Microelectromechanical Systems (MEMS)

Roger T. Howe

Dept. of Electrical Engineering
Stanford University

CS114 Guest Lecture May 11, 2020
Outline

- **Background and Stanford History**

- **Core Technologies**
  - *Structures*: fabrication and design of diaphragms, beams, ...
  - *Transduction*: moving energy between domains
  - *Electronics*: dealing with tiny signals
  - *Encapsulation*: taming surface phenomena

- **Whither MEMS?**
  - The MEMS Industry in 2022
  - New challenges: MEMS inside CMOS, intelligent structures for soft robotics
MEMS: Devices with microscale dimensions (30 nm – 300 μm), typically made using “wafer fabrication” – the tools and processes developed by the semiconductor industry.

Micro Electro Mechanical Systems

Wafer fabrication

Energy conversion: electrical to and from non-electrical domains

Ultimate goal: solutions to real problems, not “just” devices
The **DENSO Micro-Car** is a miniature version of Toyota's first passenger car, the 1936 Model AA sedan. Its size is astounding: 1/1000th the size of the actual car or about the size of a grain of rice. Dimensions are: 4.785 mm X 1.73 mm wide X 1.736 mm tall.

The Micro-Car has a total of 24 parts which come in 13 different types including body, tires, spare tire, wheels, axle, bearings, headlights, rear lights, front bumper, rear bumper, step, number plate and emblem. A 0.67 mm-sized magnetic motor consisting of five different parts including a magnet and core powers the tiny car. When supplied with 3V, 20 mA of AC current through an 18-micron-diameter copper wire, the motor reach 600 rpm.

“microtechnology demonstrator” circa 1994

http://japanesenostalgiccar.com/the-worlds-smallest-car-is-a-toyota-aa/
Wafer Fabrication

Thin film: typically less than 1 μm thick

Silicon wafer (750 μm thick)

(i) coating with photoresist

softbake

photoresist

mask

alignment

mask glass

UV

stripping

after repeating many times ...
Making More than Circuits

To make 3D structures, several techniques have been developed as extensions of wafer processing.
How did this field get started?

- At a welcome breakfast for Medical School faculty in 1960, who had just moved from San Francisco to Stanford
- Thomas Nelsen (Surgery) asked Jim Angell (EE) about an article he’d read about “miniature electronics” – he wondered if the technology could be used to make biomedical implantable devices.
- The question at breakfast led to a decade-long collaboration that led to the first silicon smart sutures and implantable pressure sensors.
Silicon Implantable Devices

Silicon “smart suture” with built-in force-sensing resistor

Silicon diaphragm pressure sensor

Pressure sensor on catheter tip

T. S. Nelsen and J. B. Angell, 1960s
What Next?

- Heart pacemakers had been invented and first used in patients in 1958 by researchers in Sweden.
- A major drawback was that the pacemaker had a single pace, whatever the patient was doing – sleeping or running up stairs.
- In the early 1970s, Jim Angell and his graduate student, Lynn Roylance, developed the concept of incorporating an activity monitor into the pacemaker … how to do that?
Miniature Silicon Accelerometers

Strain-sensing resistors are built into the suspension beam.

Cross section of the accelerometer

Pacemakers with silicon accelerometers were finally introduced in the 1990s.
Neural Probes

First silicon recording probe, 1968

Four channel stimulating probe, 1971

Neural voltage recording

Ken Wise and Jim Angell, Stanford EE
Outline

- Background and Stanford History
- Core Technologies
  - *Structures*: beams, diaphragms, and mechanisms
  - *Transduction*: moving energy between domains
  - *Electronics*: dealing with tiny signals
  - *Encapsulation*: taming surface phenomena
- Whither MEMS?
  - The MEMS Industry in 2022
  - New challenges: MEMS inside CMOS, intelligent structures for soft robotics
Surface Micromachining

Basic Requirement:

Selective etching of the sacrificial layer without attacking the structural layer … or other layers on the substrate.

Polysilicon Microstructures

R. T. Howe and R. S. Muller 1983

C. T. Nguyen and R. T. Howe 1993

Bosch Sensortech accelerometer


Analog Devices rate gyroscope
Polysilicon Lateral Resonator

Polysilicon Resonator in Action

DC + AC voltage on interdigitated comb causes electrostatic force on shuttle.

William C. Tang and R. T. Howe, Dept. of EECS, UC Berkeley
Texas Instruments Digital Mirror Device

Spring tip $\approx$ 50-60 nm amorphous TiAl$_3$-O(4%)

Yoke TiAl$_3$-N(2-4%): low strain gradient

Not shown: the mirror on top of the yoke

> 1,000,000 mirrors per chip

The Electret Microphone

The electret microphone was invented at Bell Labs in 1962 by James West and Gerhard Sessler, who discovered that a thin metallized teflon foil could be polarized to create a long-lasting electric dipole moment ... dominates market by 1970s.

\[ Q_{\text{electret}} = \text{constant}, \quad C_{\text{mic}} = f(\text{sound pressure}) \rightarrow \quad V_{\text{mic}} = V_G(t). \]

Why Replace the Electret Microphone?

- Electrets depolarize at the temperatures required by RoHS*-compliant (lead-free) solder
- Package is incompatible with electronic automated assembly equipment, so it must be hand-soldered \(\rightarrow\) expensive to re-work. Multiple microphones per mobile device (e.g., for background noise cancellation) make this problem worse
- CMOS audio signal processing chip can’t be integrated into an electret microphone package

Result: rapid adoption of MEMS microphones, *once they were technically feasible*

*RoHS = Restriction on Hazardous Substances Directive, EU– 2002/95/EC*
Free-Floating Polysilicon Diaphragms

Microphones require *stress-free* diaphragms:

**Solution:** complete release of diaphragm: support posts and dimples keep it from floating away from the substrate

Polysilicon Capacitive Microphone

10 mask process, 1.6 mm x 1.6 mm die size, 200 mm wafers
→ 46,000 dice/wafer at 100% yield (circa 2012)
Wafer cost ~ $1000/wafer  ⇒  cost/die ~ 2.1 ¢

5 x 10⁹ microphones/year, Knowles has roughly 25% of the market
→ production rate: 34 x 10⁶ per day

(only around 740 wafers/day)

P. V. Loeppert and S. B. Lee, (Knowles Electronics), Hilton Head Workshop, June 2006.
Free-Floating Diaphragm: Preventing Stiction

A self-assembled monolayer organic film forms an ultra-hydrophobic surface that allows the diaphragm to pop up after surface tension from drying water droplets cause its collapse.

Courtesy of Peter Loeppert, Knowles Electronics.
Metal Micro Machines

Key: polishing after each electrodeposition step

www.microfabrica.com
Van Nuys, California
Outline

- Background and Stanford History
- Core Technologies
  - Structures: beams, diaphragms, and mechanisms
  - Transduction: moving energy between domains
  - Electronics: dealing with tiny signals
  - Encapsulation: taming surface phenomena
- Whither MEMS?
  - The MEMS Industry in 2022
  - New challenges: MEMS inside CMOS, intelligent structures for soft robotics
Force Scaling with Dimension $s$

- Surface tension: $F \propto s^1$
- Electrostatics: $F \propto s^2$
- Shape memory alloy: $F \propto s^2$
- Pressure (hydraulics): $F \propto s^2$
- Electromagnetics: $F \propto s^4$

Electrostatic Forces

Plates are made of the same conductor (silicon, polysilicon, or metal)

$Q$: electrical charge – proportional to voltage

$E$: electric field – voltage divided by the gap $g$

Resulting force is proportional to the square of the voltage and is always attractive (plates pulled together)
Electrostatic Actuators: the Good

a) “Free” in surface micromachining processes, since isolated conductors are all that’s needed

b) Low power: parasitic $i^2R$ losses in conductors and interconnects are small since the current is small

c) Overlapping plate structures (e.g., combs) can linearize the force vs. displacement function

d) Pull-in phenomenon can be exploited to make a hysteretic actuator $\rightarrow$ simplifies control

e) Scaling of the electrostatic force is favorable, since normal air breakdown processes don’t operate in the micro/nano domain

f) Same structure can be used for applying force to a structure and for position sensing.
Electrostatic Actuators: the Bad

1. High DC voltage is often needed … or very tiny gaps to achieve high electric field and high forces
2. Coupled non-linearity with position and voltage
3. Affected by charge accumulating and drifting around on exposed insulating surfaces
4. Particles are attracted to plates connected to a voltage source
5. Collapse due to pull-in can be catastrophic if conductors touch and short-circuit. If coated with insulators, they can become charged if they touch
Capacitive Micromachined Ultrasonic Transducers (CMUTs)

a) Silicon etch to define cavity
b) Thermal oxidation
c) Oxide etch to define the bumpers
d) Thermal oxidation to form an isolation layer
e) Silicon wafer bonding
f) Silicon etch-back to form the membrane
g) Via etch
h) Al deposition and patterning

Prof. Pierre Khuri-Yakub, EE Dept., Stanford
Annular CMUT Transducers

- A major advantage of MEMS fabrication is the ability to design custom arrays, such as this annular array for endoscopic imaging:

  64 element (each with 9 CMUTs) annular array:
  10 MHz, 100 μm x 100 μm element area

Current work: high power CMUTs for ultrasonic surgery

Packaging for ultrasonic imaging in a standard endoscope form factor

Pierre Khuri-Yakub group, Stanford Electrical Engineering Dept.
Recent work by Amin Arbabian and Pierre Khuri-Yakub (Stanford EE Dept.) has shown that ultrasonics is competitive with RF for powering and communicating with sensor nodes.

Outline

- Background and Stanford History
- Core Technologies
  - Structures: beams, diaphragms, and mechanisms
  - Transduction: moving energy between domains
  - Electronics: dealing with tiny signals
  - Encapsulation: taming surface phenomena
- Whither MEMS?
  - The MEMS Industry in 2022
  - New challenges: MEMS inside CMOS, intelligent structures for soft robotics
Analog Device ADXL-50

Courtesy of Richard S. Payne, Analog Devices.
ADXL-50 Position Resolution

\[ C_1, C_2 \approx 100 \, \text{fF} \]
\[ g_o = 1 \, \mu\text{m} \]
\[ V_+ = -V_- = 2.5 \, \text{V} \]
\[ V_o(\text{noise}) \approx 0.1 \, \text{mV} \]

\[ S_x = \frac{V_o}{x} = \frac{V_+}{g_o} \approx 2.5 \, \text{V/\mu m} \]

\[ x_{rms} = \frac{V_o(\text{noise})}{S_x} = \frac{0.1 \, \text{mV}}{2.5 \, \text{V/\mu m}} = 40 \times 10^{-12} \, \text{m} = 15\% \text{ of the length of a silicon-silicon bond!} \]
Analog Devices ADRS-150 Rate Gyroscope

Full scale Coriolis-induced displacement = 2 nm

Sense capacitance ≈ 1000 fF

Minimum detectable capacitance change ≈ 12 zF = 0.012 aF

Nominal sense gap = 1.6 µm

Minimum displacement: 16 fm

< $r_e$, the classical electron radius!

John Geen, Steve Sherman, John Chang, and Steve Lewis,
MEMS Gyro Block Diagram

Outline

- Background and Stanford History
- Core Technologies
  - Structures: beams, diaphragms, and mechanisms
  - Transduction: moving energy between domains
  - Electronics: dealing with tiny signals
  - Encapsulation: taming surface phenomena
- Whither MEMS?
  - The MEMS Industry in 2022
  - New challenges: MEMS inside CMOS, intelligent structures for soft robotics
Wafer-Level Capping

Bonding processes:
- metal-metal thermocompression
- metal-semiconductor eutectic
- silicon-silicon fusion

Ambient in package:
- pressure – high for damped resonance (accelerometers)
- pressure – low for high Q (resonators, gyroscopes)
- getters to scavenge oxygen, other residual gases
- anti-stiction coatings
Microphone Encapsulation

This package has a hole in it!
Microencapsulated Silicon Resonators

Sealed with oxide or poly-Si deposition

Isolated electrical feedthroughs

Double-ended tuning fork micro-resonator


Transducers '05, Seoul, Korea
Balanced Tuning Fork Resonator

Features

- 524 kHz resonator for 32.768 kHz RTC
- ±100 over temp frequency stability
- ±5 ppm stability on RTC
- 50,000 quality factor
- Ultra-small size: 420 µm x 420 µm
- 50,000 g shock and 70 g vibration resistance, 10x better than quartz
- <1 µA system current

Silicon Time (SiTime) was launched in 2005 by Markus Lutz, Aaron Partridge, Tom Kenny, and Kurt Petersen
SiTime Timing Systems

Major application: electronic clocks for Apple Watches
Outline

- Background and Stanford History
- Core Technologies
  - Structures: beams, diaphragms, and mechanisms
  - Transduction: moving energy between domains
  - Electronics: dealing with tiny signals
  - Encapsulation: taming surface phenomena
- Whither MEMS?
  - The MEMS Industry in 2022
  - New challenges: MEMS inside CMOS, intelligent structures for soft robotics
MEMS inside CMOS

Advantage: no need for a special MEMS fab
Challenge: structures are an insulator/metal sandwich that are vulnerable to the effects of drifting charge

Kristen Dorsey and Gary Fedder (Carnegie-Mellon University), *Transducers 2011*, Beijing
Next CS114 Lecture: Stretchable Structures

Concept of a glove with strain sensors

New materials, fabrication processes, electro-mechanical designs, and applications

Capacitive strain sensors: molded Eco-flex with liquid metal (e-GaIn) electrodes

Take-Aways

- MEMS helps to bridge the divide between the digital universe and the physical world
- Making MEMS borrows from 60 years of chip fabrication, with a few extra steps
- MEMS are slowly disappearing into embedded systems, giving them enhanced self-awareness
- *There’s still much to do –*
  - Debbie Senesky (AA): harsh-environment sensors
  - Tom Soh (EE/Rad): implantable closed-loop therapeutics
  - Sindy Tang (ME): microsystems for tissue regeneration