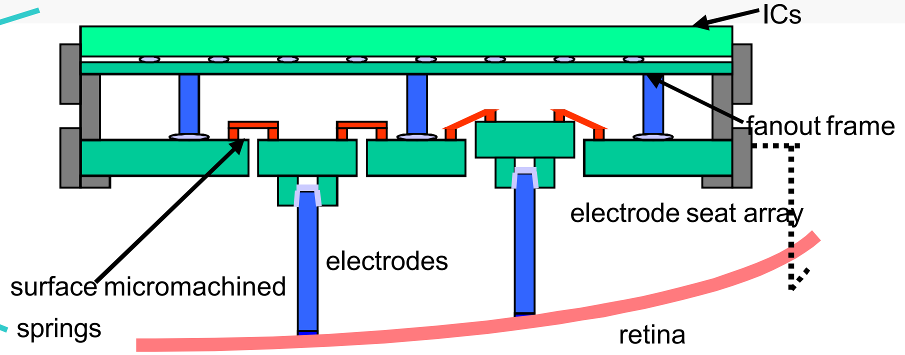
AlN resonators for RF MEMS

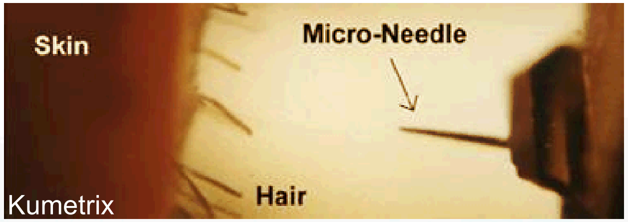
BioMEMS/Microfluidics illustrate microsystem integration

Prosthesis:
- neural probes,
- cochlear implant
- retinal implant

DOE Retinal Implant Project
(USC, ORNL, LLNL, LANL, SNL, ANL, NCSU)

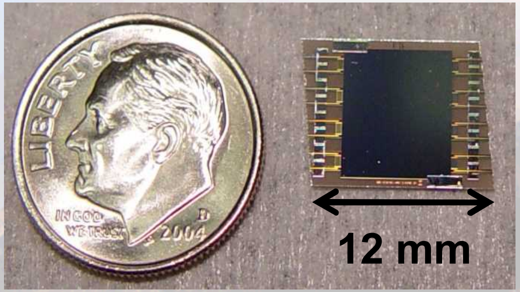




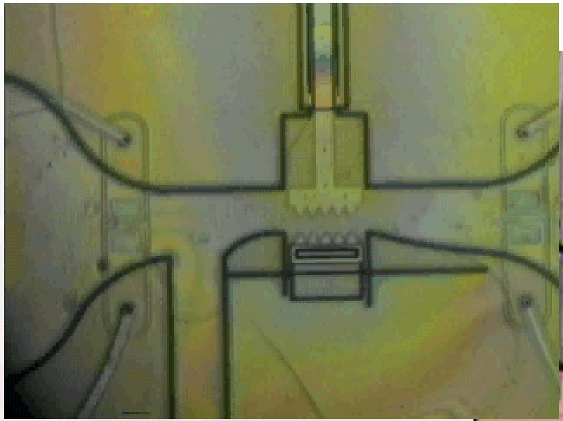


Therapeutic: Drug delivery, in-vivo monitoring

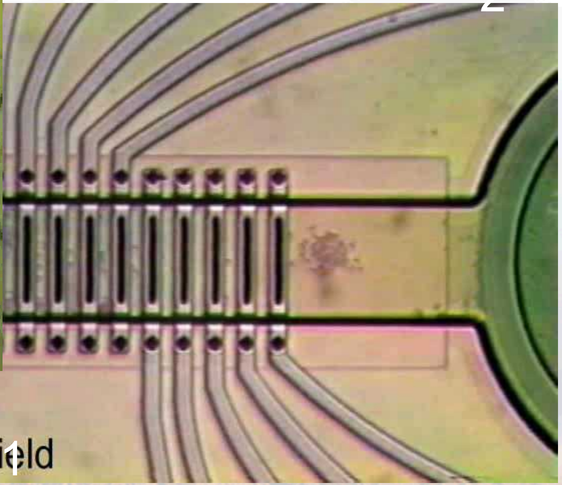
Pathogen Sensing: Shear-Horizontal Wave (SH) Surface Acoustic Wave sensor element



Cell Lysing



Cell Separation



Research Tools
Sensors

Summary

- **External events enabled Sandia to investigate microsystems when the technology was still in its infancy**
  - Occupancy of Microelectronics Development Laboratory
  - End of the Cold War
  - National Competitiveness Technology Transfer Act of 1989
- **Sandia developed its own micro-system capability based on mission needs and patient funding.**
  - People- subject matter experts augmented by targeted hires
  - Equipment – especially Chemical Mechanical Polishing
  - Facilities – flexible clean room that allowed non-standard process chemistries.
- **Familiarity expanded uses and drove technology evolution.**
- ***Our most challenging obstacles often arise not from an inability to answer questions but rather from knowing which questions to ask.***
  - There is no substitute for direct, hands-on experience and customer pull!