Wright State University

EE480/680
Micro-Electro-Mechanical Systems
(MEMS)
Summer 2006

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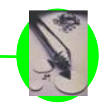
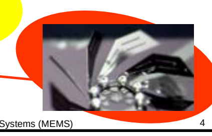
Introduction

Overview

- Definition
- Size Perspective
- Purpose
- Making MEMS
- History
- Applications

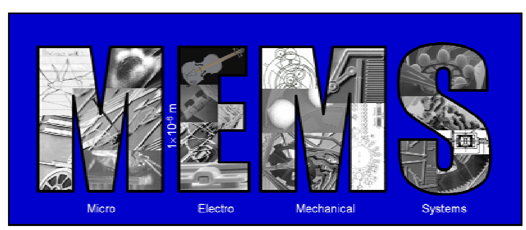




Overview Continued

- E. E. vs. M. E.
- The Literature
- Research Topics
- Conclusions

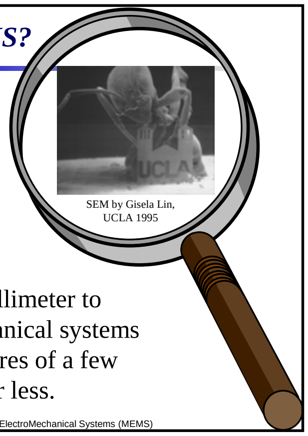
Definition



- MEMS are devices, or systems of devices, with microscopic parts, such as:
  - Mechanical Parts
  - Electrical Parts

What Are MEMS?

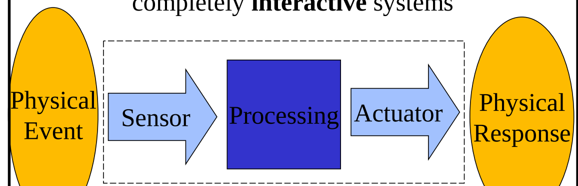
M icro
E lectro
M echanical
S ystems


SEM by Gisela Lin, UCLA 1995

MEMS are sub-millimeter to centimeter sized mechanical systems with individual features of a few micrometers or less.

What Are MEMS?

The combination of **Sensors** and **Actuators** with Integrated Circuits completes a loop allowing completely **interactive** systems



What Are MEMS?

Transducer - A device that converts energy from one form to another

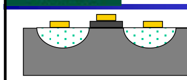
For Example:

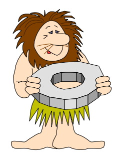
A **microphone** converts an acoustic input into an electrical signal

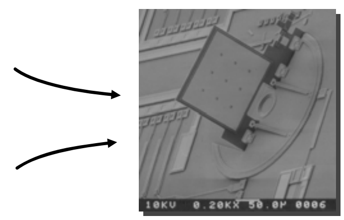
A **speaker** converts an electrical input into an acoustic output

A **flashlight** converts an electrical input into light

What Are MEMS?

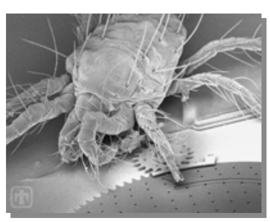

IC Fabrication

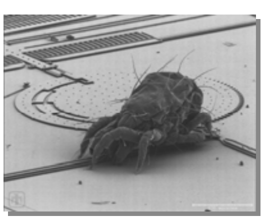

Mechanical Components


MicroElectroMechanical Systems (MEMS)

What Are MEMS?

MEMS allow us to create artificial systems that are on the same scale and functionality as insects.



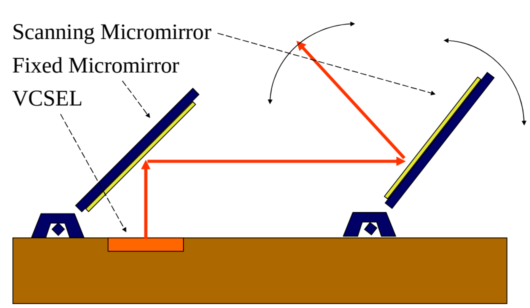


Microscopic Machines

SEMs from Sandia National Laboratory
www.mdl.sandia.gov/Micromachine/images.html

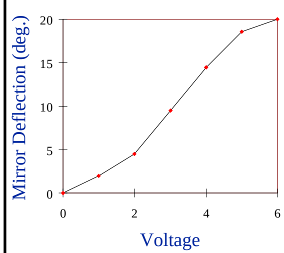
What Are MEMS?

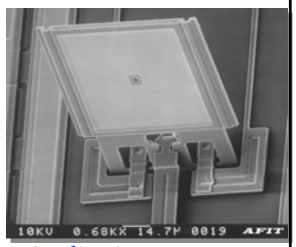
Barcode Scanner



What Are MEMS?

Scanning Micromirrors





Applications:

- Beam Alignment
- Bar Code Scanner

What Are MEMS?

Inputs Eyes and Ears	→	Brains	→	Outputs Hands and Mouth
Sensors		**Circuits**		**Actuators**

Fabrication

What Are MEMS?

- MEMS is an engineering discipline that studies the **design** and **fabrication** of micrometer to centimeter scale mechanical systems.
- MEMS devices are in widespread use, and are often referred to as solid state sensor and actuators, or solid state transducers
- MEMS fabrication is commonly referred to as micromachining
- MEMS design is often referred to as micro-systems engineering

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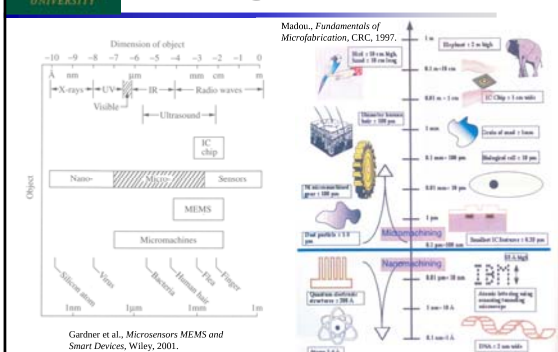
Scaling Down to the Small

Madou., *Fundamentals of Microfabrication*, CRC, 1997.

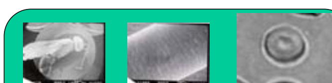


Gardner et al., *Microsensors MEMS and Smart Devices*, Wiley, 2001.

Sizes of Objects

African Elephant Height ~ 3.3 m

Rabbit (Length) ~ 3 x 10^{-1} m



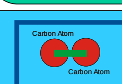
Housefly ~7.5 x 10^{-3} m

Cross section of human hair ~ 8 x 10^{-5} m

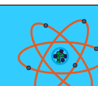
Red Blood Cell 7x10^{-6} m by 10x10^{-6} m

MEMS

Virus (Length) ~9 x 10^{-7} m



Carbon-Carbon Bond Length ~1.5 x 10^{-10} m



Atom ~10^{-10} m Nucleus ~ 10^{-14} m

Nano-technology

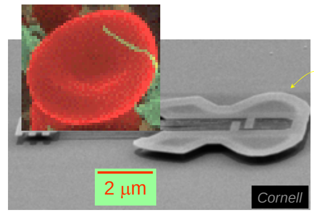
Information and Pictures from: "Introduction to the Nanoworld", Sow Chorng Haur

Size Perspective

Ant

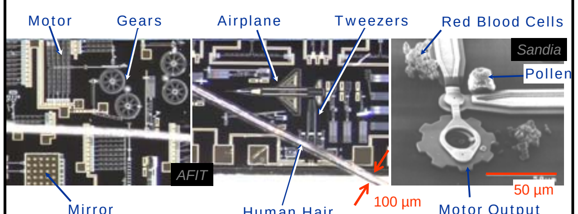
Size Perspective

- Scanning Electron Micrograph (SEM) of the world's smallest guitar
  - Made from single crystal silicon (Si)
  - If plucked, the strings would vibrate at approximately 10 MHz



50 nanometer (500 Å or 0.05 µm) wide strings

Size Perspective



The diameter of a hair is about 70 - 100 micrometers (µm)
1 µm = 1×10⁻⁶ meters

Scaling Down to the Small

- Let S ≡ length scale factor, i.e. 10, 1, 1/10, 1/100, etc.
- As length scales:
  - Length by S^1, area by S^2, volume by S^3, mass by S^3
  - Some common forces (F), acceleration (a), and transit time (t):

$$F = \begin{bmatrix} S^1 \\ S^2 \\ S^3 \\ S^4 \end{bmatrix} = \begin{bmatrix} \text{Surface Tension} \\ \text{Electrostatic} \\ \text{Electromagnetic} \\ \text{Gravitational} \end{bmatrix}, a = \begin{bmatrix} S^{-2} \\ S^{-1} \\ S^0 \\ S^1 \end{bmatrix}, t = \begin{bmatrix} S^{1.5} \\ S^1 \\ S^{0.5} \\ S^0 \end{bmatrix}$$

- Heating or Cooling Time = S^2

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Purpose

- An effort to miniaturize sensors and actuators for the purposes of:
  - Reducing size, weight, energy consumption, and fabrication cost
  - Integrating machines and electronics on the same chip
  - Replacing electronics with mechanical equivalent
  - In many cases, obtain better device performance than macro equivalent

- Making small things is new and cool, but not always the best solution

Purpose - The Possibilities

Research and development in miniaturized systems to enhance the performance and safety of U.S. civilian and military personnel.

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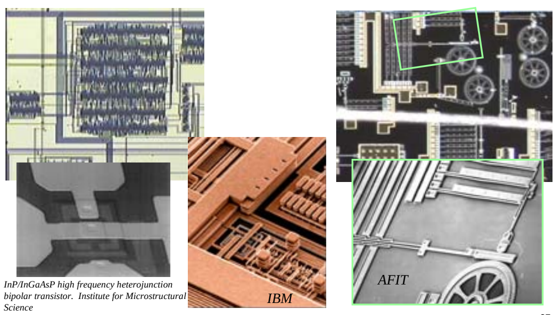
Making MEMS

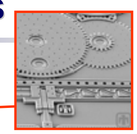
- MEMS were birthed from microelectronics fabrication:

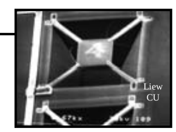


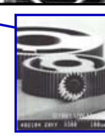
InP/InGaAsP high frequency heterojunction bipolar transistor. Institute for Microstructural Science

Making MEMS

- MEMS fabrication techniques can be categorized as follows:
  - Surface Micromachining
    - Structures made from single or multiple films that are patterned
  - Bulk Micromachining
    - Structures made from chemically etched bulk material
  - Micromolding
    - Structures made using molds, stereo lithography, milling, or combinations thereof
- Patterning and shaping, in the above techniques, is usually accomplished through:
  - Photolithography
  - Chemical Etching







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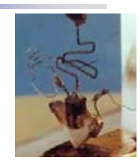
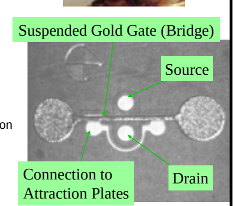
History of MEMS

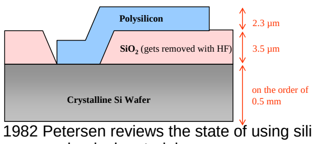
- 1904 First unipolar device (metal-semiconductor)
- December 23, 1947 First transistor was demonstrated by John Bardeen and Walter H. Brattain at Bell Labs
- 1967 First surface machined microstructure:
  - Westinghouse R&D - H. C. Nathanson, et al, "The Resonant Gate Transistor," IEEE Trans. on Electron Devices, vol. ED-14, pp. 117-133, 1967.





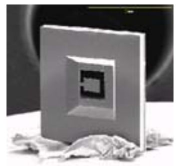
History of MEMS

- R. T. Howe et al.,1982 First polysilicon surface micromachined structure.



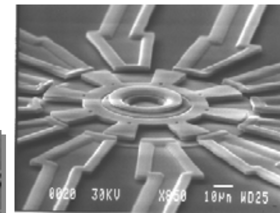
- 1982 Petersen reviews the state of using silicon as a mechanical material
- Late 80's early 90's MEMS formalizes as a distinct engineering field.

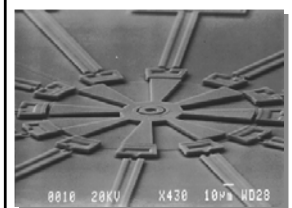
Example of bulk micromachined flow sensor from the University of Bremen



Micro-Motors and Micro-Actuators

Beginning around 1987



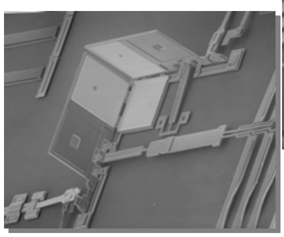


Motors and Actuators can actually change the surrounding environment

SEMs from MCNC mems.mcnc.org

Surface Micromachining

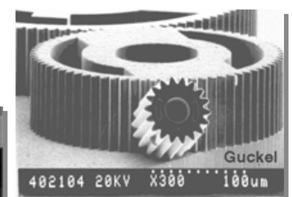
1990's

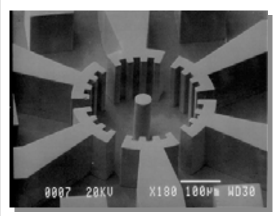


Flip Up Structures actuated with Micro-Actuators

Microforming (LIGA)

1990's and beyond





- LIGA process
- New resists explored
  - SU-8
  - Photosensitive Polyimides

SEMs from MCNCmems.mcnc.org

Why now?

- Availability of Materials and Substrates
  - Si/GaAs/Quartz wafers
  - Semiconductor grade chemicals and gasses
- Availability of IC Fabrication Capability
  - Mask Aligners
  - Deposition Equipment
- Availability of Test Equipment
  - Probe stations

Enabling the future

MEMS is an **enabling technology**.

Micro-sensors and actuators are not going to be products by themselves, but are going to be components in products. However, the MEMS component is often going to be the element that gives a product its competitive advantage

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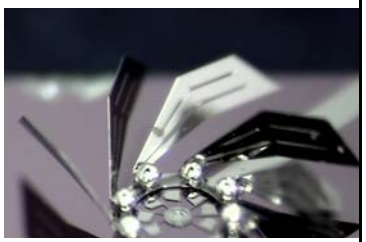


Applications

MEMS is not

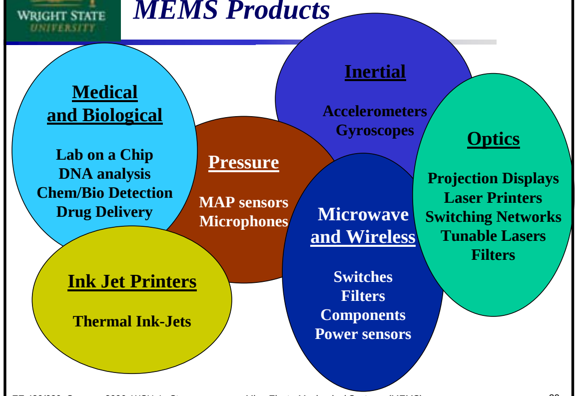
- about any one single application
- defined by a single fabrication process
- limited to a few materials

MEMS is

- a technology enabler
- a way to realize applications from all the engineering and scientific fields

You must be open to a multidisciplinary research experience

MEMS Products

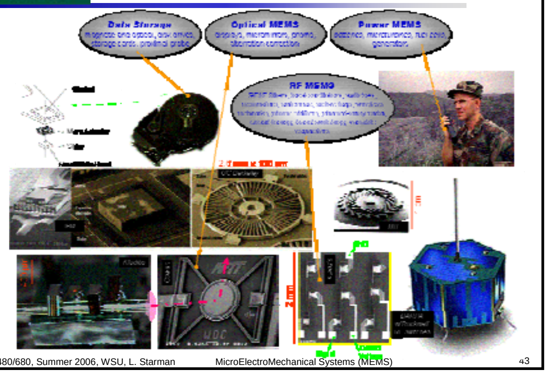


Chem-Bio Analysis

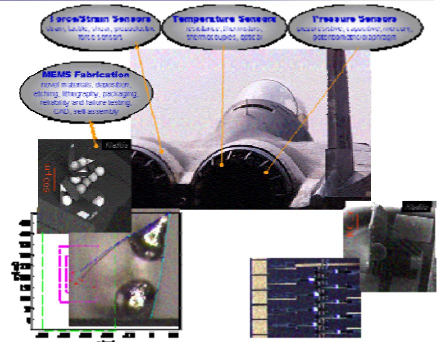
Navigation - Control

Smart Weapons – Stealth - Safety

Communication – Data - Power



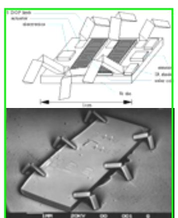
Measurement - Fabrication



Applications: Microrobots

Medical Robots

Discover, 1999



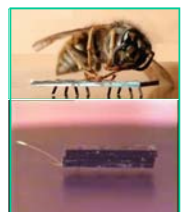
UC Berkeley

Hollow Triangular Beam Robot

Kladitis, 1999

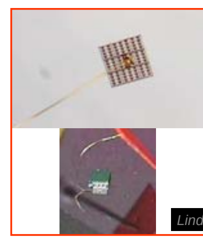
Thermal Actuator Robot

Applications: Microrobots



Ebefors, Royal Institute of Technology, 2000

Polyimide Joint Robot

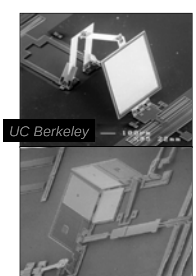


Linderman, CU

Electrostatic Scratch Drive Robot

Applications: Optical Communications

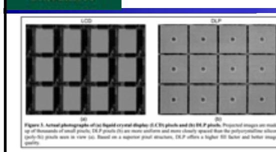
- Light reflection
  - mirrors
  - lenses
- Fiber-optics
  - switches
  - filters
- Lasers and Steering



UC Berkeley

Reid, AFIT

MEMS Products

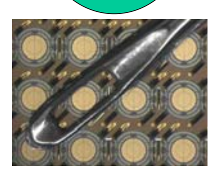


Texas Instruments DLP

Optics

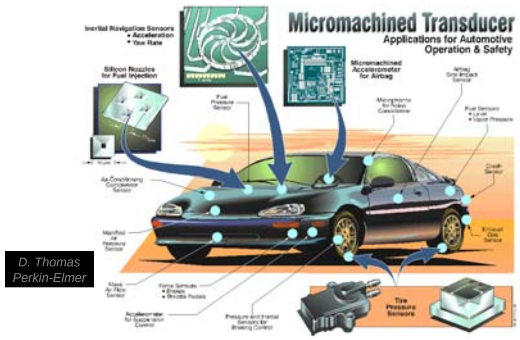
Projection Displays
Laser Printers
Switching Networks
Tunable Lasers
Filters

Silicon Light Machines Dynamic Blocking Filter



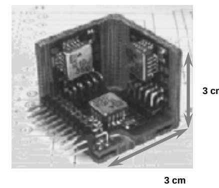
Lucent - LamdaRouter

Applications: Automotive



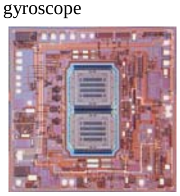
Applications: Automotive

- Accelerometer
  - change in acceleration
  - detect system changes
  - calculate position and velocity
- Currently ~ 15 per car
- Collision Sensors
- Tire Pressure Sensors
- Fuel Injectors



MEMS Products

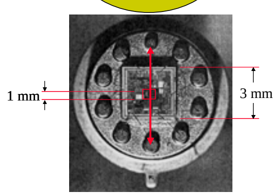
Analog devices has shipped over 100 million accelerometers and has recently released an integrated gyroscope



ADXRS 150

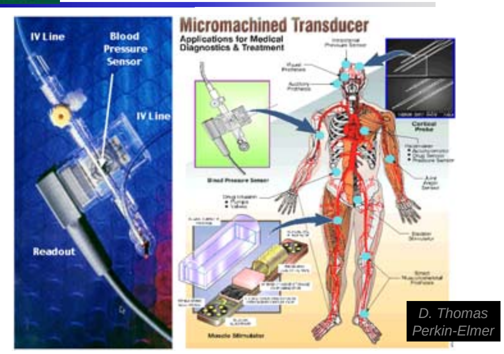
Inertial

Accelerometers
Gyroscopes



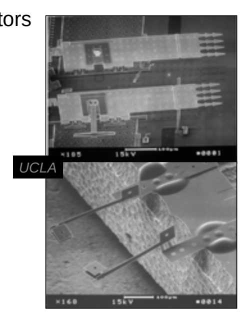
ADXL 050

Applications: Biology and Medicine



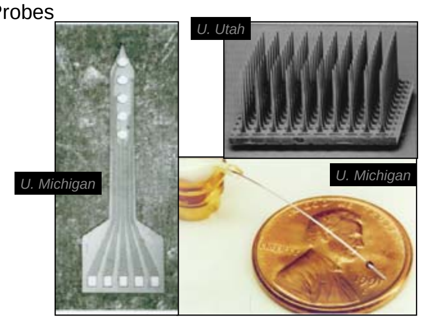
Applications: Biology and Medicine

- Individual cell manipulators
- Needles and Pumps
- Sensors
  - chemical
  - nervous system
  - blood flow
- Transmitters



Applications: Biology and Medicine

- Neural Probes

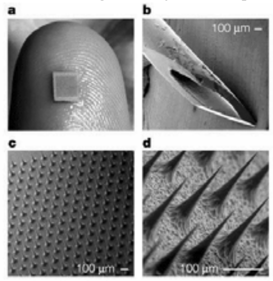


MEMS Products

Microfabricated needles – drug delivery without pain!

Medical and Biological

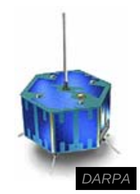
- Lab on a Chip
- DNA analysis
- Chem/Bio Detection
- Drug Delivery

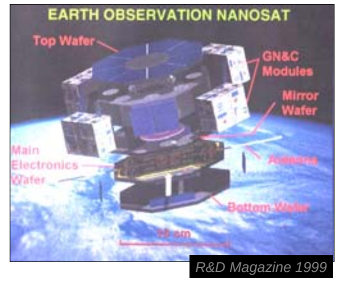


From Kaushik,S. et al. Anesth.Analg. 2001,92:502-504).

Applications: Space

- Microsatellites



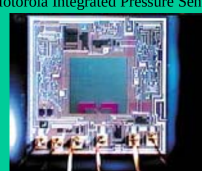


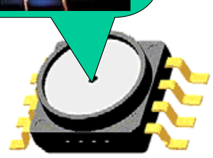
MEMS Products

Pressure

- MAP sensors
- Microphones

Motorola Integrated Pressure Sensor

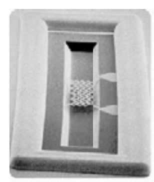




MEMS Pressure Sensors (Nexus '98)
1996: 115 million units worth $600 million
2002 (proj.): 309 million units worth $1.3 Billion

From Sensors Magazine online at: http://www.sensorsmag.com/articles/0700/62/main.shtml

MEMS Products



Thermal conductivity detector
(http://www.labs.agilent.com/news/2002features/fea_mems.html)

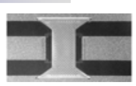
Microwave and Wireless

- Switches
- Filters
- Components
- Power sensors

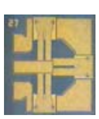
First released an RF power sensor in 1974
Currently Agilent is having success with an FBAR duplexer

Today's State-of-the-Art -- RF MEMS

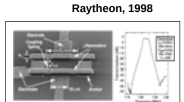
- Market predictions by WTC (2003) claim the RF MEMS market will be over $1 Billion/year by 2007
- RF MEMS Components
  - Switches
  - Variable Capacitors
  - Resonant Devices
- 3D-MERFS (DARPA MTO)
  - Integrated Actives / Passives
- Micro-machined Components
  - Integrated TEM Lines
  - 3D High-Q Inductors
  - RF Power meters
  - FBARs (Film Bulk Acoustic Resonators)



Raytheon, 1998

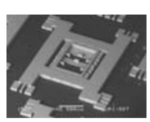


AFRL Digital Varactor, 2004



Nguyen, IEEE MTT-T, 1998.

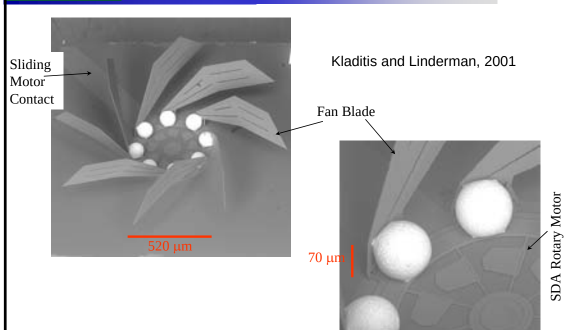
AFRL Inductor, 2004



AFRL 60 GHz Coupler, 2004

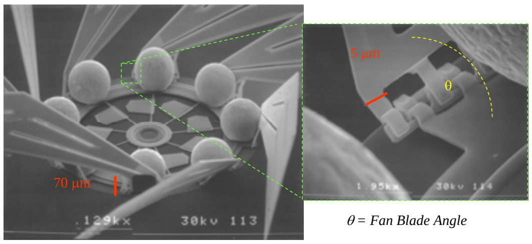
Micro Axial Flow Fan

Kladitis and Linderman, 2001



Micro Axial Flow Fan

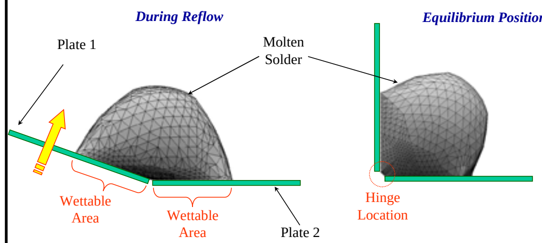
- Special scissor hinge design for close to substrate operation



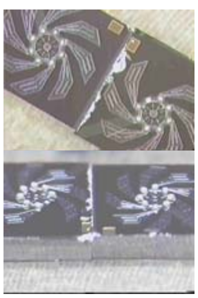
θ = Fan Blade Angle

Micro Axial Flow Fan

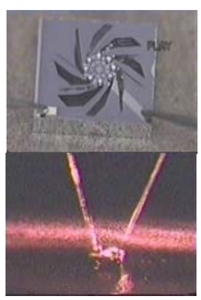
- Solder Self-Assembly



Micro Axial Flow Fan

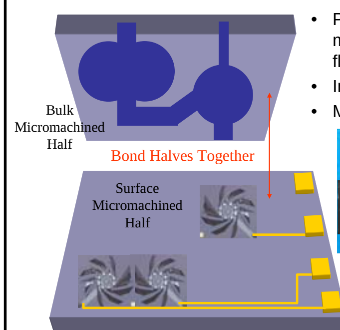


Assembly top and side



Operation

Micro Axial Flow Fan



- Pumping and mixing mechanism for chip based fluidic systems
- Individual device cooler
- Micro Propulsion

Overview

- Definition
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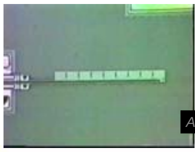
- The Literature
- Research Topics
- Conclusions

Mechanical Engineering and MEMS

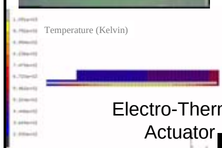
- Mechanical Engineering can be broken down into the following subdisciplines:
  - Heat Transfer
  - Thermodynamics
  - Materials Science
  - Solid Mechanics
  - Fluid Mechanics
  - Mechanical Design
  - Manufacturing
  - Dynamic Systems and Controls

Mechanical Engineering and MEMS

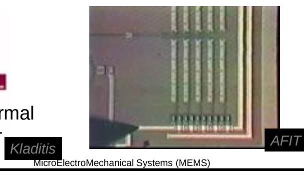
- Heat Transfer



Solder Self-Assembly



Electro-Thermal Actuator

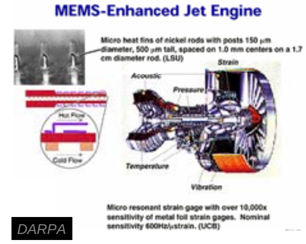


Mechanical Engineering and MEMS

- Thermodynamics

Micro Turbine

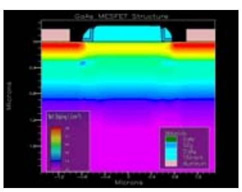
MEMS-Enhanced Jet Engine

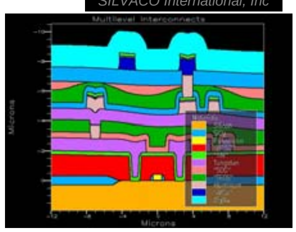


Mechanical Engineering and MEMS

- Materials Science

ATHENA
SILVACO International, Inc





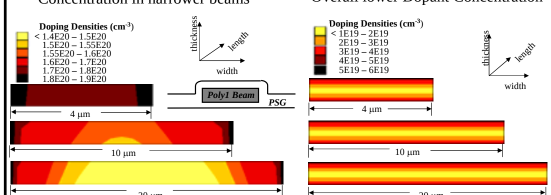
MEMS and Microelectronics Material Layers

TSUPREM Dopant Models

MUMP's Foundry Fabrication Modeled in TSUPREM

Poly1
- Illustrates Lateral Diffusion
- Peak Concentration at ends
- Higher/Uniform Dopant Concentration in narrower beams

Poly2
- No Lateral Diffusion
- Peak Concentration at top and bottom surfaces
- Overall lower Dopant Concentration



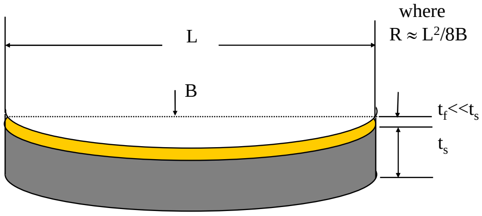
Wafer Curvature

- MUMPs Stress measurement technique
- Obtain average residual stress
- Does not measure residual stress gradient
- No localized stress information

Stoney Equation

$$\sigma_f = \frac{E_s t_s^{\ 2}}{6(1-\upsilon_s)t_f R}$$

where
$R \approx L^2/8B$



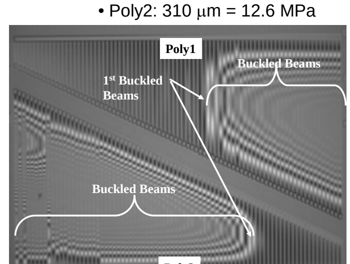
Critical Buckling Arrays

- Critical Buckling Beam Arrays
- Array parameters
  - 100-900 µm lengths
  - 10 µm increments
  - 10 µm wide

- Buckling determined by IFM
- Buckling lengths
  - Poly1: 550 µm = 4.6 MPa
  - Poly2: 310 µm = 12.6 MPa

Buckling Beam Equation

$$L = \sqrt{\frac{\pi^2 t^2 E}{3\sigma}} \quad (\mu m)$$

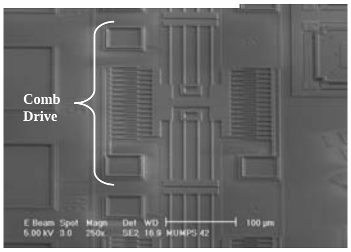


Young's Modulus Measurement

Comb Drive Resonator Equation

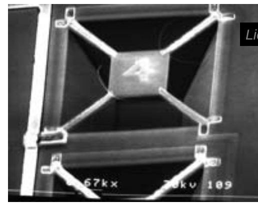
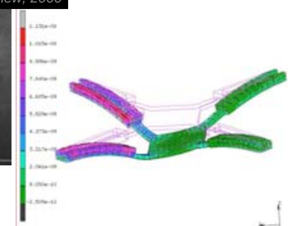
$$f = \frac{1}{2\pi}\sqrt{\frac{k_x}{M}} = \frac{1}{2\pi}\sqrt{\frac{24EI_z}{(M_p+\frac{1}{4}M_t+\frac{12}{35}M_b)L^3}} \quad (Hz)$$

- Measure Resonance
- Obtain Young's Modulus
  - Poly1: 131 GPa
  - Poly2: 162 GPa



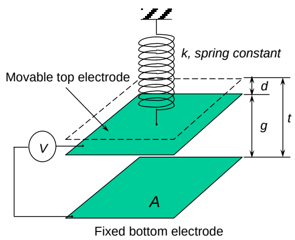
Mechanical Engineering and MEMS

- Solid Mechanics

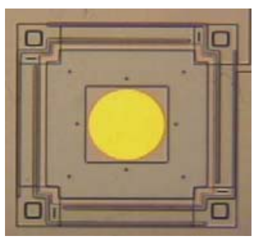



Pressure Sensor

Micromirror Schematic



- Induced Raman stress measurements



Mirror deflection

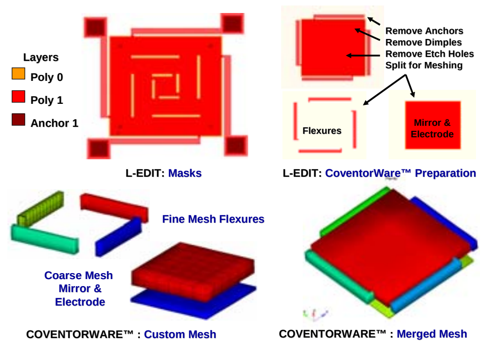
$$d = \frac{\varepsilon_0 A V^2}{2k(h-d)^2}$$

For d=0 to ~t/3

ε_0 = dielectric constant of air

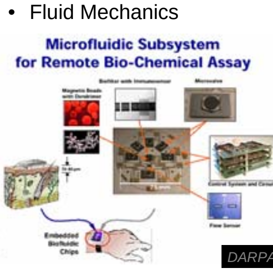
Ref: Cowan dissertation 1998

Coventorware Customized Layout

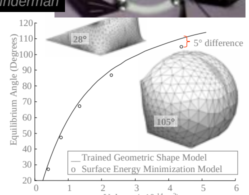


Mechanical Engineering and MEMS

- Fluid Mechanics



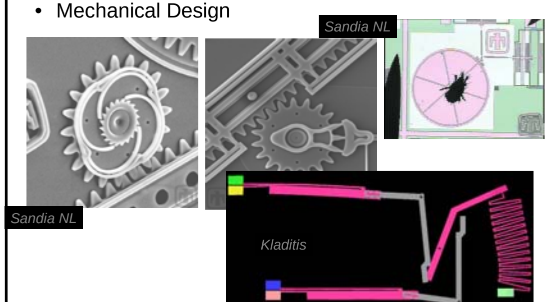
Micro Pumps and Flow Channels



Predicting Solder Shape

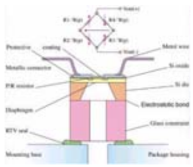
Mechanical Engineering and MEMS

- Mechanical Design



Mechanical Engineering and MEMS

- Manufacturing



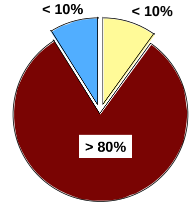

Packaging a Pressure Sensor

Switch Packaging Approaches
(Known Efforts)

Conventional (Chip-in-box) (<10%)
Dice ⇒ release ⇒ package or
Dice ⇒ package ⇒ release
Ceramic / Metal package

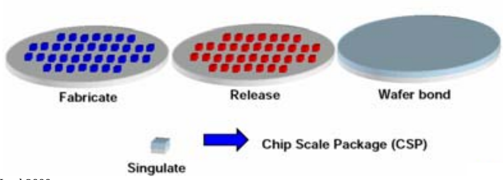
Thin-film Encapsulation (<10%)
Thin-film bubble, cap ⇒
Release through holes ⇒
Seal ⇒ Dice

Wafer Bonding (> 80%)
Release ⇒
Bond cap wafer ⇒ Dice
Metal eutectic or Glass frit seal



Wafer Level Packaging

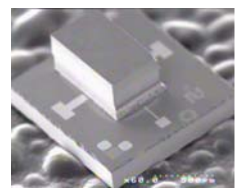
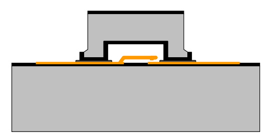
- A better approach is to do the MEMS release at the wafer level.
- Wafer level packaging (WLP) must follow the wafer level release, to avoid damaging the MEMS.
- Much smaller packages are possible



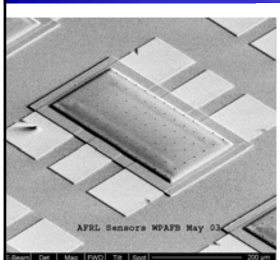
Roa, Intel 2000

Wafer-Level Cap

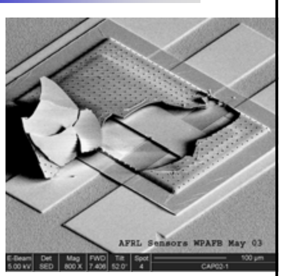
- Wafer-to-Wafer Bonding is Employed to Cap the Individual Switch Die
  - Provides Hermetic Environment
  - Low-Cost Packaging Solution
  - Optimization is in Process
- RMI has Produced Fully Functional Devices with Promising RF Results
  - High-Lifetime: $>10^{11}$ Cycles
    - Best Case
  - Optimization of RF Performance is in Process

Silicon Nitride Encapsulated Switches



Released switch under nitride cap



Nitride cap partially removed showing released switch

Overview

- Definition
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- **The Literature**
- Research Topics
- Conclusions

The Literature

- Refereed Journals
  - *Sensors and Actuators A: Physical*
  - *Sensors and Actuators B: Chemical*
  - *Sensors and Actuators C: Materials*
  - *IEEE/ASME Journal of Microelectromechanical Systems* (JMEMS)
  - *Journal of Micromechanics and Microengineering*
- Refereed Journals (occasional MEMS papers)
  - *IEEE Electron Device Letters*
  - *Journal of the Electrochemical Society*
  - *Journal of the Vacuum Society*
- Conference Proceedings
  - *Solid-State Sensor and Actuator Workshop* (Hilton Head)
  - *International Conference on Solid-Sate Sensors and Actuators* (Transducers)
  - *Micro Electro Mechanical Systems Workshops* (MEMS)
  - *Proceedings of the SPIE – International Society for Optical Engineering*

The Literature

- Books
  - S. D. Senturia, Microsystem Design, Kluwer Academic Publishers, 2001, ISBN: 0-7923-7246-8.
  - M. Madou, Fundamentals of Microfabrication, CRC Press, 2nd ed., 2002.
  - M. Gad-el-Hak, The MEMS Handbook, CRC Press, 2002, ISBN: 0-8493-0077-0.
  - W. S. Trimmer, Micromechanics and MEMS Classic and Seminal Papers to 1990, IEEE Press, 1997, ISBN: 0-7803-1085-3.
  - J. W. Gardner, V. K. Varadan, O. O. Awadelkarim, Microsensors MEMS and Smart Devices, 2001, ISBN: 0-471-86109-X.
  - G. Kovacs, Micromachined Transducers Sourcebook, McGraw-Hill, 1998.
  - L. Ristic, Sensor Technology and Devices, Artech House, 1994.

The Literature

- Patents
- Web
  - http://www.darpa.mil/mto/mems/index.html
  - http://www.memsnet.org/
  - http://www.smalltimes.com/
  - http://www.mems-exchange.org/
  - http://www.memscenter.com/memsc
  - http://memsrus.com
- Many of the references are on-line

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Past & Current Research Topics

- Examples of current AFIT MEMS related research topics
  - Microswitches AC/DC
  - RF MEMS Devices – microswitches, varactors, etc
  - Radiation Effects on MEMS
  - Actuator Encapsulation
  - Microrobots
  - Infrared Sensors
  - Microscale Safe and Arm Devices
  - Turbine Blade Health Monitoring
  - Smart Carbon Actuators
  - Three-Dimensional Memory
  - Three-Dimensional Displays
  - SUMMiT Fabrication Process – Optical Projects
  - Material Device Characterization – Raman spectroscopy

Conclusions

- Definition
  - *Small Machines*
- Size Perspective
  - *The size of blood cells*
- Purpose
  - *Reduce the size of current sensors and actuators*
- Making MEMS
  - *Photolithographical patterning and chemical etching*
- History
  - *A relatively new field*
- Applications
  - *From all the scientific fields*
- E. E. vs. M. E.
  - *Not just E.E. – by far*
- The Literature
  - *Lots of resources*
- Research Topics