BEC008-MEMS AND NEMS

UNIT I OVERVIEW AND INTRODUCTION
New trends in Engineering and Science: Micro and Nanoscale systems Introduction to Design of MEMS and NEMS, Overview of Nano and Microelectromechanical Systems,

- Applications of Micro and Nanoelectromechanical systems, Microelectromechanical systems, devices and structures Definitions,
- Materials for MEMS: Silicon, silicon compounds, polymers, metals

UNIT II MEMS FABRICATION TECHNOLOGIES

- Microsystem fabrication processes: Photolithography, Ion Implantation, Diffusion, Oxidation.Thin film depositions:
- LPCVD, Sputtering, Evaporation, Electroplating; Etching techniques: Dry and wet etching, electrochemical etching; Micromachining: Bulk Micromachining, Surface Micromachining
- High Aspect-Ratio (LIGA and LIGA-like) Technology; Packaging: Microsystems packaging, Essential packaging technologies, Selection of packaging materials

III MICRO SENSORS

- MEMS Sensors: Design of Acoustic wave sensors,
- resonant sensor, Vibratory gyroscope,
- Capacitive and Piezo Resistive Pressure sensors-
- Engineering mechanics behind these Microsensors.
- Case study: Piezo-resistive pressure sensor

UNIT IV MICRO ACTUATORS

- Design of Actuators: Actuation using thermal forces
- Actuation using shape memory Alloys,
- Actuation using piezoelectric crystals,
- Actuation using Electrostatic forces (Parallel plate, Torsion bar, Comb drive actuators), Micromechanical Motors and pumps.
- Case study: Comb drive actuators

UNIT V NANOSYSTEMS AND QUANTUM MECHANICS

- Atomic Structures and Quantum Mechanics,
- Molecular and Nanostructure Dynamics: Shrodinger Equation and Wavefunction
- Theory, Density Functional Theory, Nanostructures and Molecular Dynamics,
- Electromagnetic Fields and their quantization, Molecular Wires and Molecular Circuits.

Introduction to MEMS & NEMS Design

What are the Goals of this Course?

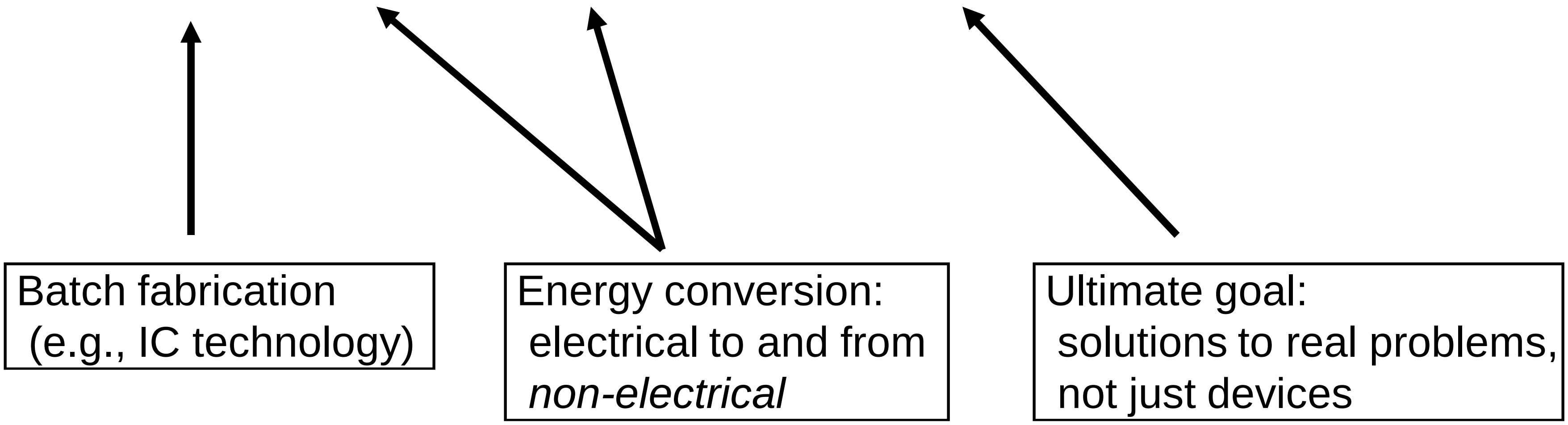
- *Accessible* to a broad audience →
  minimal prerequisites
- *Design* emphasis →
  exposure to the techniques useful
  in analytical design of structures,
  transducers, and process flows
- *Perspective* on MEMS research and
  commercialization circa 2003

Lecture Outline

- Reading Senturia: Chapter 1
- Today’s Lecture
  - ❑MEMS defined
  - ❑Historical tour of MEMS
  - ❑MEMS and nanotechnology

MEMS Defined

- Micro ElectroMechanical Systems



Batch fabrication
(e.g., IC technology)

Energy conversion:
electrical to and from
non-electrical

Ultimate goal:
solutions to real problems,
not just devices

English problems: plural or singular?

Common oxymoron: “MEMS device”

Why is batch fabrication a critical part of the definition?

Dimensional Ranges

- 1 μm < *L* < 300 μm lateral dimensions

  Surface micromachined structures … "classic MEMS"

- 300 μm < *L* < 3 mm

  Bulk silicon/wafer bonded structures … still call them MEMS and cover them in this course

- 10 nm < *L* < 1 μm

  Nano electromechanical systems … NEMS

  (overlap with MEMS … some coverage in this course)

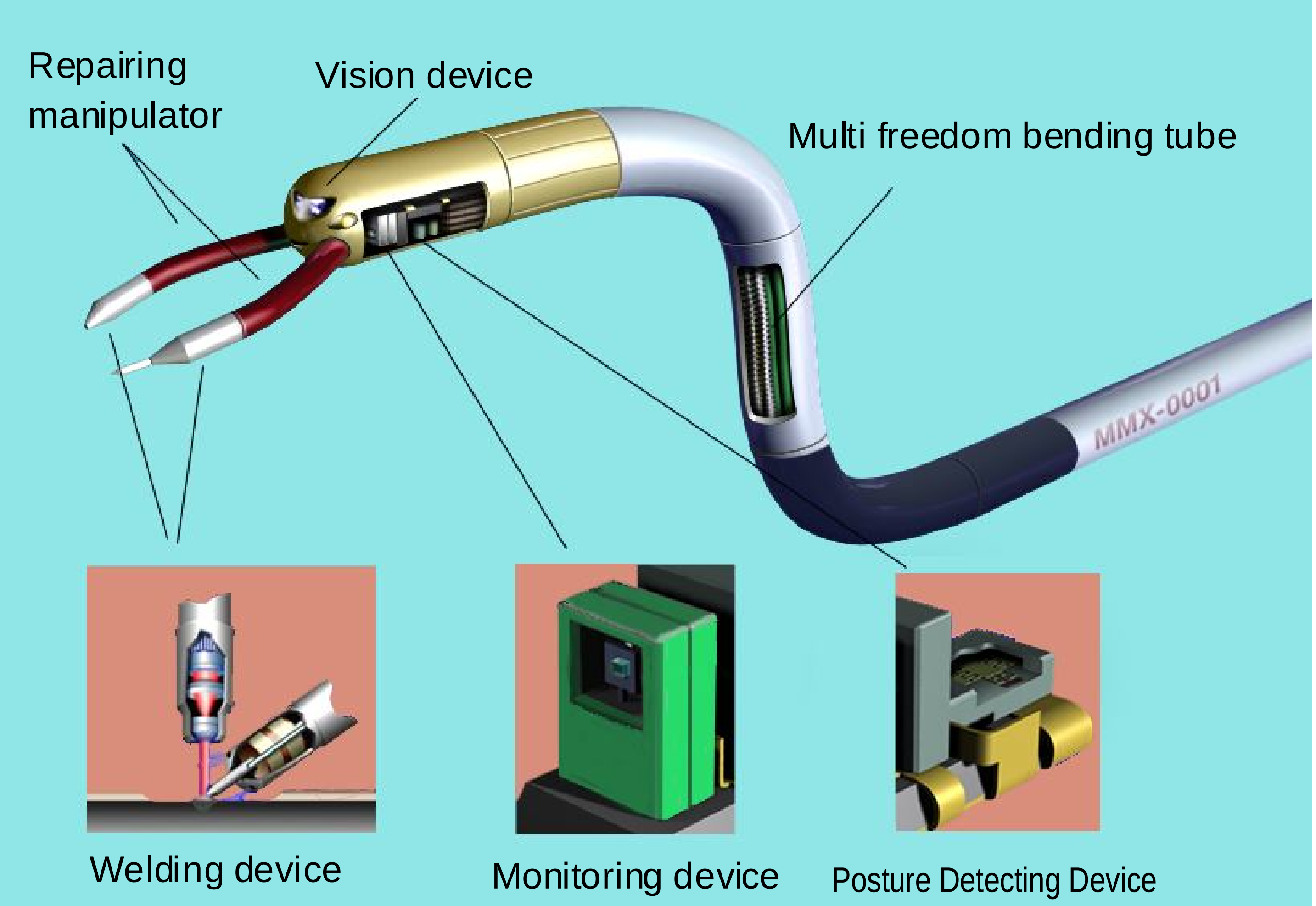
What aren’t MEMS

It runs!

Cost?

- The Denso micro-car: circa 1991 http://www.globaldenso.com/ABOUT/history/ep_91.html
- Fabrication process: micro electro-discharge machining

Experimental Catheter-type Micromachine for Repair in Narrow Complex Areas



Japanese Micromachine Project 1991-2000

Batch Fabrication Technology

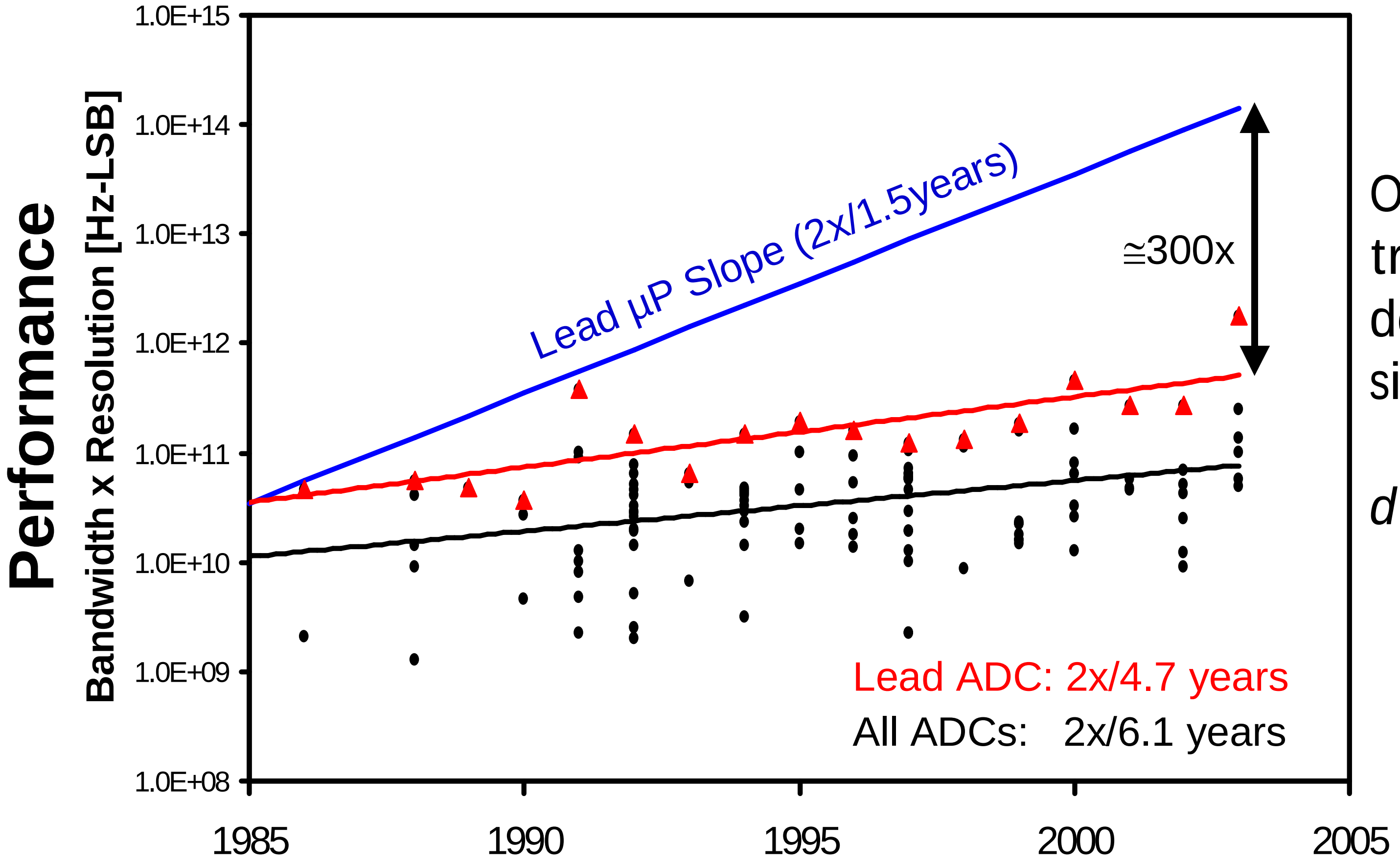
- **Planar integrated circuit technology 1958 -**
  1. Thin-film deposition and etching
  2. Modification of the top few μm of the substrate
  3. Lateral dimensions defined by photolithography, a process derived from offset printing

- Result: CMOS integrated circuits became the ultimate "enabling technology" by circa 1980

- Moore's Law

  Density (and performance, broadly defined) of digital integrated circuits increases by a factor of two every year.

Moore’s Law

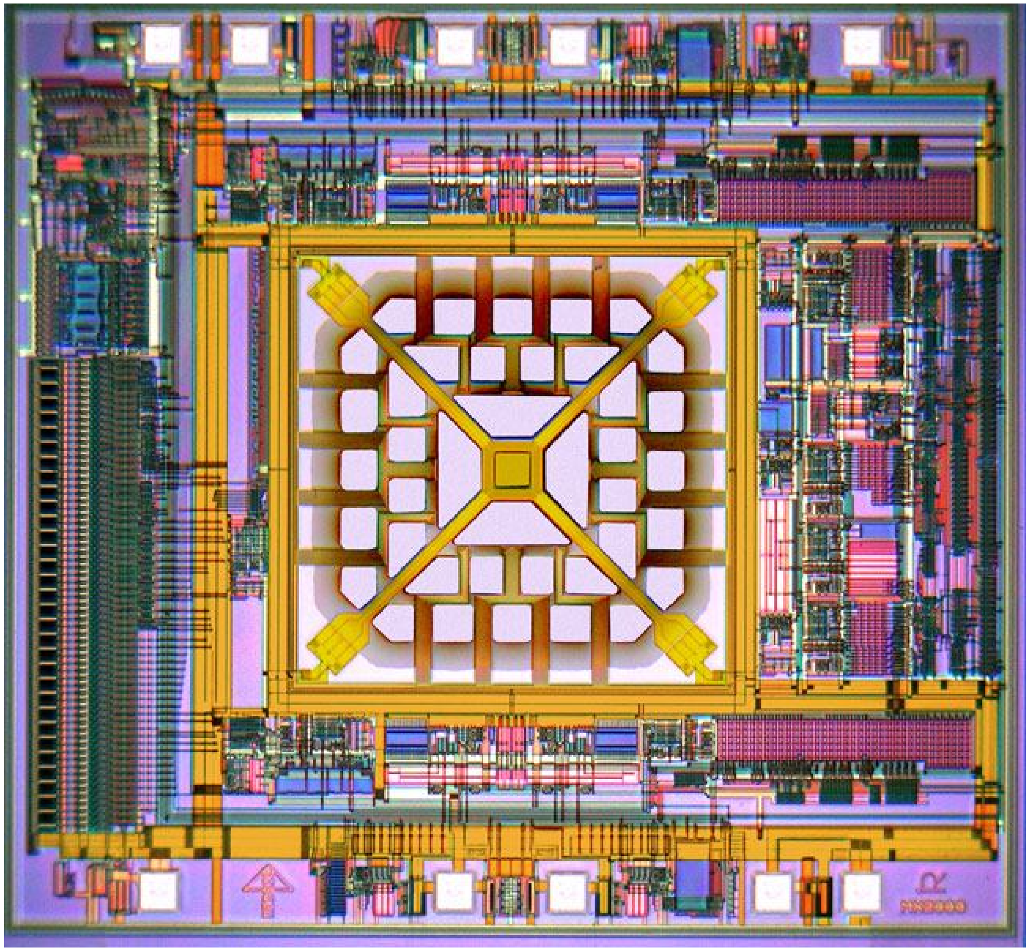


Original form:
transistor density
doubles every year
since 1962

$d = (Y - 1962)^2$

Gordon E. Moore, Cramming more components onto integrated circuits,” *Electronics*, April 19, 1965. Update: G. E. Moore, “No exponential is forever … but we can delay ‘forever,’” *IEEE Int. Solid-State Circuits Conf*., Feb. 10, 2003.

A Microfabricated Inertial Sensor



MEMSIC
(Andover, Mass.)

Two-axis thermal-bubble accelerometer

Technology: standard CMOS electronics with post processing to form thermally isolated sensor structures

- *Note*: I'm a technical advisor to MEMSIC
  a spinoff from Analog Devices.

Other Batch Fabrication Processes

- Historically, there aren’t that many examples outside of chemical processes

- However, that’s changing:

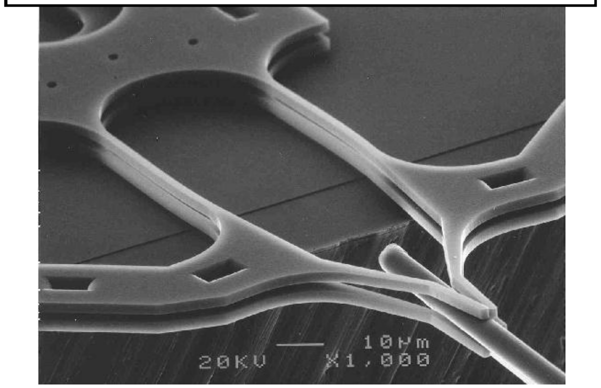
  Soft (rubber-stamp) lithography

  Parallel assembly processes →

    enable low-cost fabrication of MEMS from micro/ nano components made using other batch processes … “heterogeneous integration”

Microassembly Processes

Parallel Pick-and-Place

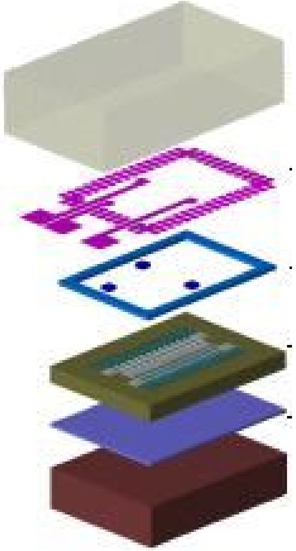


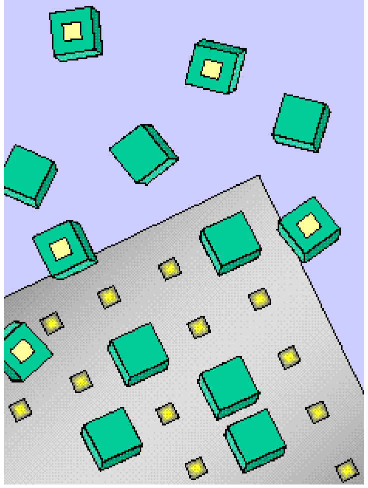
Parallel assembly processes promise inexpensive, high-volume heterogeneous integration of MEMS, CMOS, and photonics

www.memspi.com, Chris Keller, Ph.D. MSE 1998

Fluidic Self-assembly

Wafer-Level
Batch
Assembly





Many challenges:
> interconnect
> glue

www.microassembly.com
Michael Cohn, Ph.D. EECS, 1997

Uthara Srinivasan, Ph.D., Chem.Eng. 2001

A Brief History of MEMS:
1. Feynmann's Vision

- Richard Feynmann, Caltech (Nobel Prize, Physics, 1965)
  American Physical Society Meeting, December 29, 1959:

  "What I want to talk about is the problem of manipulating and controlling things on a small scale. …. In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction."

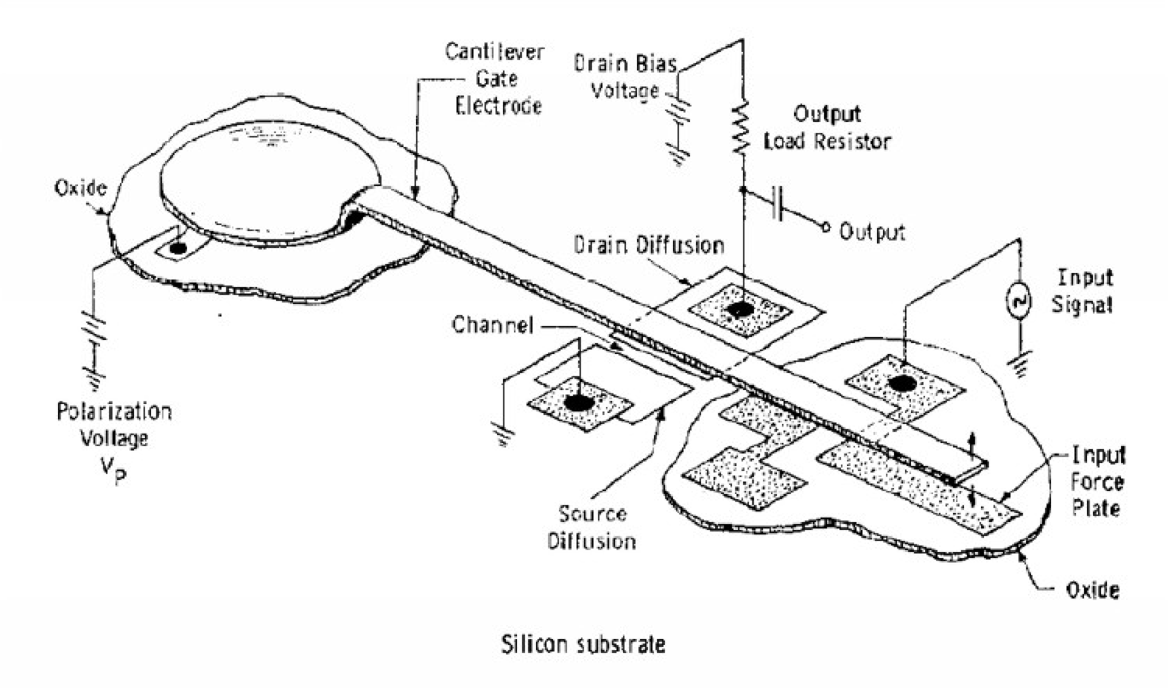
  "… And I want to offer another prize -- … $1,000 to the first guy who makes an operating electric motor---a rotating electric motor which can be controlled from the outside and, not counting the lead-in wires, is only 1/64 inch cube."

  … he had to pay the electric motor prize only a year later

  - http://www.zyvex.com/nanotech/feynman.html

2. Planar IC Technology

- 1958 Robert Noyce – Fairchild and Jack Kilby (Nobel Prize, Physics, 2000) - Texas Instruments invent the integrated circuit
- By the early 1960s, it was generally recognized that this was the way to make electronics small … and cheaper



Harvey Nathanson
and William Newell,
surface-micromachined
resonant gate transistor,
Westinghouse, 1965

Did Harvey hear about
Richard Feynman’s talk in
1959? I don’t think so …

Why Didn’t MEMS Take Off in 1965?

- Resonant gate transistor was a poor on-chip frequency reference → metals have a high temperature sensitivity and don’t have a sharp resonance (low-Q) … specific application didn’t “fly”
- In 1968, Robert Newcomb (Stanford, now Maryland) proposed and attempted to fabricate a surface micromachined electromagnetic motor after seeing the Westinghouse work
  - Energy density scaling for this type of motor indicated performance degradation as dimensions were reduced …
  - Materials incompatibility with Stanford’s Microelectronics Lab research focus on electronic devices became a major issue

Another Historical Current:
Silicon Substrate (Bulk) Micromachining

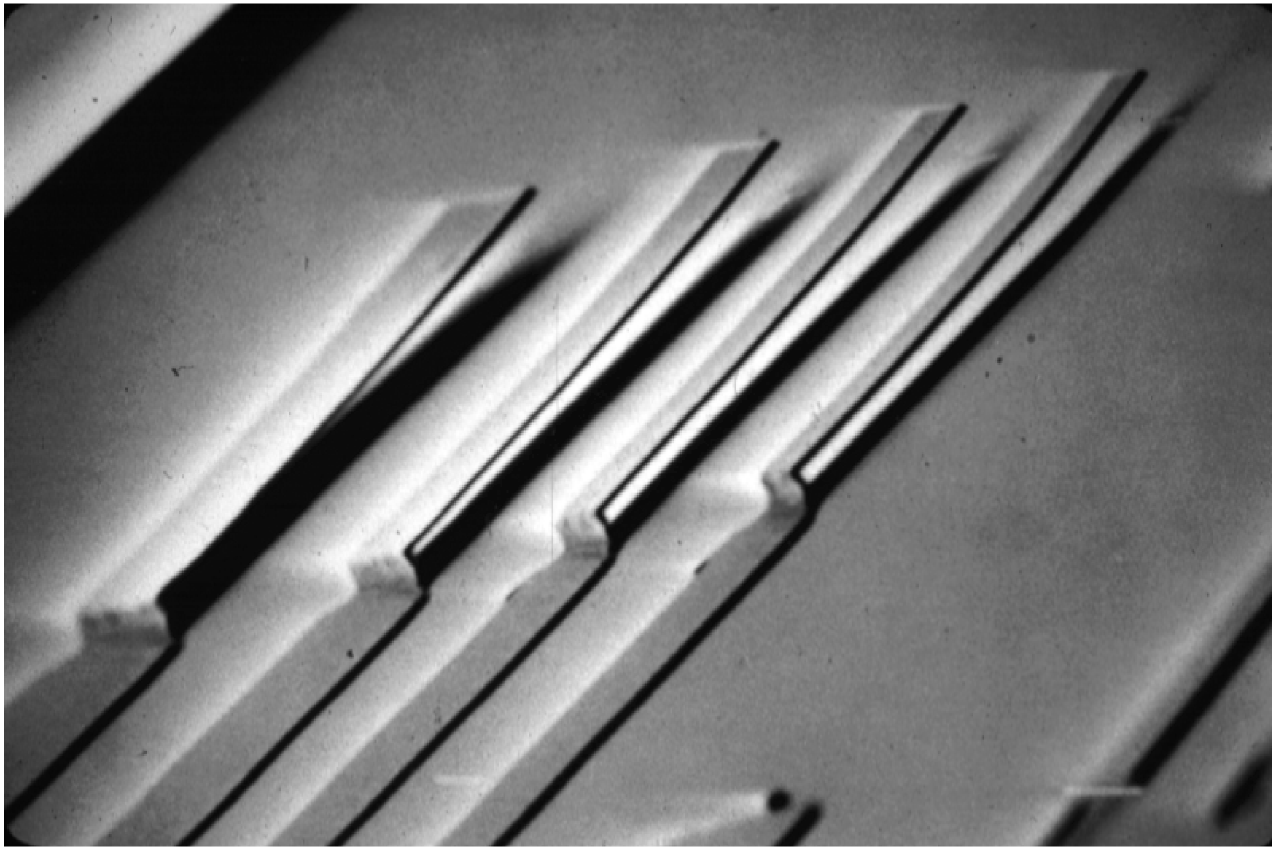
- 1950s: silicon anisotropic etchants (e.g., KOH) discovered at Bell Labs
- Late 1960s: Honeywell and Philips commercialize piezoresistive pressure sensor utilizing a silicon membrane formed by anisotropic etching
- 1960s-70s: research at Stanford on implanted silicon pressure sensors (Jim Meindl), neural probes, and a wafer-scale gas chromatograph (both Jim Angell)
- 1980s: Kurt Petersen of IBM and ex-Stanford students Henry Allen, Jim Knutti, Steve Terry help initiate Silicon Valley “silicon microsensor and microstructures” industry
- 1990s: silicon ink-jet print heads become a commodity

When the Time is Right …

- Early 1980s: Berkeley and Wisconsin demonstrate polysilicon structural layers and oxide sacrificial layers … rebirth of surface micromachining
- 1984: integration of polysilicon microstructures with NMOS electronics
- 1987: Berkeley and Bell Labs demonstrate polysilicon surface micromechanisms; MEMS becomes the name in U.S.; Analog Devices begins accelerometer project
- 1988: Berkeley demonstrates electrostatic micromotor, stimulating major interest in Europe, Japan, and U.S.; Berkeley demonstrates the electrostatic comb drive

Polysilicon Microstructures

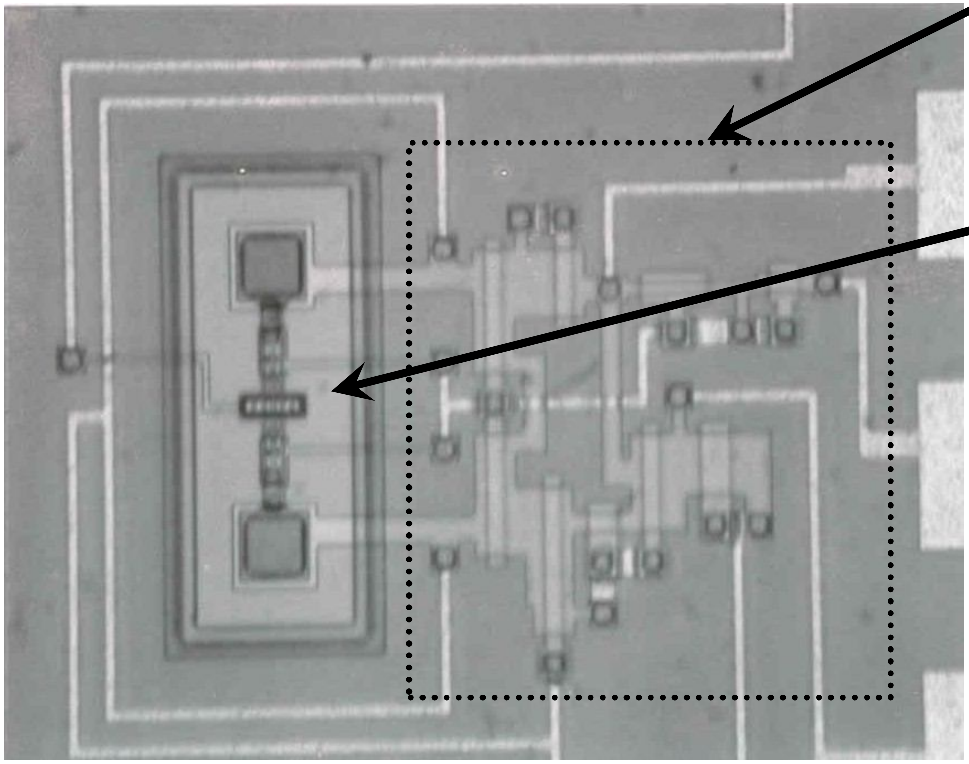
- UC Berkeley 1981-82



R. T. Howe and
R. S. Muller,
ECS Spring Mtg.,
May 1982

Polysilicon MEMS + NMOS Integration

- UC Berkeley 1983-1984

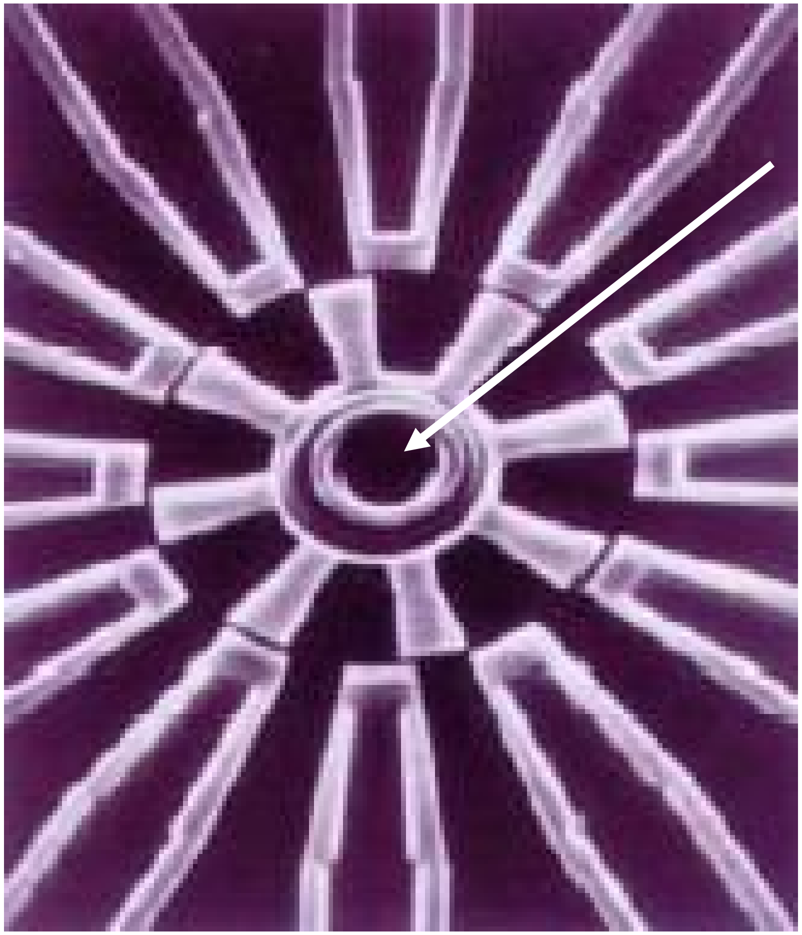


Transresistance amplifier

Capacitively driven and sensed 150 μm-long polysilicon microbridge

R. T. Howe and
R. S. Muller,
IEEE IEDM,
San Francisco,
December 1984

Polysilicon Electrostatic Micromotor



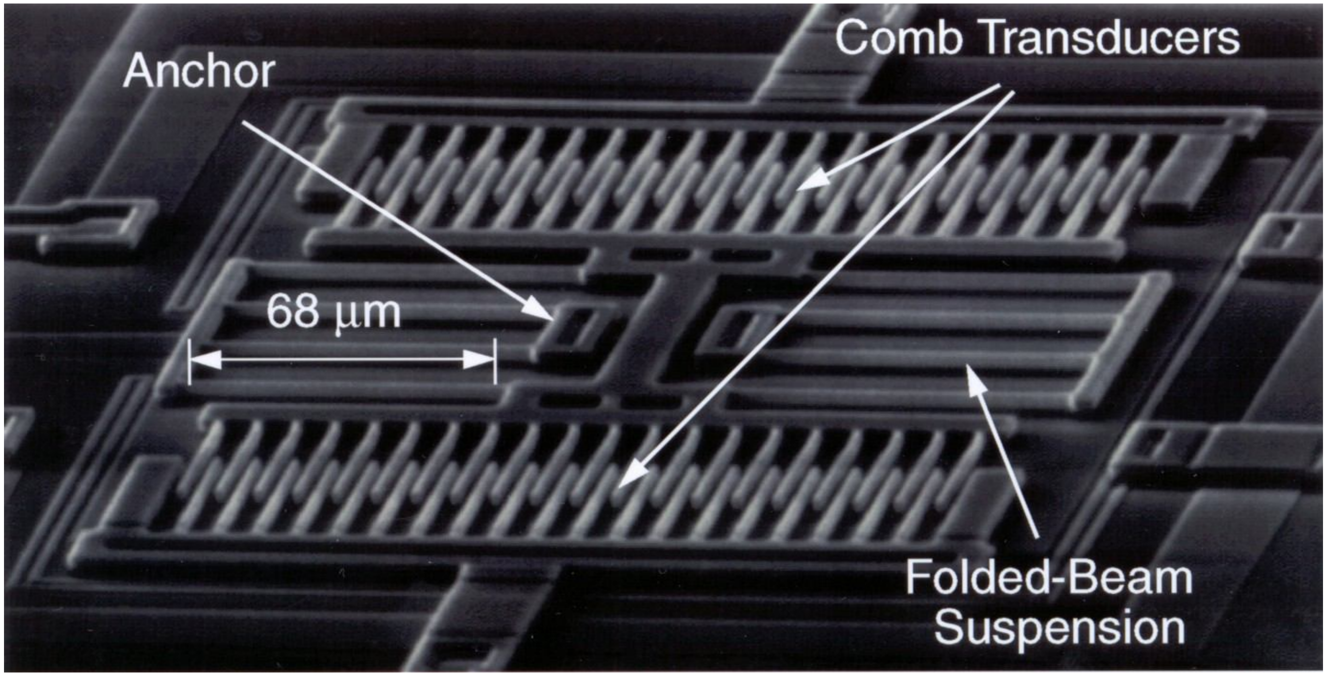
Self-aligned pin-joint, made possible by conformal deposition of structural and sacrificial layers

Prof. Mehran Mehregany,
Case Western Reserve Univ.

Electrostatic Comb-Drive Resonators

- W. C. Tang and R. T. Howe, BSAC 1987-1988

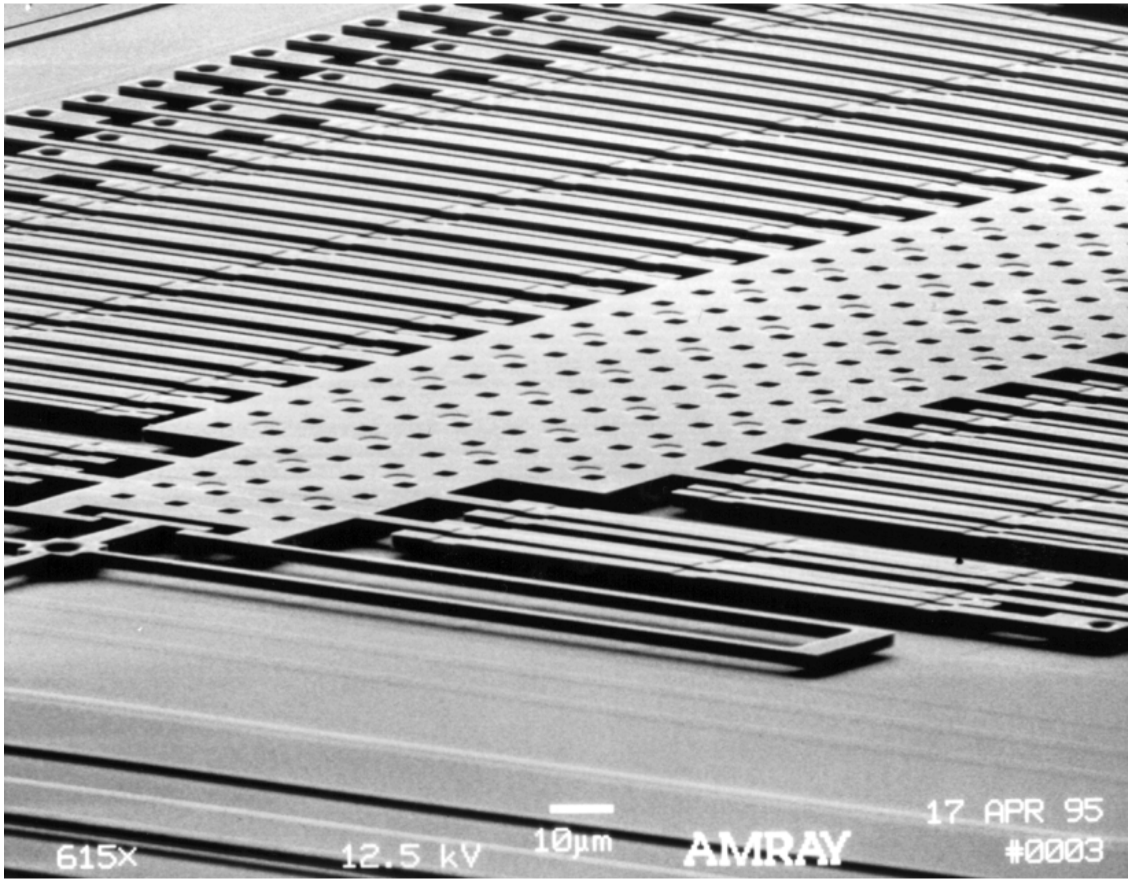
New idea: structures move *laterally* to surface



C. Nguyen and
R. T. Howe,
IEEE IEDM,
Washington, D.C.,
December 1993

Analog Devices Accelerometers

- Integration with BiMOS linear technology
- Lateral structures with interdigitated parallel-plate sense/feedback capacitors



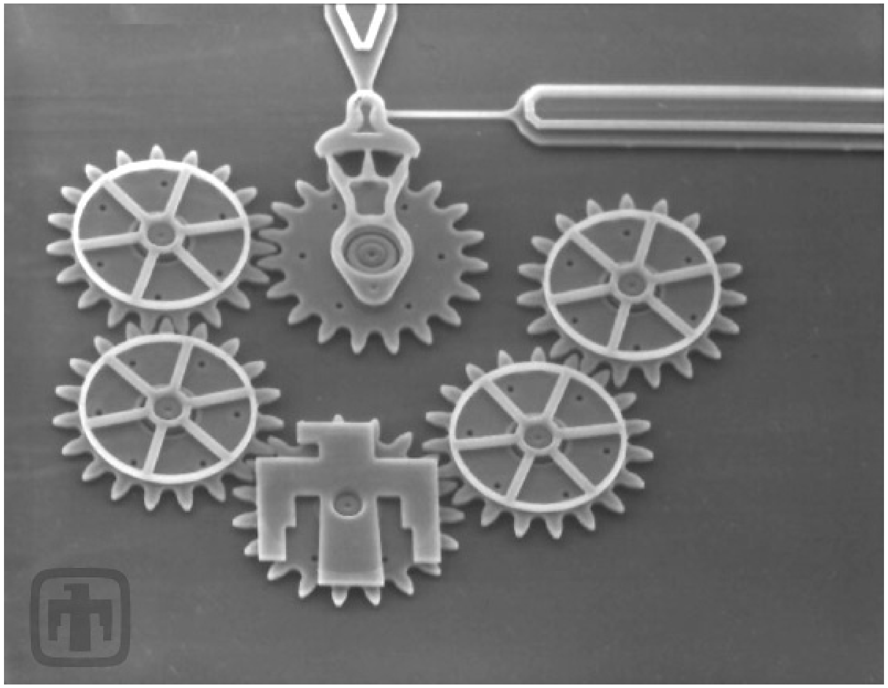
ADXL-05 (1995)

Courtesy of Kevin Chau,
Micromachined Products
Division, Cambridge

Surface Micromachining Foundries

1. MCNC MUMPS technology (imported from Berkeley) 1992-
2. Sandia SUMMiT-IV and -V technologies: 1998 –
   4 and 5 poly-Si level processes

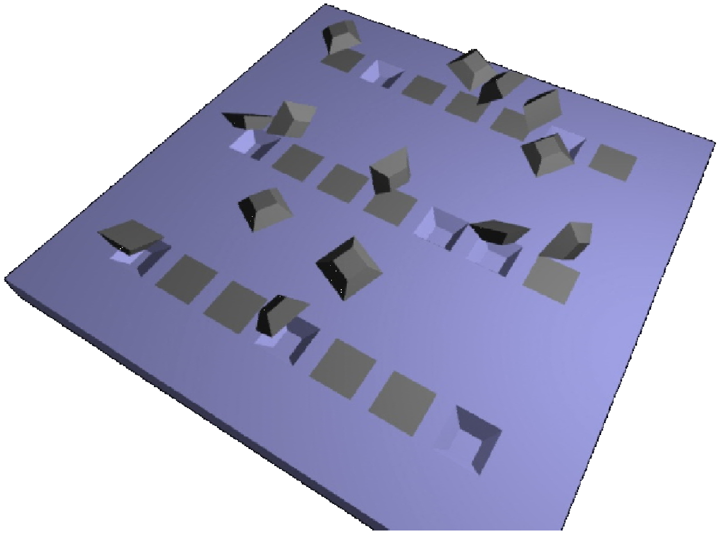
result: more universities, companies do MEMS



M. S. Rodgers
and J. Sniegowski,
Transducers 99

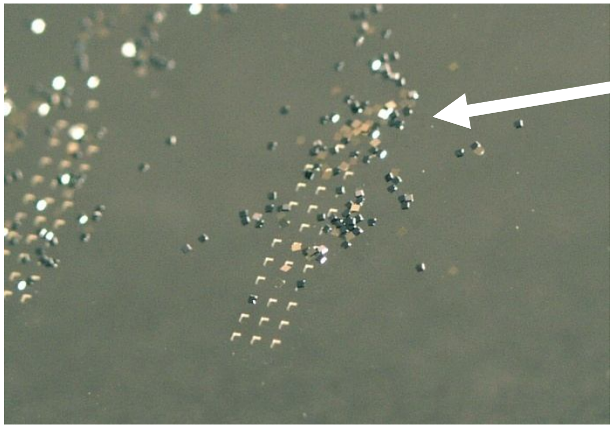
(Sandia Natl. Labs)

Self-Assembly Processes



Alien Technologies, Gilroy, Calif.

chemically micromachined "nanoblock" silicon CMOS chiplets fall into minimum energy sites on substrate



nanoblocks being fluidically self-assembed into embossed micro-pockets in plastic antenna substrate

ALIEN

More Recent History

- Mechanical engineers move into MEMS, starting with Al Pisano in 1987 … expand applications and technology beyond EE's chip-centric view
- DARPA supports large projects at many US universities and labs (1994 – 200?) with a series of outstanding program managers (K. Gabriel, A. P. Pisano, W. C. Tang, C. T.-C. Nguyen, J. Evans)
- Commercialization of inertial sensors (Analog Devices and Motorola polysilicon accelerometers 1991 →) ≈ 10^8 by each company by 2002
- Microfluidics starts with capillary electrophoresis circa 1990; micro-total analysis system (μ-TAS) vision for diagnosis, sensing, and synthesis
- Optical MEMS boom and bust: 1998 – 2002.

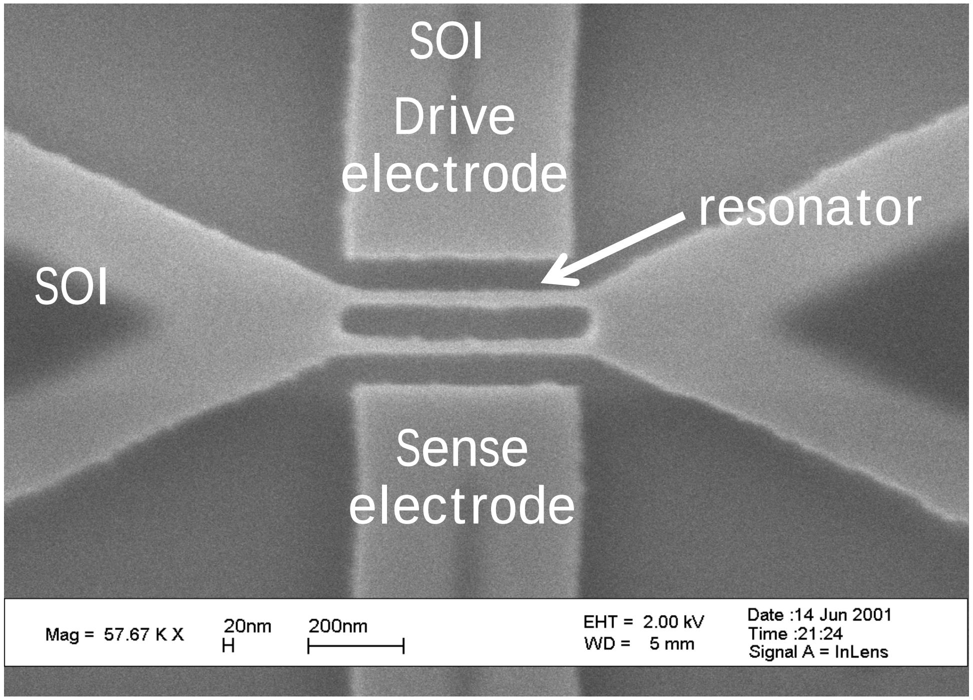
MEMS and Nanotechnology I

- Richard Feynmann’s 1959 talk:
  - “But it is interesting that it would be, in principle, possible (I think) for a physicist to synthesize any chemical substance that the chemist writes down. Give the orders and the physicist synthesizes it. How? Put the atoms down where the chemist says, and so you make the substance.”
- Eric Drexler, 1980s: visionary promoting a molecular engineering technology based on “assemblers” … had paper at first MEMS workshop in 1987
- Early 1990s: U.S. MEMS community concerned that “far-out” nanotech would be confused with our field, undermining credibility with industry and government

MEMS and Nanotechnology II

- Buckyballs, carbon nanotubes, nanowires, quantum dots, molecular motors, … together with the atomic-force microscope (AFM) as an experimental tool →
  - Synthetic and “top-down” nanotechnology earns respect of MEMS community
- Why is nanotechnology interesting?
  - Molecular control of sensing interface (chemical detection)
  - Synthetic processes promise to create new batch-fabrication technologies
  - Planar lithography is reaching into the nano regime (state-of-the are is 50 nm line/space; spacer lithography has reached 7 nm)
  - New computational devices: neural, quantum computing

1 GHz NEMS Resonator



Si double-ended tuning fork
- tine width = 35nm
- length = 500 nm
- thickness = 50 nm

Interconnect parasitic elements are critical → need nearby electronics

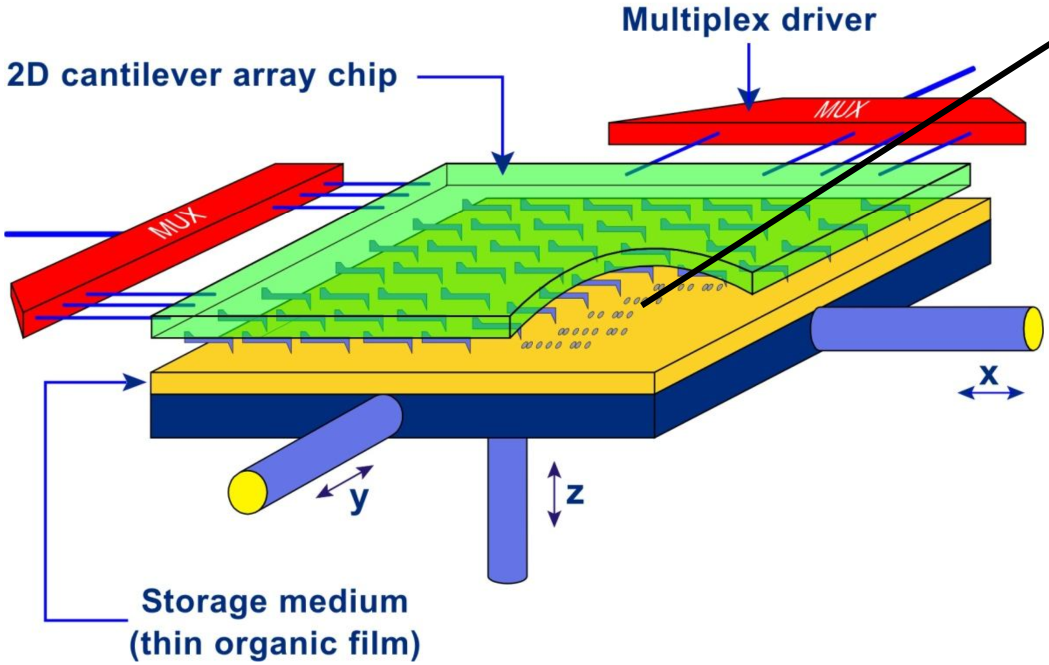
Uses vertical channel FINFET process on SOI substrate

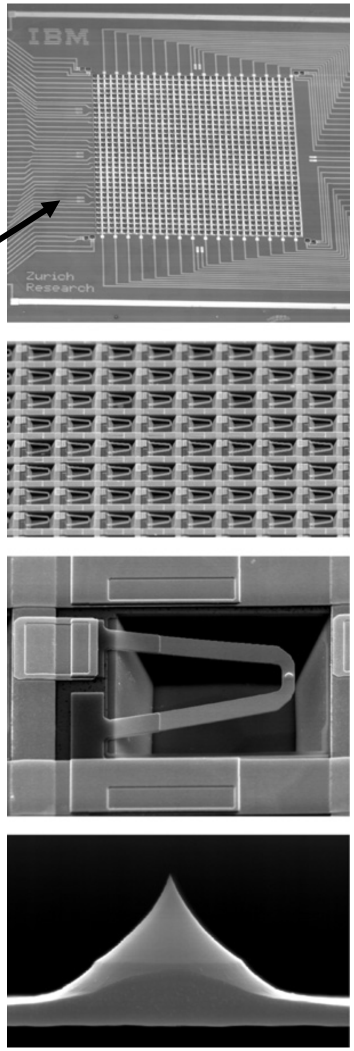
MEMS (NEMS?) Memory: IBM's Millipede

Array of AFM tips write and read bits: potential for low and adaptive power

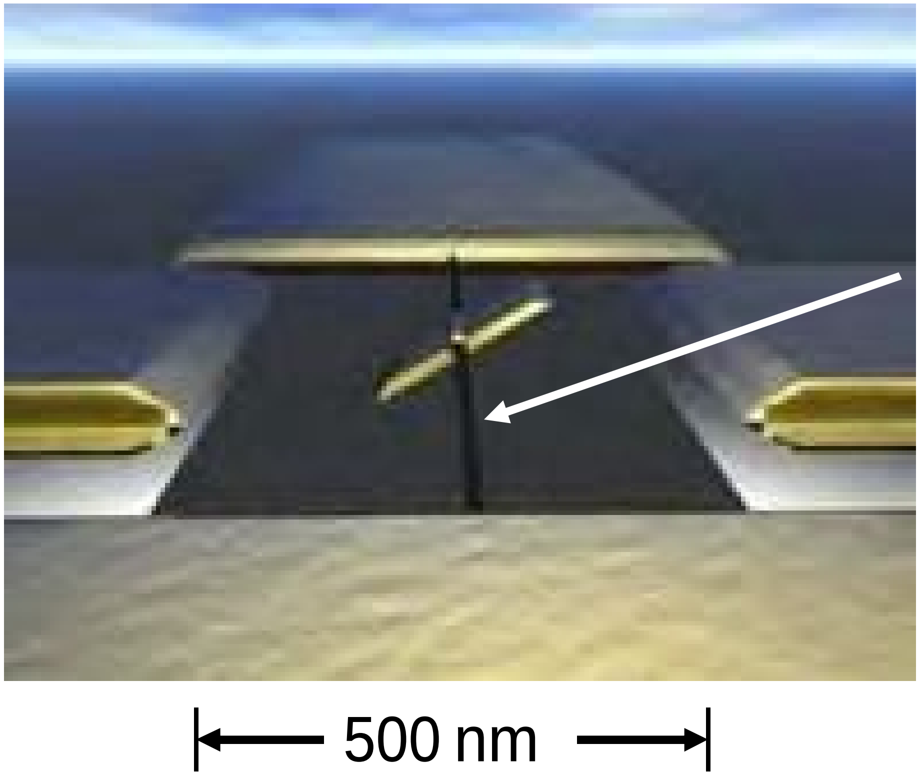
"MILLIPEDE"

Highly parallel, very dense AFM data storage system



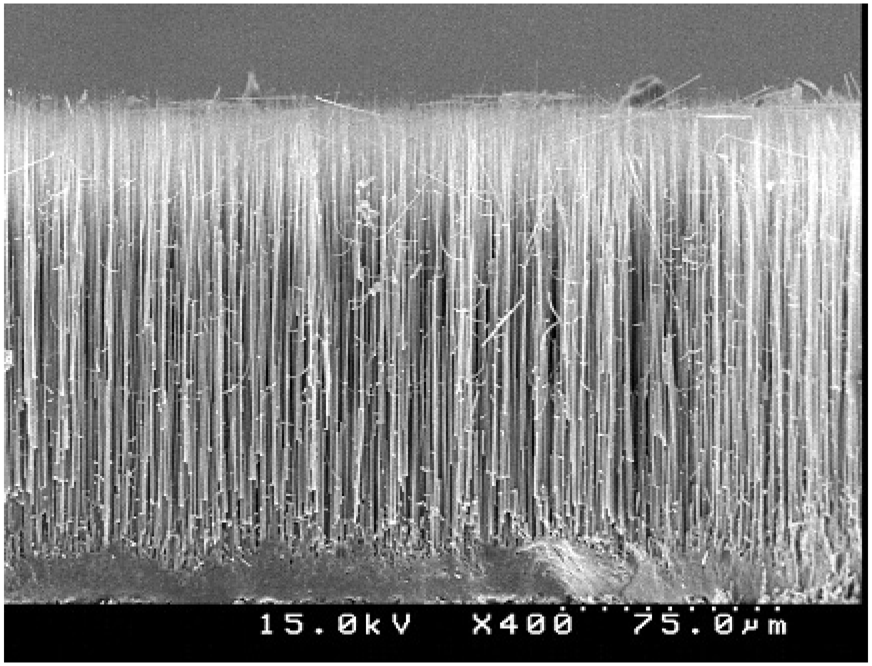


Electrostatic NEMS Motor

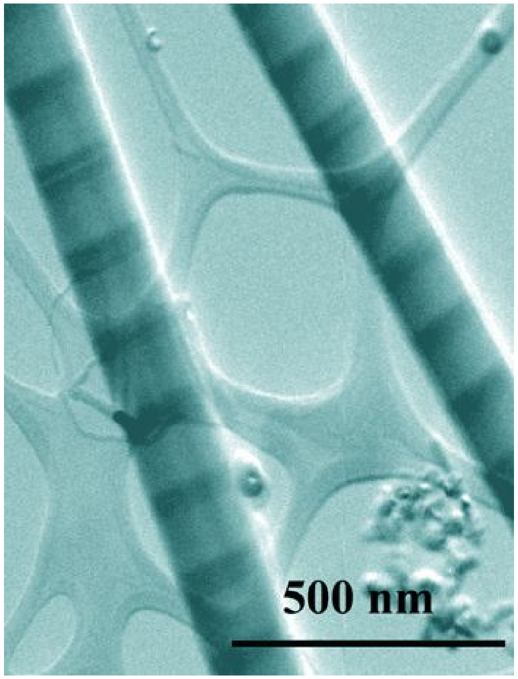


multi-walled carbon nanotube
rotary sleeve bearing

New Micro/Nano Structural Materials and Processes



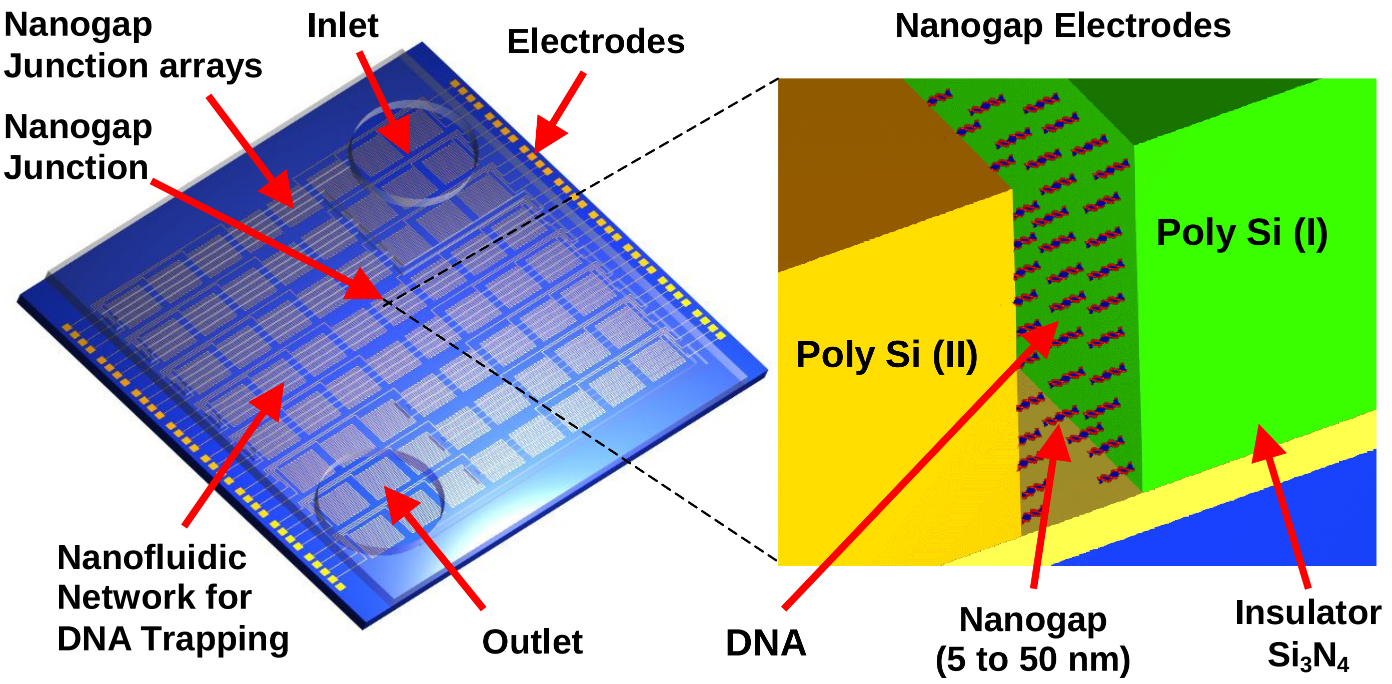
SiC nanowires



Si/SiGe superlattice nanowires

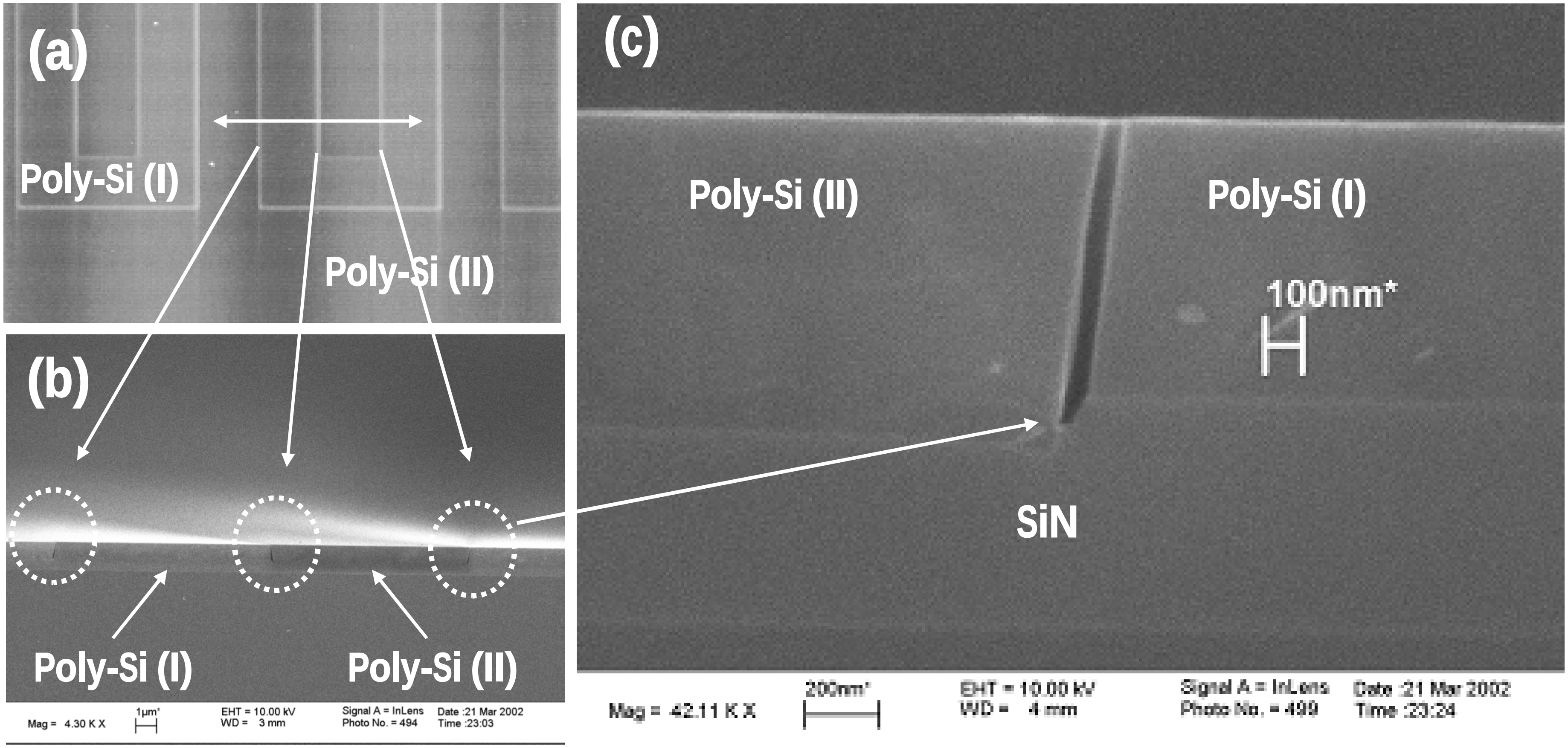
Nanogap DNA Junctions

- Development of ultrafast and ultrasensitive dielectric DNA detection
- Applications to functional genomics or proteomics chips, as well as an exploration of nanogap DNA junction-based information storage and retrieval devices



SEMs of a Nanogap DNA Junction

Top View



Opportunities in Blurring the MEMS/NEMS Boundary

- Aggressive exploitation of extensions of “top-down” planar lithographic processes
- Synthetic techniques create new materials and structures (nanowires, CNT bearings)
- Self-assembly concepts will play a large role in combining the top-down and bottom-up technologies
- Application: mainstream information technology with power consumption being the driver
  - “Beyond CMOS” … really, extensions to CMOS > 2015
  - Non-volatile memories
  - Communications