Self-assembly and Nanotechnology 10.524

Lecture on
Microelectromechanical Systems (MEMS)
& NEMS

Instructor: Prof. Zhiyong Gu (Chemical Engineering)

April 24, 2013
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- Nanoelectromechanical systems (NEMS)
- Example I: Catalytic nanomotors
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MEMS AND Microsystems

Lecturer: Dr. Hongwei Sun
Mechanical Engineering
What is MEMS? Microsystems?

**MEMS:**
Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology.

**Microsystems:**
Engineering systems that could contain MEMS components that are design to perform specific engineering functions.

Micro accelerometer and Comparison with Conventional one (Courtesy of NASA Glenn Research Center)

μChemLab™ by Sandia National Laboratory
Scale of MEMS and Microsystems

Ant with MEMS Gear
Gear: 100um

FIGURE 1.5 Various objects and their linear size.
Microsystems vs MEMS

(Microelectromechanical Systems) MEMS
# Micro/Nano Technology Development

<table>
<thead>
<tr>
<th>Topics</th>
<th>Knowledge Base</th>
<th>Work to Date</th>
<th>Leading Region</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MEMS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Components (for biosensing)</td>
<td>Advanced</td>
<td>Extensive</td>
<td>US ~ Japan ~ Europe</td>
</tr>
<tr>
<td>Integrated systems</td>
<td>Incomplete</td>
<td>Significant</td>
<td>Europe</td>
</tr>
<tr>
<td>Integration of biomaterials</td>
<td>Minimal</td>
<td>Isolated examples</td>
<td>Europe, US</td>
</tr>
<tr>
<td><strong>Micro-fluidics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discrete devices</td>
<td>Advanced</td>
<td>Extensive</td>
<td>US</td>
</tr>
<tr>
<td>Integrated systems</td>
<td>Incomplete</td>
<td>Minor</td>
<td>Europe ~ US &gt; Japan</td>
</tr>
<tr>
<td><strong>Mass sensors</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piezo devices</td>
<td>Advanced</td>
<td>Extensive</td>
<td>None</td>
</tr>
<tr>
<td>Si cantilevers</td>
<td>Incomplete (esp. liquid operation)</td>
<td>Significant (dry) Minor (wet)</td>
<td>US ~ Europe</td>
</tr>
<tr>
<td>Integrated biomaterials</td>
<td>Incomplete</td>
<td>Significant</td>
<td>Europe ~ Japan</td>
</tr>
<tr>
<td><strong>Nano-technology</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Top-down” (nanofab.)</td>
<td>Incomplete</td>
<td>Significant</td>
<td>US &gt; Europe</td>
</tr>
<tr>
<td>“Bottom-up” (molec. organized materials)</td>
<td>Incomplete</td>
<td>Extensive</td>
<td>US, Japan, Europe</td>
</tr>
<tr>
<td>Integration into complex (bio) systems</td>
<td>Incomplete</td>
<td>Little</td>
<td>Europe ~ US</td>
</tr>
</tbody>
</table>


MicroElectroMechanical Systems (MEMS)

- **Scale:** from below 1 µm to above 1 mm
- **Manufacture:** batch fabrication technology
- **Function:** micro -mechanics, -electronics, -fluidics, -optics, ...
Where MEMS is manufactured?

<table>
<thead>
<tr>
<th>class</th>
<th>maximum number of particles per cubic foot of air of diameter greater than or equal to each indicated size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1 µm</td>
</tr>
<tr>
<td>1</td>
<td>35</td>
</tr>
<tr>
<td>10</td>
<td>350</td>
</tr>
<tr>
<td>100</td>
<td>—</td>
</tr>
<tr>
<td>1000</td>
<td>—</td>
</tr>
<tr>
<td>10000</td>
<td>—</td>
</tr>
<tr>
<td>100000</td>
<td>—</td>
</tr>
</tbody>
</table>

- integrated circuits
- miniature ball bearings; photo labs; medical implants
- color TV tubes; hospital operating room
- ball bearings
MEMS Development flowchart

Device/system design: mechanics, electronics, electrostatics, fluidics

System analysis: modeling, simulation

Process design: chemistry and physics of fabrication

Fabrication: clean room

Testing: scope, probe station, SEM, ...
# Common Microfabrication techniques

<table>
<thead>
<tr>
<th>Process Type</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithography</td>
<td>photolithography, screen printing, electron-beam lithography, x-ray lithography</td>
</tr>
<tr>
<td>Thin-Film Deposition</td>
<td>chemical vapor deposition (CVD), plasma-enhanced chemical vapor deposition (PECVD), sputtering, evaporation, spin-on application, plasma spraying, etc.</td>
</tr>
<tr>
<td>Electroplating</td>
<td>blanket and template-delimited electroplating of metals</td>
</tr>
<tr>
<td>Directed Deposition</td>
<td>electroplating, stereolithography, laser-driven chemical vapor deposition, screen printing, transfer printing</td>
</tr>
<tr>
<td>Etching</td>
<td>plasma etching, reactive-ion enhanced (RIE) etching, deep reactive ion etching (DRIE), wet chemical etching, electrochemical etching, etc.</td>
</tr>
<tr>
<td>Directed Etching</td>
<td>laser-assisted chemical etching (LACE)</td>
</tr>
<tr>
<td>Machining</td>
<td>drilling, milling, electric discharge machining (EDM), diamond turning, sawing, etc.</td>
</tr>
<tr>
<td>Bonding</td>
<td>fusion bonding, anodic bonding, adhesives, etc.</td>
</tr>
<tr>
<td>Surface Modification</td>
<td>wet chemical modification, plasma modification</td>
</tr>
<tr>
<td>Annealing</td>
<td>thermal annealing, laser annealing</td>
</tr>
</tbody>
</table>

*Table of example processes used in micromachining.*
MEMS vs. Microelectronics

<table>
<thead>
<tr>
<th>Microelectronics</th>
<th>MEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si, Si compounds, plastic</td>
<td>Si, Si compounds, plastic + polymer, metals, quartz…</td>
</tr>
<tr>
<td>Specific electric functions</td>
<td>Perform electrical, optical, mechanical, biological func.</td>
</tr>
<tr>
<td>Stationary!</td>
<td>Normally include moving parts!!!</td>
</tr>
<tr>
<td>Primarily 2-D structures</td>
<td>Complex 3-D structures</td>
</tr>
<tr>
<td>Complex patterns with high density</td>
<td>Relatively simple pattern</td>
</tr>
<tr>
<td>Non-contact with Media</td>
<td>Sensor is interfacing with contact media</td>
</tr>
<tr>
<td>Mature IC design methodology &amp; standards</td>
<td>Lack of engineering design rule and standards</td>
</tr>
<tr>
<td>Fabrication techniques are mature</td>
<td>Not mature</td>
</tr>
<tr>
<td>Mass production</td>
<td>Custom-needs basis</td>
</tr>
<tr>
<td>Well established packaging technology</td>
<td>Infant stage</td>
</tr>
</tbody>
</table>

Prof. Jiang Zhe, Univ. of Akron
History of MEMS development

History of MEMS

1939  PN-junction semiconductor (W. Schottky)
1948  Transistor (J. Bardeen, W.H. Brattain, W. Shockley)
1954  Piezoresistive effect in semiconductors (C.S. Smith)
1958  First integrated circuit (IC) (J.S. Kilby)
1959  “There’s Plenty of Room at the Bottom” (R. Feynman)
1965  Surface micromachined FET accelerometer (H.C. Nathanson, R.A. Wickstrom)
1967  Anisotropic deep silicon etching (H.A. Waggener et al.)
1977  Silicon electrostatic accelerometer (Stanford)
1979  Integrated gas chromatograph (S.C. Terry, J.H. Jerman and J.B. Angell)
History of MEMS development

History of MEMS

1982  “Silicon as a Mechanical Material” (K. Petersen)
1983  Integrated pressure sensor (Honeywell)
1985  LIGA (W. Ehrfeld et al.)
1986  Silicon wafer bonding (M. Shimbo)
1988  Batch fabricated pressure sensors via wafer bonding (Nova Sensor)
1992  Bulk micromachining (SCREAM process, Cornell)
1993  Digital mirror display (Texas Instruments)
1994  Commercial surface micromachined accelerometer (Analog Devices)
1999  Optical network switch (Lucent)
Successful MEMS Products

- Automotive industry: manifold air pressure sensor, air bag sensor (accelerometer with self-test)

- TI digital mirror display (DMD) video projection system (development cost ~ $1B)

- Inkjet nozzles (HP, Canon, Lexmark) up to 1600 x 1600 resolution (~ 30M units per year)

3. User-refillable cartridges can deliver 10-pl drops with a 10-μm drop-placement accuracy.

[J. Bryzek, 1998]
Applications of MEMS and Microsystems

Automotive applications...
- Linear accel. (air bag)
- Air bag (driver)
- Acoustic (collision)
- Temperature (comfort)
- Pressure (fuel, EGR, O₂, air/fuel)
- Air flow (air/fuel)
- Gyroscopes (navigation)
- NOx (emissions)
- Angular accel. (transmission)

Biomedical...
- Biochips, blood pressure sensing, genetic analysis, proteomics, diagnostics, drug delivery...

Communications...
- Optical switching and routing, relays, wireless communication, information systems...

Aerospace...
- Aircraft, micro-satellites, space exploration...

MEMS/ Microsystems

Disposable lab on a chip (Calyper Technologies, Inc.)

DNA Analysis chip (Fabricated at Danvers MEMS, Inc.)

Micronasaltes (Fabricated at Stanart MEMS, Inc.)

Digital Mirror Device (DMD) Light Switch (Texas Instruments)

Micro-Fresnel Lens (Fabricated at Standard MEMS, Inc.)

MEMS Gyroscope (Fabricated at Standard MEMS, Inc.)
Market of MEMS and Microsystems

Roger Grace Associates

<table>
<thead>
<tr>
<th>Application Sector</th>
<th>2000</th>
<th>2004</th>
<th>CAGR(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IT/Peripheral</td>
<td>8,700</td>
<td>13,400</td>
<td>11.5</td>
</tr>
<tr>
<td>Medical/Biochemical</td>
<td>2,400</td>
<td>7,400</td>
<td>32.5</td>
</tr>
<tr>
<td>Industrial/Automation</td>
<td>1,190</td>
<td>1,850</td>
<td>11.6</td>
</tr>
<tr>
<td>Telecommunications</td>
<td>130</td>
<td>3,650</td>
<td>128.1</td>
</tr>
<tr>
<td>Automotive</td>
<td>1,260</td>
<td>2,350</td>
<td>16.9</td>
</tr>
<tr>
<td>Environmental Monitoring</td>
<td>520</td>
<td>1,750</td>
<td>35.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>14,200</td>
<td>30,400</td>
<td>21.0</td>
</tr>
</tbody>
</table>

*(in Millions of US $)*
MEMS transducers (sensor & actuator)

Detecting signals → MEMS sensor → usable signals

Thermal -- temperature, heat, heat flow
Mechanical -- force, pressure, velocity, acceleration, position
Chemical -- concentration, composition, reaction rate
Magnetic -- field intensity, flux density, magnetization
Optic -- intensity, wavelength, polarization, phase
Electrical -- voltage, current, charge
MEMS transducers (sensor & actuator)

Actuating means

MEMS actuator

Mechanical movement

Thermal force
Shape memory alloy
Piezoelectric crystal
Electrostatic force
Typical MEMS/Microsystems-accelerometer

MEMS sensor:

Micro accelerometer and Comparison with Conventional one (Courtesy of NASA Glenn Research Center)

Deceleration signal → Sensing element → Signal transduction unit → Output signal

Packaging

Power supply
Typical MEMS/Microsystems-accelerometer

- **Purpose:** microchip sensor to detect acceleration
- **Functional Features:**
  - Proof Mass
  - Suspension Arms
  - Substrate with Circuitry
  - Axis of Response
  - **Sensing Function**
  - Capacitive

  Capacitance Varies with Gap Spacing

Conastantine, Friedman & Goldberg
Typical MEMS-based projection system

MEMS transducers:

Digital light processor of Taxes Instrument (TI)
http://www.dlp.com/dlp_technology/default.asp
Typical MEMS/Microsystems- \( \mu \)ChemLab

Microsystems:

Function:
Liquid-phase system: discriminate proteins to detect and identify biotoxins, viruses, and bacterial agents.
Gas-phase system: detection of chemical warfare agents and a selection of toxic industrial chemicals, explosives, and organic solvents.

Components:
The breadboard provides power conditioning and switching, thermal monitoring and control of gas analysis components, analog-to-digital data conversion, fan, pump, and valve control, and operational timing and sequencing. The Gas Module is made up of microfabricated Preconcentrators, Gas Chromatograph separation columns, and Surface Acoustic Wave chemical detectors.

Examples of MEMS and Microsystems- \( \mu \text{ChemLab} \)

Sketch of gas-phase system
Sample collection and concentration units in μChemLab

Micromachined Collection and pre-concentration unit

Micromachined Gas chromatography
SAW sensor in μChemLab

Array of Surface Acoustic Wave (SAW) detector
Examples of MEMS and Microsystems: bioMEMS

other MEMS applications:

**sensors**
- potential, pressure, force, pH, chemistry

**actuators**
- pumps, valves, probes, grippers, ...

**systems**
- Integrated microfluidic platforms
- Lab-on-a-chip systems
Examples of MEMS and Microsystems- Insulin MEMS pump

Diabetes is a medical condition where the body does not manufacture its own insulin. Insulin is used to metabolise sugar and, if it is not available, the person suffering from diabetes will eventually be poisoned by the build-up of sugar. It is important to maintain blood sugar levels within a safe range as high levels of blood sugar have long-term complications such as kidney damage and eye damage. These are not however, normally dangerous in the short-term. Very low levels of blood sugar (hypoglaecemia) are potentially very dangerous in the short-term. They result in a shortage of sugar to the brain which causes confusion and ultimately a diabetic coma and death. In such circumstances, it is important for the diabetic to eat something to increase their blood sugar level.

*Pump size = 6mm x 10mm*
Examples of Microsystems (Lab-on-a Chip)- DNA analysis

DNA analysis

Blood, tissue, etc

Sample prep
- cell lysis
- purification
- concentration

Reagent handling
- pumping/valving
- micromixing

Amplification
- micro PCR

Detection
- optical
- mass spec
- conductometric

Separation
- CE
- LC
- IEF

Labeling
- fluorescent dyes
- radiolabels
- binding events
Examples of Microsystems (Lab-on-a Chip) - DNA analysis

Integrated DNA Analysis

[Diagram showing components: Sample Loading, Fluid Drop Metering, Thermal Reaction, Gel Loading, Separate & Detect, Glass, Silicon, PC Board, Wire Bonds, Air Lines.]

Drawing courtesy of C. Mastrangelo, U. Michigan
Microsystems- DNA detector

• Adsorption of small molecules induces surface stress through electrostatic interactions and steric hindrance, which can bend a cantilever

• This study applied the above principle to DNA fragments, which should only induce significant surface stress if the fragment on the cantilever is a precise match.

Fig. 1. Scanning electron micrograph of a section of a microfabricated silicon cantilever array (eight cantilevers, each 1 μm thick, 500 μm long, and 100 μm wide, with a pitch of 250 μm, spring constant 0.02 N m⁻¹; Micro- and Nanomechanics Group, IBM Zurich Research Laboratory, Switzerland).

Prof Jiang Zhe U. of Akron
Examples of MEMS and Microsystems - DNA detector
Books and references

MEMS books:

2. Chang Liu, *Foundation of MEMS*, 2005
MEMS website and Journals, conferences

Website:  http://www.memsnet.org/

Journals:  Journal of Microelectromechanical System (J.MEMS)  
(IEEE/ASME)  
Sensors and Actuators (ELSEVIER)  
Journal of Micromechanics & Microengineering  
And more

MEMS companies:  http://www.memsnet.org/links/ (hundreds of companies)

Conferences:
1. Hilton Head, Solid-State Sensors, Actuator, and Micrsystem Workshop, Transducer Research Foundation
2. International MEMS conference (IEEE)
3. Micro Total Analysis System (uTAS)
And more at http://home.earthlink.net/~trimmerw/mems/Conferences.html
Website:  http://www.memsnet.org/
Nanoelectromechanical Systems (NEMS)
NEMS or nanoelectromechanical systems are similar to MEMS but smaller. They hold promise to improve abilities to measure small displacements and forces at a molecular scale.

There are two approaches most researchers accept as standard paths to NEMS. The top-down approach can be summarized as "a set of tools designed to build a smaller set of tools". For example, a millimeter sized factory that builds micrometer sized factories which in turn can build nanometer sized devices. The other approach is the bottom-up approach, and can be thought of as putting together single atoms or molecules until a desired level of complexity and functionality has been achieved in a device. Such an approach may utilize molecular self-assembly or mimic molecular biology systems.

A combination of these approaches may also be used, in which nanoscale molecules are integrated into a top-down framework.

From Wiki

Self-assembly and Nanotechnology
Schematic of surface micromachining approach used to nanofabricate NEMS devices. The pattern shapes are created by a scanning electron beam (E-beam) exposing a polymeric polymethylmethacrylate (PMMA) resist. The motion may be actuated by applying a voltage between the electron on the moving element and the electrode on the substrate.

Self-assembly and Nanotechnology  
Science 2000, 290, 1532
NEMS and E-beam Lithography

Electron micrograph of NEMS objects fabricated in single-crystal silicon by using electron beam lithography and surface micromachining. (A) A torsional oscillator from (15), (B) a compound torsional oscillator, (C) a series of silicon nanowires from (16), and (D) an oscillating silicon mesh mirror

*Self-assembly and Nanotechnology*  
Science 2000, 290, 1532
Carbon Nanotube Nanomotor

Rotational bearings based upon multiwall carbon nanotubes. By attaching a gold plate (with dimensions of order 100nm) to the outer shell of a suspended multiwall carbon nanotube, they are able to electrostatically rotate the outer shell relative to the inner core. These bearings are very robust; Devices have been oscillated thousands of times with no indication of wear. The work was done in situ in an SEM. These nanoelectromechanical systems (NEMS) are the next step in miniaturization that may find their way into commercial aspects in the future.

Nanomotor constructed at UC Berkeley. The motor is about 500nm across: 300 times smaller than the diameter of a human hair.
Carbon Nanotube Nanomotor

a) Schematic motor layout. R: nanotube-suspended metal plate rotor
A1, A2: anchors; S1,S2,S3: stators

b) SEM image of completed nanomotor

(Fennimore, Yuzvinsky, Zettl et al, Nature 2003)
Nanotube Rotational Bearing

Self-assembly and Nanotechnology
Ultrahigh Frequency Nanotube Resonators

Amplitude (in logarithmic scale) and phase of the electrical current in a vacuum 106 Torr (triangles) and in air (circles) for a nanobridge resonator made from coating a bare suspended CNT device with 2.5 nm indium. The data were taken at $V_{g0}$, $V_{g12}$mV, and $V_{d}$ 46 mV by the $I^I$ method.

Self-assembly and Nanotechnology

PRL 97, 087203 (2006)
Example I: Self-Propelled Nanorotors

Schematic of nanobarcodes synthesis. (a) Gold sputtering onto an alumina membrane. (b) Electrodeposition of gold plugs. (c) Electrodeposition of a sacrificial layer of copper. (d) Electrodeposition of nickel segment. (e) Electrodeposition of gold segment. (f) Selective dissolution of alumina. (g) Selective dissolution of copper.


Self-assembly and Nanotechnology
Self-Propelled Nanorotors

(a) Optical microscope snapshots of a nanorod rotating counterclockwise. (b) Optical microscope snapshots showing the dynamics of a suspended nanorod with a near-linear movement followed by tethering to a surface impurity that induces a circular movement.

Example: Catalytic Nanomotors


Self-assembly and Nanotechnology

An SEM image at 35000 magnification of 1.5 mm 400 nm striped metallic rod. Respective segment sizes (nm): Au, 350; Ni, 100; Au, 200; Ni, 100; Pt, 550.

Catalytic Nanomotors


Self-assembly and Nanotechnology
Catalytic Nanomotors

Microfabricated gold “gears” with platinum on one side of each of the teeth. The result is the counterclockwise rotation of the structure when placed in hydrogen peroxide solution.

Self-assembly and Nanotechnology  
Self-Assembly of Electronic Systems

Millimeter scale


200 μm scale


Self-assembly and Nanotechnology
Self-Assembled Self-folding Micro-Containers


Self-assembly and Nanotechnology
Self-Assembled Self-folding Micro-Containers

Self-assembly and Nanotechnology
Self-Assembled Self-folding Micro-Containers

Leong, Gu, Koh, Gracias. JACS 2006, 128, 11336-11337
Self-Assembly of Nanowires


Magnetic assembly

Self-Assembly of Nanowires

Large scale bundles during membrane dissolution

“Glued” 3D bundles

“Glued” 2D networks

Self-assembling route to Nanotechnology

A flowchart delineating the factors that must be considered when approaching the self-assembly of a nanoscale system

Nanorobots for Medicine (Surgery)

The depicted blue cones shows the sensors “touching” areas that triggers the nanorobots’ behaviors.
The atherosclerotic lesion was reduced due nanorobots activation. The temperatures in the region turn in expected levels.
Next Lecture on May 1 – Last Lecture!

- May 1 (3:30-6pm): 1st half of final presentations (alphabetical order): 16 students

- May 7 (final exam time: 3-6pm): 2nd half of final presentations (alphabetical order): 17 students

- May 7: Final report due (by emails)

- Room: KI302

Self-assembly and Nanotechnology