**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?

Micro Electro Mechanical Systems (MEMS) are sub-millimeter to centimeter sized mechanical systems with individual features of a few micrometers or less.

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

物理事件 → 处理 → 执行器 → 物理响应

物理事件感测 → 处理 → 执行器 → 物理响应

MEMS 允许我们创建人工系统，它们在同一批量和功能方面类似于昆虫。

例如：
- 一个麦克风将声学输入转换为电信号
- 一个扬声器将电信号转换为声学输出
- 一个手电筒将电信号转换为光

MEMS 允许我们创建人工系统，它们在同一批量和功能方面类似于昆虫。

Micro-Electro-Mechanical System (MEMS)

MEMS 允许我们创建人工系统，它们在同一批量和功能方面类似于昆虫。

Microscopic Machines

MEMS 允许我们创建人工系统，它们在同一批量和功能方面类似于昆虫。

Barcode Scanner

Scanning Micromirror
Fixed Micromirror
VCSEL
What Are MEMS?

Scanning Micromirrors

Applications:
- Beam Alignment
- Bar Code Scanner

Mirror Deflection (deg.)

Voltage

What Are MEMS?

Inputs
- Eyes
- Ears

Sensors

Brains

Circuits

 Outputs
- Hands
- and Mouth

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

Overview

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

Scaling Down to the Small

Sizes of Objects

African Elephant
Height ~ 3.3 m

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

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

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

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

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

Housefly
~ 7.5 x 10^{-3} m

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

Scaling Down to the Small

- Let $S = \text{length scale factor}$, 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 ($t$):
    \[
    F = \begin{bmatrix}
    S^3 & S^2 & S^1 & S^0 \\
    S^2 & S^1 & S^0 & S^{-1} \\
    S^1 & S^0 & S^1 & S^{1.5} \\
    S^0 & S^{-1} & S^1 & S^3 \\
    \end{bmatrix}
    \]
    \[
    a = \begin{bmatrix}
    S^3 & S^2 & S^1 & S^0 \\
    S^2 & S^1 & S^0 & S^{-1} \\
    S^1 & S^0 & S^1 & S^{1.5} \\
    S^0 & S^{-1} & S^1 & S^3 \\
    \end{bmatrix}
    \]
    \[
    t = \begin{bmatrix}
    S^3 & S^2 & S^1 & S^0 \\
    S^2 & S^1 & S^0 & S^{-1} \\
    S^1 & S^0 & S^1 & S^{1.5} \\
    S^0 & S^{-1} & S^1 & S^3 \\
    \end{bmatrix}
    \]
  - Heating or Cooling Time $= S^2$

Overview

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

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.

- 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

Overview

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

Making MEMS

- MEMS were birthed from microelectronics fabrication:
  - IBM InP/InGaAsP high frequency heterojunction bipolar transistor. Institute for Microstructural Science
  - AFIT

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

Overview

- 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 microfabricated microstructure:

History of MEMS

- Suspended Gold Gate (Bridge)
- Source
- Connection to Attraction Plates
- Drain
**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.

**Micro-Motors and Micro-Actuators**

Beginning around 1987

Motors and Actuators can actually change the surrounding environment

**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

**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.
Overview

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

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

- Medical and Biological
  - Lab on a Chip
  - DNA analysis
  - Chem/Bio Detection
  - Drug Delivery
- Inertial
  - Accelerometers
  - Gyroscopes
- Pressure
  - MAP sensors
  - Microphones
- Microwave and Wireless
  - Switches
  - Filters
  - Components
  - Power sensors
- Optical
  - Projection Displays
  - Laser Printers
- Medical
  - Lab on a Chip
  - DNA analysis
  - Chem/Bio Detection
  - Drug Delivery

Chem-Bio Analysis

- Inertial
  - Accelerometers
  - Gyroscopes
- Optical
  - Projection Displays
  - Laser Printers

Navigation - Control

- Inertial
  - Accelerometers
  - Gyroscopes
- Optical
  - Projection Displays
  - Laser Printers

Smart Weapons – Stealth - Safety

- Inertial
  - Accelerometers
  - Gyroscopes
- Optical
  - Projection Displays
  - Laser Printers
Communication – Data - Power

Measurement - Fabrication

Applications: Microrobots

Applications: Microrobots

Applications: Optical Communications

MEMS Products
Applications: Automotive

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

Applications: Automotive

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

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

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

Inertial

Accelerometers

Gyrosopes

ADXRS 150

ADXL 050

Applications: Biology and Medicine

- Neural Probes

Applications: Biology and Medicine

- Neural Probes
**MEMS Products**

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


**MEMS Products**

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

**Applications: Space**

- Microsatellites

**MEMS Products**

- Pressure
  - MAP sensors
  - Microphones

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


**MEMS Products**

- 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)

AFRL Inductor, 2004
AFRL 60 GHz Coupler, 2004
AFRL Digital Varactor, 2004
AFRL 60 GHz Coupler, 2004
AFRL Inductor, 2004

**Micro Axial Flow Fan**

Kladitis and Linderman, 2001

Fan Blade

SDA, Bionic Valve
Micro Axial Flow Fan

- Special scissor hinge design for close to substrate operation

 theta = Fan Blade Angle

Micro Axial Flow Fan

- Solder Self-Assembly

During Reflow
Plate 1
Wettable Area
Wettable Area
Melting Solder
Plate 2
Hinge Location

Equilibrium Position

Micro Axial Flow Fan

- Assembly top and side Operation

Overview

- Definition
- Size Perspective
- Purpose
- Making MEMS
- History
- Applications
- E. E. vs. M. E.
- 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
- MEMS-Enhanced Jet Engine
- Micro Turbine

**Mechanical Engineering and MEMS**

- Materials Science
- Micro Turbine Fabrication
- TSUPREM Dopant Models

**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
  - Doping Densities (cm⁻³)
    - 4 μm: 1.4E20 – 1.5E20
    - 10 μm: 1.5E20 – 1.55E20
    - 20 μm: 1.55E20 – 1.6E20
    - 40 μm: 1.6E20 – 1.7E20
    - 100 μm: 1.7E20 – 1.8E20

- Poly2
  - No Lateral Diffusion
  - Peak Concentration at top and bottom surfaces
  - Overall lower Dopant Concentration
  - Doping Densities (cm⁻³)
    - 4 μm: < 1E19
    - 10 μm: < 2E19
    - 20 μm: < 3E19
    - 40 μm: < 4E19
    - 100 μm: < 5E19

**Wafer Curvature**

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

Stoney Equation

\[ \sigma_f = \frac{E t_f^2}{6(1-v_i)} \left( \frac{1}{t_i} \right) R \]

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

\[ L = \sqrt{\frac{\pi^2 E t_f}{3 \sigma}} \text{ (µm)} \]
Young's Modulus Measurement

Comb Drive Resonator Equation

\[ f = \frac{1}{2\pi} \sqrt{\frac{k}{M}} = \frac{1}{2\pi} \sqrt{\frac{24E_t}{\left(M_2 + \frac{1}{2}M_1 + \frac{1}{3}M_0 \right) L^2}} \quad (Hz) \]

- 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

\[ d = \frac{\varepsilon_0 A V^2}{2k(b - d)} \quad \text{For } d \to 0 \sim \frac{\varepsilon_0}{d_0} \]

\( \varepsilon_0 \) = dielectric constant of air

L-EDIT: Masks

COVENTORWARE™: Custom Mesh

Finesse Mesh Flutes

COVENTORWARE™: Merged Mesh

COVENTORWARE™: : Preparation

Fluid Mechanics

Microfluidic System for Remote Bio-Chemical Assay

Micro Pumps and Flow Channels

Mechanical Engineering and MEMS

- Mechanical Design

Sandia NL
**Mechanical Engineering and MEMS**

- Manufacturing

Packaging a Pressure Sensor

---

**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

---

**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

![Fabriate - Release - Wafer bond](image)

- Chip Scale Package (CSP)

---

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

- **Referred 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

- **Referred 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

The Literature

- **Books**

The Literature

- **Patents**
  - **Web**
    - [http://www.memsnet.org/](http://www.memsnet.org/)
    - [http://www.smalltimes.com/](http://www.smalltimes.com/)
    - [http://www.memscenter.com/memsc](http://www.memscenter.com/memsc)
    - [http://memsrus.com](http://memsrus.com)

- Many of the references are on-line

Overview

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

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
  - Microbots
  - 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**