Capacitive sensors

- Typically used to measure displacement
- $C \sim \varepsilon_0 A/d$

Example: Pressure Transducer

$$C(x) = C(x(P))$$
CO Microsensor Process Flow

Source: http://www.itri.org.tw/mems/
MEMS Mechanical Switch

- **Contact Areas:** 0.4x0.4 $\mu m^2$ to 8x8 $\mu m^2$
- **Devices from** 50 $\mu m$ to 250 $\mu m$ long
Mechanical Switch Process Flow

- **Pre-alignment**
- **Isolation Growth**
  - 6000A Low Temp Oxide
  - 1000A Stoichiometric Silicon Nitride
- **Poly 0 Deposition**
- **Poly 0 Formation**
- **RIE to isolation w/ overetch**
- **Main Sacrificial Deposition**
  - 5500A Low Temp Oxide
- **Dimple Formation**
  - DRIE to Isolation or timed DRIE
Mechanical Switch Process Flow

Fine refill sacrificial (HTO)

Anchor holes

Elec1 Layer

Sacrificial Release

Fine Sacrificial Deposition
650A High Temp Oxide

Anchor Formation
DRIE to isolation layer

Poly 1 Deposition
5500A @ 615C n-doped
Poly 1 Formation
RIE etch to Main Sac

Sacrificial Release
HF:HCl 20’ then critical pt. dry

Process Finished
Example of Thermal Bimorph Actuator

$\alpha_{\text{(gold)}} = 14 \times 10^{-6} \, ^{\circ}\text{C}$

$\alpha_{\text{(Si)}} = 2.6 \times 10^{-6} \, ^{\circ}\text{C}$
Process Flow of Micro-tweezers by selective CVD Tungsten

(a) Si<sub>3</sub>N<sub>4</sub> - Si Substrate
(b) SiO<sub>2</sub> - W beams
(c) Si<sub>3</sub>N<sub>4</sub> - Si<sub>3</sub>N<sub>4</sub>
(d) W - W
(e) W beams
(f) 0 volts - open
15 volts - closed
Process Flow of MEMS Rotating Mechanisms

In-Plane Movement

Micro-turbine Engine
Example: Lateral Resonator

- Electrostatic force is applied by a comb drive to a suspended shuttle.
- Motion is detected capacitively by a sense comb.
Using electrostatic actuator, convenient voltage is limited to ~ 200V
Electrostatic Gated Pneumatic Valve
Process Flow of Electrostatic Gated Pneumatic Valve

1. **Silicon**
   - **Thermal Oxide**
   - **Silicon Substrate**

2. **KOH Etched Pit**

3. **Electroplated Cu** *(Sacrificial Layer)*

4. **Polyimide**
   - **Au Electrodes**
   - **Buried (SOI) Oxide**

5. **Plasma Etch of Polymide**
   - **Nitride Etch Mask (for 500 µm Si etch)**
   - **KOH Etched Pit**

6. **Sacrificial Cu Etched**
   - **Buried Oxide Etched**
SCREAM Process

Step 1: Deposit Mask Oxide
- Mask Oxide
- Silicon Substrate

Step 2: Photolithography
- Exposed photoresist
- Mask Oxide
- Silicon Substrate

Step 3: Transfer Pattern
- Resist
- Mask Oxide
- Silicon Substrate

Step 4: Strip Resist
- Mask Oxide
- Silicon Substrate

Step 5: Deep Silicon Etch
- Mask Oxide
- Silicon Substrate

Step 6: Deposit PECVD Oxide
- Sidewall Oxide
- Mask Oxide
- Silicon Substrate

Step 7: Vertical Oxide Etch
- Mask Oxide
- Silicon Substrate

Step 8: Silicon Etch #2
- Mask Oxide
- Silicon Substrate

Step 9: Isotropic Release Etch
- Mask Oxide
- Silicon Substrate

Step 10: Sputter Deposit Metal
- Aluminum
- Mask Oxide
- Silicon Substrate

Al electrodes

Question: Why 2nd Si etch?
Monolithic MEMS/IC Integration Approaches

• **Interleaved process**
  – Processing steps for MEMS and IC are interleaved in the process flow.

• **Modular process**
  – Allows for separate development & optimization of MEMS and electronics components
  – Use of IC and/or MEMS foundries a possibility
Challenges of Modular processes

• **MEMS-first Approach**
  – Topography is an issue.
  – Degradation of MEMS devices during high-temperature IC process steps.
  – Electronics must be protected during HF release-etch.

• **IC-first Approach**
  – MEMS must be low temperature process
  – Electronics must be protected during HF release-etch.
Interleaved Process Example

(Analog Devices Inc.)

- Metallization process steps performed last
- Performance of MEMS and electronics compromised
MEMS-first Process Example
(Sandia National Lab)

- MEMS fabricated in 12μm-deep trench
  - Filled with SiO$_2$ and planarized using CMP
- Modular process, but IC foundries wary
MEMS-Last Process Example

(UC-Berkeley)

• Non-standard refractory W metallization
  – melting point > 3000°C!

• IC foundries not interested
New MEMS-Last Technology

(A. Franke, UC-Berkeley)

- Standard CMOS process (Al-based metallization)
- Poly-SiGe as structural material
  - processing temperatures < 500°C possible
- Amorphous-Si protects CMOS during HF release-etch
The cavities are formed after formation of the lower electrode, when a thick SiO\textsubscript{2} layer and the upper electrode are deposited. In the upper electrode, multiple holes are etched, a plasma or wet etchant for SiO\textsubscript{2} is applied through the holes to attack the thick SiO\textsubscript{2} layer, the SiO\textsubscript{2} under the holes is removed and small cavities of SiO\textsubscript{2} are formed and connected gradually. Finally the connected cavities produce a large cavity under the upper electrode. The final cavity size depends on the hole size and etching conditions, including time, gas flow rate and gas components.

Source: Hitachi, 2009
MEMS-based Sensor & Actuator Growth

2007-2012 Sales = 19% CAGR
2007-2012 Units = 27% CAGR

Source: WSTS, IC Insights
DNA analysis in Microchannels

Stretching DNA and sequencing
– Cao et al. (Princeton)

Entropic trap
– Han & Craighead (Cornell, MIT)

30µm

75nm

30µm
Optical observation of single molecules in their natural state – Cornell Univ.

- Light-impeding Al holes
- Zero-mode waveguides

**Fig. 1.** An apparatus for single-molecule enzymology using zero-mode waveguides.

**Fig. 3.** A fused silica coverslip with zero-mode waveguides arrays. (A) The coverslip, with overlying gasket to isolate arrays for individual experiments. Successive increases in scale are shown in (B) to (D). A scanning electron microscope image of an individual waveguide is shown in (D). The bright spots in (C) correspond to defects in the metal film. The large bright pattern in the upper right corner is a coded orientation marker.
Responsive Drug Delivery System

Heterogeneous Integration of Microsystems

Professor Nathan Cheung, EECS

For reference only

Si-Ge Low Power CMOS

Encapsulated battery with switch/LED

Encapsulated Power source

BioMEMS Emitters /Filter/Detectors

Green LED

Blue LED

5mm

Si microfluidic channels

InGaN LEDs on Si

MOS IC

Optical Modulator

SiGeO

Spectrometer

LED display

Micro pump

Laser Emitter Arrays

Micro-fluidic channels

Low Power CMOS

For reference only

Professor N Cheung, U.C. Berkeley
Summary of MEMS Processing Module

- Stress, Strain, Young’s Modulus, Poisson Ratio, Yield Stress
- Thin-film stress (intrinsic, thermal expansion, external)
- Substrate warpage calculations – Stoney’s Equation
- Stiction problems and solutions
- Bonding and Molding (qualitative)
- Principle of MEMS sensing and actuation (qualitative)
- Given a MEMS structure, design the process flow
- MEMS-CMOS Integration Sequence - Interleaved, MEMS-first, MEMS-last