

Wright State University


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

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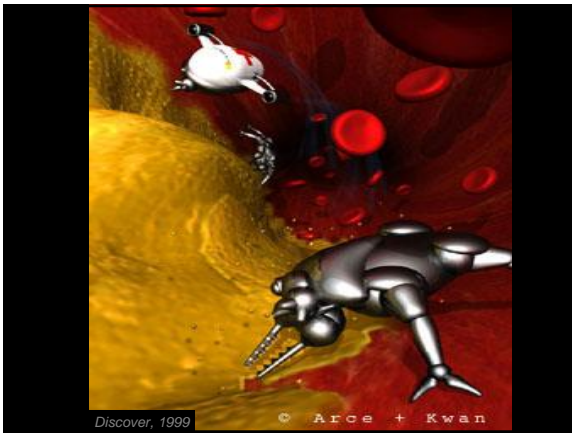



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Introduction



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Overview


- Definition — MEMS = ?
- Size Perspective
- Purpose
- Making MEMS
- History
- Applications

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Overview Continued

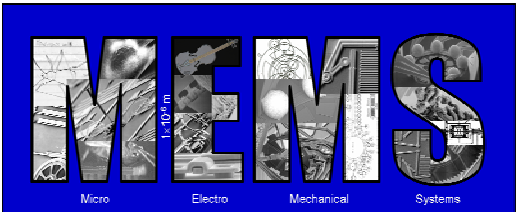
- E. E. vs. M. E.
- The Literature
- Research Topics
- Conclusions



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Definition

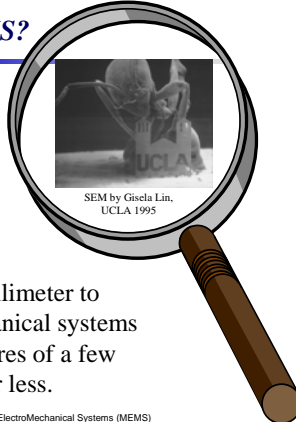


- MEMS are devices, or systems of devices, with microscopic parts, such as:
 - Mechanical Parts
 - Electrical Parts

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WRIGHT STATE UNIVERSITY **What Are MEMS?**

Micro
Electro
Mechanical
Systems



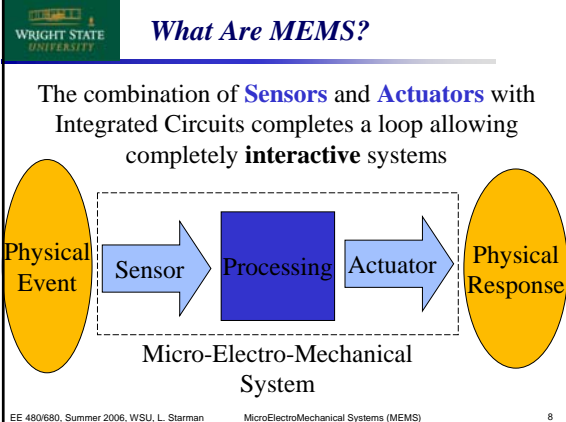
SEM by Gisela Lin, UCLA 1995

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

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WRIGHT STATE UNIVERSITY **What Are MEMS?**

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



Physical Event → Sensor → Processing → Actuator → Physical Response

Micro-Electro-Mechanical System

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WRIGHT STATE UNIVERSITY **What Are MEMS?**

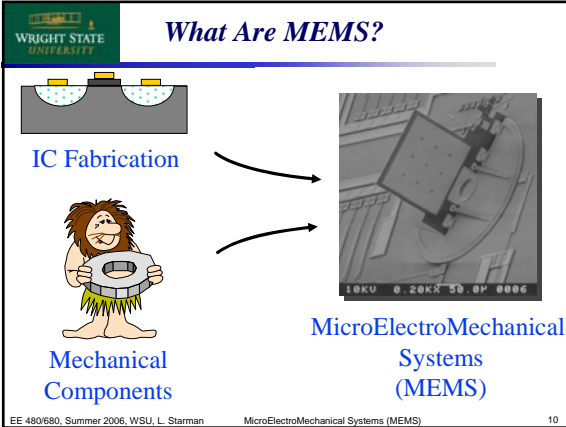
Transducer - A device that converts energy from one form to another

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

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WRIGHT STATE UNIVERSITY **What Are MEMS?**



IC Fabrication

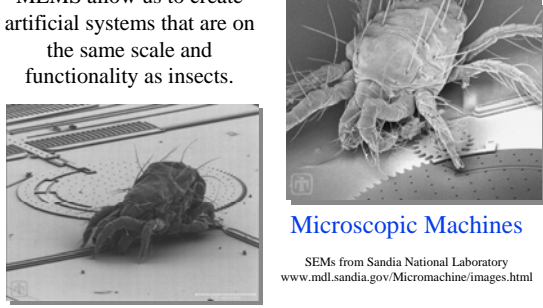
Mechanical Components

MicroElectroMechanical Systems (MEMS)

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WRIGHT STATE UNIVERSITY **What Are MEMS?**

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



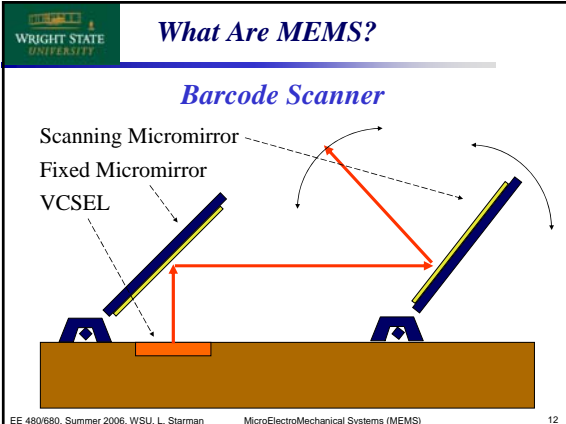
Microscopic Machines

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

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WRIGHT STATE UNIVERSITY **What Are MEMS?**

Barcode Scanner



Scanning Micromirror

Fixed Micromirror

VCSEL

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What Are MEMS?

Scanning Micromirrors

Applications:

- Beam Alignment
- Bar Code Scanner

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What Are MEMS?

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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

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Sizes of Objects

Information and Pictures from: "Introduction to the Nanoworld", Sow Chong Haur
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Size Perspective

Ant

UW-Madison

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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

2 μm

Cornell

50 nanometer (500 Å or 0.05 μm) wide strings

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Size Perspective

Motor Gears Airplane Tweezers Red Blood Cells Sandia Pollen AFIT Mirror Human Hair Motor Output

100 μm 50 μm

The diameter of a hair is about 70 - 100 micrometers (μm)
 $1 \mu\text{m} = 1 \times 10^{-6} \text{ meters}$

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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

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Purpose - The Possibilities

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

- Miniature Health Monitoring System
- General Sensor/Detector Arrays
- Miniature Navigation System
- High Performance Wireless Comm Systems
- Personal Heads Up Displays
- Miniature Optical Communication System
- Guided Small Arms Munitions
- Miniature Chem/Bio Analysis System

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Making MEMS

- MEMS were birthed from microelectronics fabrication:

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

IBM

AFIT

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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.

Suspended Gold Gate (Bridge)

Source

Drain

Connection to Attraction Plates

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History of MEMS

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

Example of bulk micromachined flow sensor from the University of Bremen

- 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.

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Micro-Motors and Micro-Actuators

Beginning around 1987

Motors and Actuators can actually change the surrounding environment

SEMs from MCNC
mems.mcnc.org

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Surface Micromachining

1990's

Flip Up Structures actuated with Micro-Actuators

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Microforming (LIGA)

1990's and beyond

SEMs from MCNCmems.mcnc.org

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

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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

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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

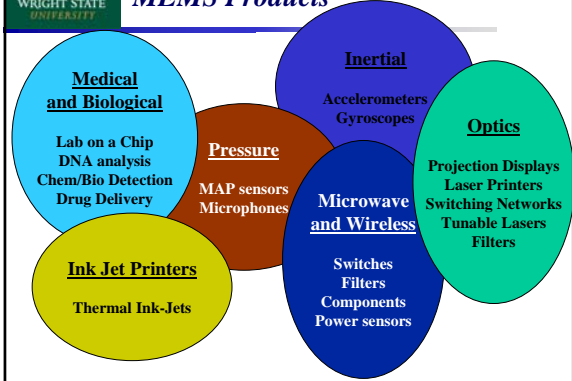
- a technology enabler
- a way to realize applications from all the engineering and scientific fields

You must be open to a multidisciplinary research experience

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MEMS Products



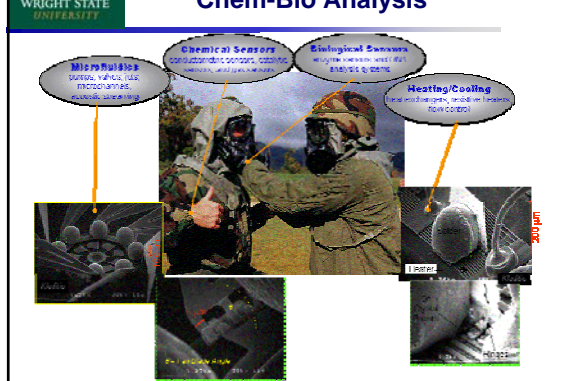
The diagram shows five overlapping circles representing product categories:

- Medical and Biological:** Lab on a Chip, DNA analysis, Chem/Bio Detection, Drug Delivery
- Inertial:** Accelerometers, Gyroscopes
- Optics:** Projection Displays, Laser Printers, Switching Networks, Tunable Lasers, Filters
- Pressure:** MAP sensors, Microphones
- Microwave and Wireless:** Switches, Filters, Components, Power sensors
- Ink Jet Printers:** Thermal Ink-Jets

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Chem-Bio Analysis




Applications in Chem-Bio Analysis:

- Microfluidics:** pumps, valves, mixers, microchannels, multi-well plates
- Chemical Sensors:** conductometric sensors, catalytic, electrochemical, and colorimetric
- Biological Sensors:** enzyme, antibody, aptamer, DNA, antibody & aptamer
- Heating/Cooling:** microfluidics, fluid-on-chip, flow control

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Navigation - Control




Applications in Navigation - Control:

- Force Transducers:** piezoelectric, smart materials, micro-optomechanics
- Flow Sensors:** thermal, differential, resistive, magnetic, pressure, gravimetric
- Rate Sensors:** rate gyroscopes, ultrasonic, digital rotor, electrostatic, reed relay
- Acceleration Sensors:** piezo, piezo-resistive, strain, capacitive, piezoelectric, piezoresistive, piezoelectric
- Aero-hydrodynamics:** flow, microfluidics, microfluidics

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Smart Weapons – Stealth - Safety



Applications in Smart Weapons – Stealth - Safety:

- Biological Chemical:** enzyme, antibody, aptamer, DNA, antibody & aptamer
- Resistive Sensors:** piezoresistive, piezoelectric, piezoresistive, piezoelectric, piezoresistive
- Optical Sensors:** optical, piezoelectric, piezoresistive, piezoelectric, piezoresistive
- Magnetic Sensors:** piezoelectric, piezoresistive, piezoelectric, piezoresistive
- Micro-Optomechanical Systems:** microfluidics, microfluidics

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Communication – Data - Power

Data Storage
High speed, low cost, low power, low latency, reliable data

Optical MEMS
Optics, micro mirrors, gratings, diffractive structures

Power MEMS
Resonators, microactuators, fuel cell actuators

RF MEMS
Switches, capacitors, filters, antennas, resonators, waveguides, variable capacitors, phase shifters, attenuators, modulators, filters, filters, filters and filters, filters

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Measurement - Fabrication

Force/Strain Sensors
Mass, force, stress, pressure, force, force, force

Temperature Sensors
Resistance, capacitance, piezoelectric, piezoresistive, optical

Pressure Sensors
Piezoelectric, piezoresistive, capacitive, piezoelectric/piezoresistive

MEMS Fabrication
Top-down, bottom-up, deposition, etching, lithography, packaging, assembly, characterization, test, packaging

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Applications: Microrobots

Medical Robots
Discover, 1999

Hollow Triangular Beam Robot
UC Berkeley

Thermal Actuator Robot
Kladitis, 1999

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Applications: Microrobots

Polyimide Joint Robot
Ebefors, Royal Institute of Technology, 2000

Electrostatic Scratch Drive Robot
Linderman, CU

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Applications: Optical Communications

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

UC Berkeley

Reid, AFIT

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MEMS Products

Optics

- Projection Displays
- Laser Printers
- Switching Networks
- Tunable Lasers
- Filters

Texas Instruments DLP

Silicon Light Machines
Dynamic Blocking Filter

Lucent - LamdaRouter

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Applications: Automotive

Micromachined Transducer
Applications for Automotive Operation & Safety

D. Thomas Perkin-Elmer

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Applications: Automotive

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

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MEMS Products

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

Inertial Accelerometers Gyroscopes

ADXR5 150

ADXL 050

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Applications: Biology and Medicine

Micromachined Transducer
Applications for Medical Diagnostics & Treatment

D. Thomas Perkin-Elmer

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Applications: Biology and Medicine

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

UCLA

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Applications: Biology and Medicine

- Neural Probes

U. Utah

U. Michigan

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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).

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Applications: Space

- Microsatellites

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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.sensormag.com/articles/070062/main.shtml>

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MEMS Products

Thermal conductivity detector
(http://www.labs.agilent.com/news/2002/features/fea_memts.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

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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)

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Micro Axial Flow Fan

Kladitis and Linderman, 2001

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Micro Axial Flow Fan

- Special scissor hinge design for close to substrate operation

$\theta = \text{Fan Blade Angle}$

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Micro Axial Flow Fan

- Solder Self-Assembly

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Micro Axial Flow Fan

Assembly top and side Operation

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Micro Axial Flow Fan

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

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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

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WRIGHT STATE UNIVERSITY **Mechanical Engineering and MEMS**

- Heat Transfer

Kladitis Solder Self-Assembly

AFIT Electro-Thermal Actuator

Temperature (Kelvin)

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WRIGHT STATE UNIVERSITY **Mechanical Engineering and MEMS**

- Thermodynamics

MEMS-Enhanced Jet Engine

Micro heat fins of nickel rods with posts 150 μm diameter, 500 μm tall, spaced on 1.0 mm centers on a 1.7 cm diameter rod. (LSU)

Acoustic Pressure

Temperature

Vibration

Micro resonant strain gage with over 10,000x sensitivity of metal foil strain gages. Nominal sensitivity 600Hz/μstrain. (UCSB)

MIT Micro Turbine

DARPA

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- Materials Science

ATHENA SILVACO International, Inc

Multilayer Interconnects

MEMS and Microelectronics Material Layers

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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

Doping Densities (cm⁻³)

4 μm 10 μm 20 μm

width

width

width

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

Stoney Equation

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

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

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- 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

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

Poly1 Buckled Beams

Poly2 Buckled Beams

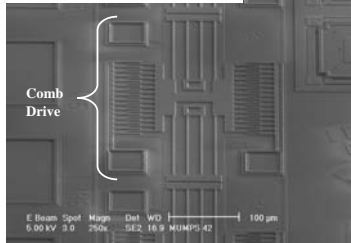
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WRIGHT STATE UNIVERSITY **Young's Modulus Measurement**

Comb Drive Resonator Equation

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

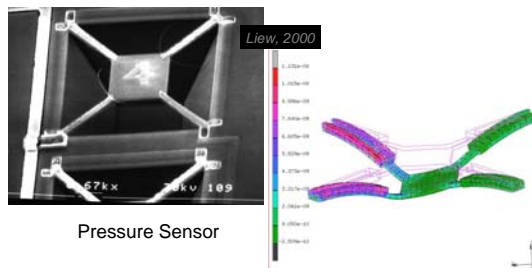
- Measure Resonance
- Obtain Young's Modulus
 - Poly1: 131 GPa
 - Poly2: 162 GPa



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WRIGHT STATE UNIVERSITY **Mechanical Engineering and MEMS**

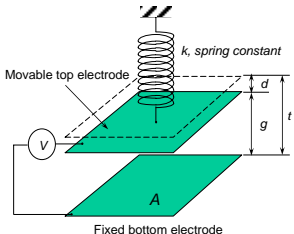
- Solid Mechanics



Pressure Sensor

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WRIGHT STATE UNIVERSITY **Micromirror Schematic**



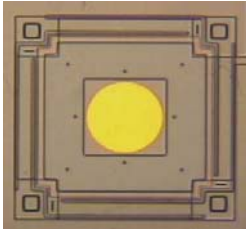
- Induced Raman stress measurements

Mirror deflection

$$d = -\frac{\epsilon_0 AV^2}{2k(h-d)^2} \quad \text{For } d=0 \text{ to } \sim t/3$$

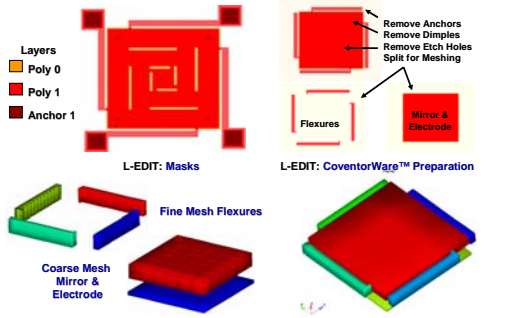
ϵ_0 = dielectric constant of air

Ref: Cowan dissertation 1998



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WRIGHT STATE UNIVERSITY **Coventorware Customized Layout**



Layers: Poly 0, Poly 1, Anchor 1

L-EDIT: Masks, L-EDIT: CoventorWare™ Preparation

Fine Mesh Flexures, Coarse Mesh Mirror & Electrode

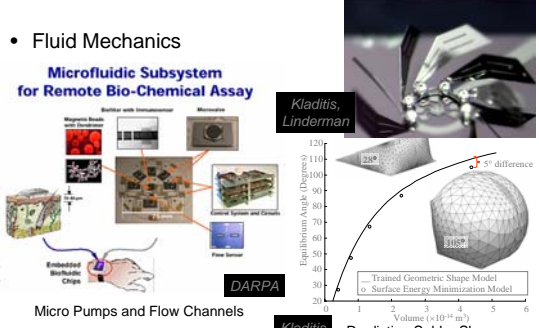
COVENTORWARE™: Custom Mesh, COVENTORWARE™: Merged Mesh

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WRIGHT STATE UNIVERSITY **Mechanical Engineering and MEMS**

- Fluid Mechanics

Microfluidic Subsystem for Remote Bio-Chemical Assay



Kladitis, Linderman

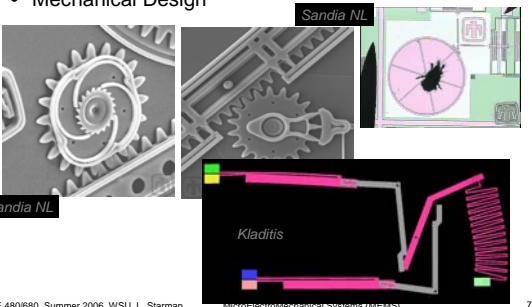
Micro Pumps and Flow Channels

Predicting Solder Shape

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WRIGHT STATE UNIVERSITY **Mechanical Engineering and MEMS**

- Mechanical Design



Sandia NL, Kladitis

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WRIGHT STATE UNIVERSITY Mechanical Engineering and MEMS

- Manufacturing

Packaging a Pressure Sensor

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WRIGHT STATE UNIVERSITY Switch Packaging Approaches (Known Efforts)

- Conventional (Chip-in-box) (<10%)
Dice \Rightarrow release \Rightarrow package or
Dice \Rightarrow package \Rightarrow release
Ceramic / Metal package
- Thin-film Encapsulation (<10%)
Thin-film bubble, cap \Rightarrow
Release through holes \Rightarrow
Seal \Rightarrow Dice
- Wafer Bonding (> 80%)
Release \Rightarrow
Bond cap wafer \Rightarrow Dice
Metal eutectic or Glass frit seal

Approaches

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WRIGHT STATE UNIVERSITY 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

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WRIGHT STATE UNIVERSITY 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

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WRIGHT STATE UNIVERSITY Silicon Nitride Encapsulated Switches

Released switch under nitride cap Nitride cap partially removed showing released switch

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WRIGHT STATE UNIVERSITY Overview

- Definition
- Size Perspective
- Purpose
- Making MEMS
- History
- Applications
- E. E. vs. M. E.
- The Literature
 - Research Topics
 - Conclusions

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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-State Sensors and Actuators* (Transducers)
 - *Micro Electro Mechanical Systems Workshops* (MEMS)
 - *Proceedings of the SPIE – International Society for Optical Engineering*

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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.

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The Literature

- Patents
- Web
 - <http://www.darpa.mil/mto/mems/index.html>
 - <http://www.memsnnet.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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WRIGHT STATE UNIVERSITY

Overview

- Definition
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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

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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

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