Introduction to Microelectromechanical Systems (MEMS)

Lecture 15 Topics

- The Future of MEMS
  - Micromechanical Computation
  - MEMS Security Lock
  - MEMS in Space
  - Ubiquitous MEMS
  - Biomedical MEMS Applications

MEMS Overview

- Micromachining: lithography, deposition, etching, …
Mechanical Computation

Issues:

• Low robustness of CMOS to radiation and temperature changes
• MEMS relays for sufficiently high voltages / currents to switch themselves
• Fan-in / fan-out at least 2
• Micro relays: contacts and sticking, isolation, switching speed

[Kruglick and Pister Transducers 1999]
MEMS Security Lock

Sandia National Labs
Intelligent Micromachine Initiative
www.mdl.sandia.gov/

MEMS security lock:
- 24 bit code needs to be entered to trigger optical switch
- Fits into missile war head

MEMS Security Lock

24 bit lock mechanism
MEMS Security Lock

Pin traversing the 24-bit maze

Anti-reverse mechanism

Elevated micro mirror
MEMS in Space

Issues:

• Propulsion
• Navigation: accelerometers, gyroscopes, GPS
• Remote Sensing: spectrometers, chemical sensors, ...
• Communication: wireless, optical

Fig. 1. Digital micro-Propulsion micro-Spacecraft Array (AeroSpace Corporation [1]).

MEMS in Space

• Digital Micro Propulsion: 1M thrusters on wafer, 0.1 mNsec impulse, 100 W power

[Lewis et al. MEMS 1999]

Fig. 3. Configuration of the Digital Propulsion micro-Thruster Chip.

3 x 5 Thruster array

Fig. 5. Top View of a Portion of a Diaphragm Layer Wafer, Containing Six Dice and Showing Three Different Sizes of Burst Diaphragms.
Micro Pyrotechnics

Medical application:
High pressure from micro explosion delivers drug from capillary into skin.

Current technique:
Iontophoresis (non-invasive drug delivery through skin with electrical current).

Future technique:
Pyrotechnic micro-syringe. Transdermal drug delivery with micro explosion.

Injection system suitable for transdermal drug delivery device (3 pyrotechnic microactuators)

MEMS in Space

Micro Turbines [C.-C. Lin et al., MEMS 1999]

Figure 1. Exploded view of the micro-bearing rig. The five layers are: 1. Forward foundation plate (FFP), 2. Forward endplate (FEP), 3. Rotor plate (RP), 4. Aft endplate (AEP), and 5. Aft foundation plate (AFP).

Figure 2. Schematic cross-sectional drawing indicating the location of the bearings and the SEM of the actual device cross-section.
Invisible Computing is a term invented by Donald Norman to describe the coming age of ubiquitous task-specific devices that combine computation, communication, sensing, and actuation. The devices are so highly optimized to particular tasks that they blend into the world and require little technical knowledge on the part of their users.

It is likely that these devices will cause a major paradigm shift away from the PC and towards distributed, smart appliances. They will interact with their environment (and with themselves) in a multitude of ways. Therefore, sensors, actuators, and transceivers will constitute an integral part in their design. Recent developments in MEMS will constitute some of the underlying technologies: MEMS devices, sensor networks, and distributed and mobile computation.

Hardware components:
- Arrays and networks of micro sensors and actuators
- Wireless MEMS
- Distributed and reconfigurable networks

Boriello et al, UW CSE & Xerox PARC
[www.cs.washington.edu/research/portolano](http://www.cs.washington.edu/research/portolano)
Invisible Computing Scenario

- Alice begins the day with a cup of coffee and her personalized newspaper. When her carpool arrives, she switches to reading the news on her handheld display, where she notices an advertisement for a new 3-D digital camera. It looks like something that would interest her shutterbug-friend Bob, so Alice asks her address book to place the call.

Invisible Computing Scenario

- Bob's home entertainment system softens the volume of his custom music file as his phone rings. Alice begins telling Bob about the camera, and forwards him a copy of the advertisement which pops up on his home display. Bob is sold on the product, and after hanging up with her, he asks his electronic shopping agent to check his favorite photography stores for the lowest price and make the purchase.
Invisible Computing Scenario

- When the camera arrives, Bob snaps some photos of his neighbor’s collection of antique Portuguese navigation instruments. After reviewing the photo album generated automatically by a web-based service, Bob directs a copy of his favorite image to the art display in his foyer. He also sends a pointer to the photo album to Alice and instructs his scheduling agent to set up a lunch date so that he can thank her for the suggestion.

Bio MEMS

- Minimally invasive microsurgery instruments
- In vitro and in vivo experiments at cellular scale
- Implantable sensors and computers for health monitoring, prostheses, and human augmentation
  - Cochlear implants
  - Retinal implants
  - Neuronal implants
- DNA amplification (PCR)
- Gene Probe Arrays
- Biometrics
DNA Replication

From Genentech, Inc.
www.gene.com

DNA Amplification

Polymerase Chain Reaction (PCR):
invented 1983 by Kary B. Mullis (Nobel Prize 1993)
allows replication of selective DNA sequences

PCR goes through a number of cycles of “DNA amplification.” After each cycle, the quantity of the target DNA subsequence doubles (while all other DNA remains the same).

Key: thermo-stable polymerase (DNA copying enzyme) extracted from Thermus aquaticus (taq), Yellowstone

30 cycles result (theoretically) in a 1 billion-fold amplification.
Polymerase Chain Reaction

Recipe:
- Primers (to select DNA target sequence)
- DNA polymerase (DNA copying enzyme)
- Thermocycle:
  - A few minutes at 94-96°C (DNA denaturizes into single strands)
  - A few minutes at 50-65°C (primers anneal to their complementary strands)
  - A few minutes at 72°C (polymerase binds and extends a complementary DNA strand from each primer)

Applications:
- Genetic tests, mutation detection, genetic fingerprinting
- Detection of bacterial or viral infections
- Forensic tests, evolutionary biology
- ...
MEMS for PCR

Advantages of downscaling PCR systems:

- More rapid thermocycles and higher gain through reduced thermal mass and high thermal isolation
- Disposable systems (no cleaning, no drift)

[Northrup et al 1993]

MEMS for PCR

Hardwired PCR thermocycles

[μTAS 1998]
MEMS Integrated PCR

Coming soon:

Fully integrated handheld PCR system with optical interrogation and fluorescent detection

[From Cepheid, Inc., www.cepheid.com]

Nucleic Acid Hybridization

[Diagram of nucleic acid hybridization]
Affymetrix GeneChip

Probe Array Synthesis Process

Incyte DNA Microarrays

- 10,000 genes / array
- Glass substrates, deposit
- Teamed with Stanford
Heart Cell Force Sensor

Micro clamps fabricated in standard CMOS with XeF$_2$ back-end release etch

Overhanging clamps folded out over edge of chip with Al hinges

SEM picture of device with clamps, Wheatstone bridge, amplifier, and wirebonds to Quartz package. [G. Lin et al. 1997 (UCLA)]

Heart Cell Force Sensor

Experimental results:
• Spring constant $k \approx 10$N/m
• Deflection $\approx 2$µm
  force $\approx 20$µN

Optical micrographs before (top) and after (bottom) deflection [G. Lin et al. 1997]
Heart Cell Force Sensor

Calibration curve (manual deflection with optical measurement)

Response to change in calcium concentration

[G. Lin et al. 1997]

Overview

• Recording, interpreting, and stimulation of neural activity in live, freely-behaving animals

• Closing the gap between electronic and biological information processing

Tritonia diomedea (marine mollusk native to Pacific Northwest)

Neural microprobe (bio-interface)

Microprocessor (silicon electronics)
Motivation

• Recent rapid developments at the intersection of MEMS, biology, and information technology
• “Bio:Info:Micro”

Long-term goals:
- Modeling of neural information processing
- Biologically inspired computers
- Neural prostheses

Bio-Implant Team At The University of Washington

• Karl Böhringer and Yael Hanein (Electrical Engineering): MEMS, microfabrication
• Thomas Daniel (Zoology): dynamic models of insect flight
• Denice Denton (Electrical Engineering): thin film technology and biocompatibility
• Chris Diorio (Computer Science & Engineering): silicon electronics, biologically inspired computing
• Buddy Ratner (Bioengineering): surface modification and biocompatibility
• Dennis Willows (Zoology): intracellular neural preparations, neuroscience
Overview

- Related Work: MEMS and Biomedical Microsystems
- Background
- Intracellular preparations
- Fabrication
- Surface modification and biocompatibility
- Data compression
- Conclusions

Related Work

- **MEMS: Microelectromechanical Systems**
  - Explosive growth in micro sensors, micro optics (“digital mirror display”), biomedical instrumentation (“DNA chips”, “lab on a chip”)
- **Biomedical microsystems**
  - Cochlear implants
  - Retinal implants
  - Biomedical monitoring system
  - Intercellular probes
- **Focus here on microelectrodes at electronic/ionic (silicon/biology) interface**
Cochlear Implants

Human hearing: the cochlea - a mechanical spectrum analyzer
Hair cells in cochlea transduce sound (mech. vibration) into nerve signals
Cochlear implants bypass damaged hair cells

Note: artificial cochlea by Haronian and MacDonald 1995

Image source: Advanced Bionics Corporation

Retinal Implants

- Visual prosthesis situated on retinal surface
- Direct stimulation of visual nerves (bypassing rods and cones)
- Restore partial vision for - Retinal pigmentosa - age-related macular disease
**Electrochemical µSensors**

- Disposable bioanalyzer cartridges for point-of-care and field-portable biochemical instrumentation
- Programmable, reconfigurable system for detection of bacterial and viral pathogens
- Low-cost integrated electrode arrays for chemical sensing and voltammetry

Collaboration of
- University of Washington
- Micronics Inc., Redmond WA
- Saigene Co., Redmond WA

Microfluidic disposable cartridge for blood analysis.
*Image source: Micronics Inc.*

**Neural Microprobes**

- Monitor neuronal signaling at the cellular level
- Stimulate neuronal activity (also: muscle activity)
- Closed-loop application: functional neuromuscular stimulation (FNS)

- Neuronal action potentials
- Extracellular (near neuronal tissue): ±50 µV
- Intracellular (inside individual neuron): -70 mV ... +30 mV
Design Issues

- **Size**
  Tips at same scale as probed objects

- **Power**
  Energy consumption: batteries, wireless link - lifetime; heat dissipation - safety

- **Functionality**
  Amplification, encoding, filtering, compression

- **Biocompatibility**
  “harsh environment,” packaging and sealing

- **Stability and Reliability**

- **Cost**
  
  [Najafi 1997]

Micromachined Silicon
Extracellular Microprobes

Exploring the central nervous system at the cellular level.

[Najafi and Wise (U. Michigan)]
64-site Multiplexed Stimulating Probe Array

Micromachined with On-Chip CMOS Electronics
Stimulation and Recording Modes
400μm Site Separations, Extendable to 3D Arrays
Key to Neural Prostheses for use in the Central Nervous System

[Kim and Wise 1994 (University of Michigan)]

Three-Dimensional Probe

Probe Shanks With Four Sites per Shank

[Hoogerwerf, Bai and Wise 1990 and 1994 (University of Michigan)]
Recording From Rat Somatosensory Cortex

[Bower and Kovacs 1997 (CalTech/Stanford)]

Commercial Microelectrode Arrays

Silicon multi-tip probes for chronic implants in mammals.

Source: Bionic Technologies Inc.
Intracellular Recording in Freely Behaving Animals

**Novel approach:**
- Intracellular recording: higher data quality
- Freely behaving animals in natural environment: data realism

**Goals:**
- Self-contained implantable microsystem
- Long-term recordings:
  10 - 100 sites for several days

---

**Intra vs. Extra Cellular Recording**

Extracellular and intracellular recordings from a single reidentifiable neuron of Tritonia (Pedal 5).

(A) Intracellular: 3 orders of mag. higher dynamic range; extracellular: no data on action potential shape or resting pot.

(B) Intracellular: post-synaptic potentials clearly visible

(C) Extracellular: noise from other neurons obscures data

(D) Shape of single action potential in larger time scale

Scale bar:
(A, C) Extracellular: 25µV, 5sec; Intra: 25mV, 5sec.
(B) Extracellular: 10µV, 5sec; Intra: 10mV, 5sec
(D) Extracellular: 25µV, 0.2sec; Intra: 25mV, 0.2sec
Tritonia Diomedea

A large sea slug:
- Natural habitat Pacific Northwest
- Has been studied for many years at UW Friday Harbor Labs
- Among the largest neurons (up to 500 µm) but also small neurons (5 µm)

Tritonia Surgery

Implant procedure: Tritonia is suspended in a salt water tank during surgery (performed by D. Willows, University of Washington, Friday Harbor Laboratories)
System Architecture

Intracellular neuronal recording system: Stand-alone implantable microsystem with probe tips, amplifier, semicustom microcontroller, A/D conversion, data compression and storage.

Microfabrication Process (version 1, part 1)

• Patterning of Si substrate with photoresist

• Dicing of 200 µm – 300 µm grooves

• Isotropic reactive ion etching (RIE)
Microfabrication Process (version 1, part 2)

- Sputtering of thin films: Cr/Au and Si$_3$N$_4$
- Photoresist spin-on; back etch to expose tip; removal of Si$_3$N$_4$
- Removal of photoresist
- Electroplating of Ir or Pt black

Simulation of Processing (version 1)

- RIE (Reactive Ion Etching) process simulated with ATHENA software package
Preliminary Results (version 1)

- Pedestals are 300µm tall and 250 µm x 250 µm at the base
- Needles are up to 80 µm tall, with tip diameter < 1 µm

Microfabrication Process (version 2)

- Dicing with saw
- RIE SF₆ etch
- Continue with metallization and passivation as in v. 1
- Note: no lithography
- Challenge: through holes for multiple contacts
Preliminary Results (version 2)

• 300 µm tall Si needles achieved with partial dicing and RIE

Fabrication Alternatives

• Dicing and wet etching of Si (see extracellular needles fabricated at the University of Utah)

• Surface micromachined probes

• LIGA process (Alf Morales, Sandia Livermore)

Wet etching of diced pedestals (University of Washington 2000)
Biocompatibility

- **Short term**
  - Protein adsorption
  - Clogging with cells
  - Immune response
  - Inflammation

- **Long term**
  - Encapsulation
  - Mutagenesis

Implanted Electrodes

- Interface between electronic and ionic conduction
- Small intracellular electrodes: bottleneck
- During implant experiments, protein and cell clogging occurs often within seconds and increases resistivity by orders of magnitude
Non-Fouling Micromachined Coatings

A cell pattern achieved by culturing bovine aortic endothelial cells on and silicon nitride surface with pp4G pattern (200x magnification). Despite the multilayer formation of these cells on silicon nitride, they remained within the boundary of silicon nitride.

A fluorescence microscope image (100x magnification) from a protein adsorption experiment on a patterned pp4G and SiO₂ surface. Adsorbed proteins yield green fluorescence. Adsorbed proteins covered exposed SiO₂ while pp4G coated areas resisted protein adsorption. The Au squares also appeared dark due to the well-known fluorescence quenching effect of Au.

Biocompatible Electrode Thin Film Coatings

• Polyethylene glycol like coatings: plasma polymerized tetruglyme (pp4G) (CH₃-O-(CH₂-CH₂-O)₄-CH₃)

(a) Electroplated platinum electrodes (dark squares) with PP4G coating on silicon nitride surface. The two smallest electrodes ((b) bare and (c) coated) after 24 hours in a medium solution with Bovine Aortic Endothelial cells.
Resistivity Measurements

(a) AC conductivity of bare electrodes in a medium solution with 10% FBS.
(b) The conductance at 10 Hz of bare and coated electrodes (stars and triangles respectively) in a medium solution with 10% FBS.

Coping with Neural Data

- Goal: 16 bit data @ 2kHz (per site) for 24h
- Assume 10 sites, 32Mbit RAM, 20 spikes/min
- Without compression: 1.5min recording

- Data compression:
  - Template encoding for spikes
  - Run-length encoding for non-spikes
    compression must be done on-the-fly with low-power processor
- Requires at least 800:1 compression
The Data

- Cell voltage is sampled at 2000Hz, 16 bits
- 99% non-spike area, 1% spikes
- Much similarity between separate spikes
- Important information is in spike timing, spike shape, and general baseline movement

Algorithm Overview

- Templating for spikes
- Run Length Encoding for non-spikes
- Achieves Compression Ratio > 800
- Allows recording for 36 hours
- Lossy, but with low error
**Template Instantiation**

![Diagram showing template instantiation with measurements for time since last spike, absolute height, template 1 and 2 index, baseline 1 and 2, and widths 1 and 2.]

**Template Instancing**

- Conservatively uses a 10% error margin

<table>
<thead>
<tr>
<th>Category</th>
<th>Entropy</th>
<th>Estimated Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td>12.27</td>
<td>14</td>
</tr>
<tr>
<td>index 1</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>index 2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>width 1</td>
<td>4.65</td>
<td>6</td>
</tr>
<tr>
<td>width 2</td>
<td>5.86</td>
<td>6</td>
</tr>
<tr>
<td>baseline 1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>baseline 2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>height</td>
<td>3.64</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>37.42</td>
<td>41</td>
</tr>
</tbody>
</table>
Experimental Results

Effect of Template Parameterization
(Unlimited Sized Dictionary)

- Width Scaling
- Vertical Offset
- Dual Scaling
- Split Templates
- Height Scaling

Non-Spike Encoding

- Use Run Length Encoding (RLE):

...49 49 49 50 50 50 49 49 49 49 49 48...

\[
\text{length value} \quad \ldots 3 49 4 50 5 49 \ldots
\]

\[
\text{length delta} \quad \ldots 3 1 4 -1 5 -1 \ldots
\]

- Lengths and deltas are Huffman Coded
- CR=20 0.40 bits/sample
## Final Results

<table>
<thead>
<tr>
<th>Category</th>
<th>Evaluation Set Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Spikes</td>
<td>2228</td>
</tr>
<tr>
<td>Templates 1</td>
<td>38</td>
</tr>
<tr>
<td>Templates 2</td>
<td>28</td>
</tr>
<tr>
<td>Spike PRD</td>
<td>8.70%</td>
</tr>
<tr>
<td>Hours at this rate for ten probes</td>
<td>36.3 (CR=815)</td>
</tr>
<tr>
<td>Compressed Data Sizes</td>
<td>(Kbits)</td>
</tr>
<tr>
<td>RLE deltas</td>
<td>57 (17.5%)</td>
</tr>
<tr>
<td>RLE lengths</td>
<td>169 (51.6%)</td>
</tr>
<tr>
<td>Template Storage</td>
<td>8 (2.5%)</td>
</tr>
<tr>
<td>Template Instancing (estimated)</td>
<td>93 (28.4%)</td>
</tr>
</tbody>
</table>

**Diagram:**
- **Exact Peaks**
- **Non-Spike RLE**
Other Current Work

- Implant Procedures
delivery of microprobe chip into biological tissue

- System Integration
power management, assembly and wiring, packaging
Conclusions

- MEMS provides new possibilities for microfabricated systems for bio-informatics
- Goal: Intracellular recording and stimulation in live, freely behaving animals
- Biocompatible coatings for electrodes
- Data compression: 1000:1 with custom algorithms
  - 1MHz processor / 32Mbit memory
- Long-term benefits, including:
  - Advances in neuroscience
  - Neural implants and prostheses
  - Biologically inspired computing

Tritonia Diomedea

Copyright: J.A. Murray
Tritonia Diomedea
(Sea Slug)

Tritonia Brain

Approximately 10,000 neurons
Each up to 0.5 mm in diameter

7 mm
Further Reading on MEMS

Books
- Senturia 2000 MEMS Design
- Maluf 2000 Non-technical introduction
- de los Santos 1999 RF and Microwave MEMS
- Kovacs 1998 Extensive reference book
- Madou 1997 General introduction

Journals
- ASME/IEEE Journal of Microelectromechanical Systems
- Sensors and Actuators A (Physical)
- Journal of Micromachining and Microengineering
- Other application-specific journals

Conferences
- IEEE MEMS Workshop (annually)
- International Conference on Solid State Sensors & Actuators - “Transducers” (odd years)
- Solid State Sensor & Actuator Workshop - “Hilton Head” (even years)
- Eurosensors (annually)
- Micro Total Analysis Systems - “µTAS” (even years, now annually)
- IEEE/LEOS International Conference on Optical MEMS - “MOEMS”