Wright State University

EE480/680
Micro-Electro-Mechanical Systems (MEMS)
Summer 2006

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Transducers: Sensors

Overview

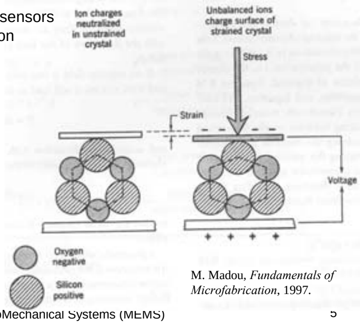
- Piezoelectric
- Piezoresistive
- Thermoresistive
- Capacitive
- Other
- Microelectronics and MEMS

Sensors

- A good reference for sensor interface circuits:
  - J. W. Gardner, *Microsensors Principles and Applications*, John Wiley & Sons Ltd, 1994, ISBN 0-471-94136-0.

Sensors: Piezoelectric

- A piezoelectric material induces a charge or develops a voltage across itself when deformed
  - Anisotropic behavior
  - High Q - Low Damping
  - Offset, temperature effects, parasitic currents limit operation to AC > 5 Hz - DC operation impractical
  - High output impedance makes piezoelectric sensors sensitive to load and electromagnetic radiation
  - Small displacement output



M. Madou, *Fundamentals of Microfabrication*, 1997.

Sensors: Piezoelectric

Table 7.14 Piezoelectric coefficients of materials at 300 K.

Material	Type	Form	Coefficient, Ξ_{33} (pC/N)	Permittivity, ε_r
Quartz (X-cut)	Glass	Bulk	2.33	4.0
PVDF	Polymer	Film	1.59	-
P(VDF-TrFE)	Polymer	Film	18.0	6.2
ZnO	Ceramic	Bulk	11.7	9.0
ZnO	Ceramic	Film	12.4	10.3
$BaTiO_3$	Ceramic	Bulk	190	4,100
PZT	Ceramic	Bulk	370	300- 3,000

J. W. Gardner, *Microsensors: Principles and Applications*, 1994

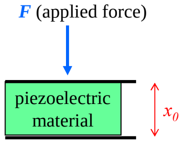
$PbZrTiO_3$ (PZT) can also be deposited as a thin film

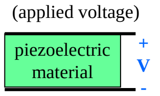
$$q = \Xi F$$

$$q = CV$$

$$C = \frac{\varepsilon_0 \varepsilon_r A}{x_0}$$

$$V = \frac{\Xi F x_0}{\varepsilon_0 \varepsilon_r A}$$





$$\varepsilon = \Xi \mathrm{H}$$

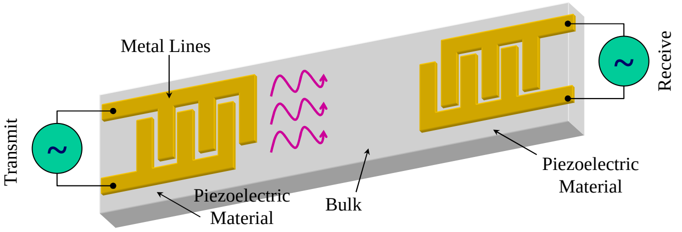
$$\varepsilon = \frac{x - x_0}{x_0} = \frac{\Delta x}{x_0}$$

$$\mathrm{H} = \frac{V}{x_0}$$

$$\Delta x = \Xi V$$

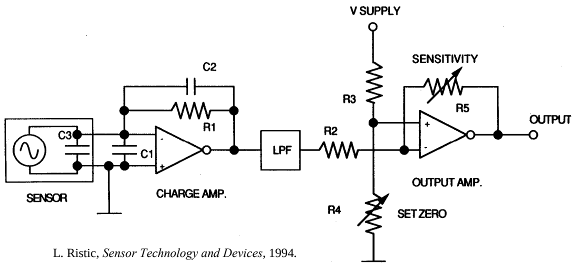
Sensors: Piezoelectric

- Ex. Surface Acoustic Wave (SAW) device
  - Generates surface waves (30 MHz - 1 GHz)
  - Senses surface waves
  - Phase and/or frequency of the sensed wave is changed while traveling through the bulk
  - Anything that changes the bulk will affect the phase and/or frequency
    - temperature, chemicals, vibration, strain, viscosity, density, etc.



Sensors: Piezoelectric

- A piezoelectric charge amplification circuit



L. Ristic, *Sensor Technology and Devices*, 1994.

Piezoelectric devices include actuators, temperature sensors, pressure sensors, accelerometers, ultrasound transducers, etc.

Sensors: Piezoresistive

- Piezoresistance is when a material’s resistance changes when the material is stressed.
    - Anisotropic behavior
    - Temperature sensitive

TABLE 4.5 Resistivity and Piezoresistance at Room Temperature[25,49]

	ρ (Ω cm)	π_{11}[a]	π_{12}[a]	π_{44}[a]
p-Si	7.8	+6.6	−1.1	+138.1
n-Si	11.7	−102.2	+53.4	−13.6

[a] Expressed in 10^{-12} cm^2 dyne^{-1} or 10^{-11} Pa^1.

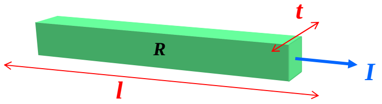
M. Madou, *Fundamentals of Microfabrication*, 1997.

$$\frac{\Delta R}{R} = \sigma_l \pi_l + \sigma_t \pi_t$$

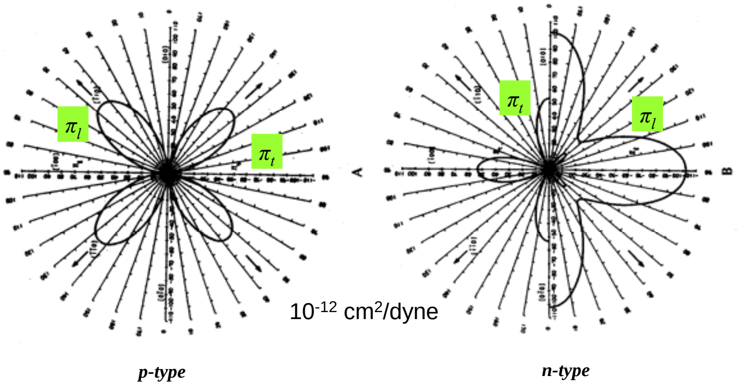
Ex. For the longitudinal direction of <110>, the longitudinal (*l*) and transverse (*t*) coefficients are:

$$\pi_l = \tfrac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44})$$

$$\pi_t = \tfrac{1}{2}(\pi_{11} + \pi_{12} - \pi_{44})$$



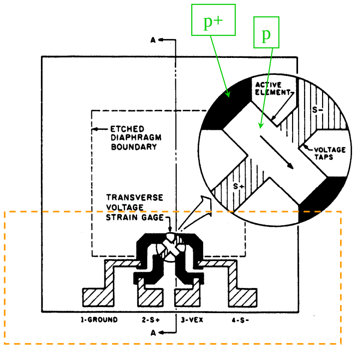
Sensors: Piezoresistive

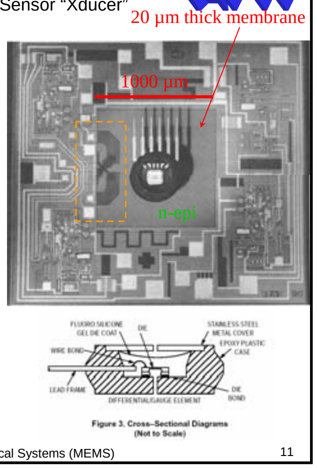


M. Madou, *Fundamentals of Microfabrication*, 1997.

Sensors: Piezoresistive

- Ex. Motorola Manifold-Absolute-Pressure (MAP) Sensor “Xducer”
    - Piezoresistor oriented to take advantage of π_{44}.
    - Differential voltage sensed between S+ and S-.



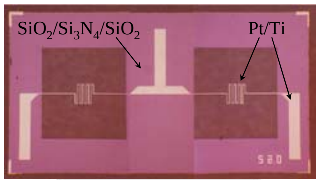


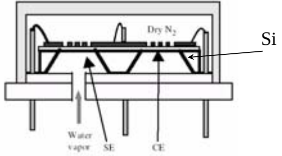
Sensors: Thermoresistive

- This type of sensing takes advantage of the fact that resistance varies with temperature.
- A linear approximation:
    - $R = R_0[1 + \alpha_R(T - T_0)]$
- α_R is the Temperature Coefficient of Resistance (TCR)
    - Platinum: $\alpha_R = 3.9 \times 10^{-4}$ K^{-1}
    - n-Si: $\alpha_R = 2.5 \times 10^{-3}$ K^{-1}

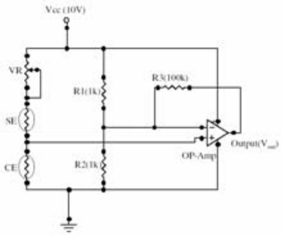
Sensors: Thermoresistive

- Ex. Humidity Sensor
  - D. H. Lee et al., “A Micromachined Robust Humidity Sensor for Harsh Environment Applications, 2001.

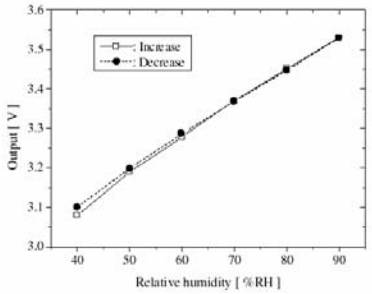


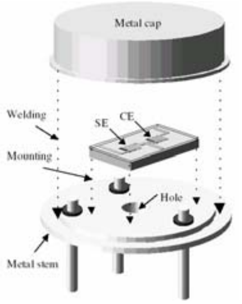


Pt resistors are self heated to 350 °C, as humidity increases, resistor cools, thereby reducing resistance.



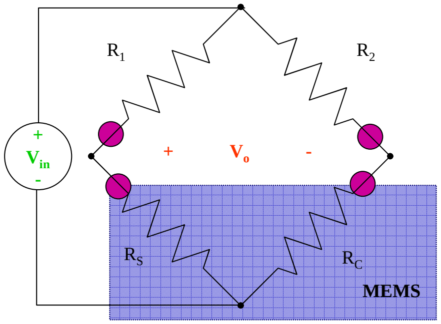
Sensors: Thermoresistive





Sensors: Change in Resistance

- Don’t forget the Wheatstone Bridge



Typically:

R_S = MEMS sensor

R_C = MEMS compensation sensor

R_1 & R_2 = External bias or MEMS resistors

● = Trim resistor locations

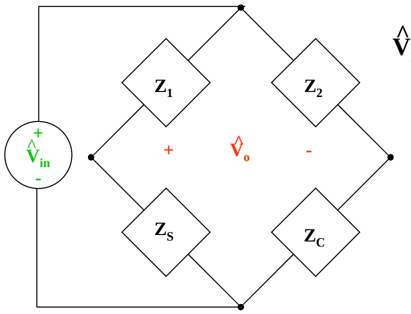
$$\frac{dV_o}{dR_S} = \frac{R_1 V_{in}}{(R_1 + R_S)^2}$$

Sensitivity greatest when $R_1 = R_S$

Trimming is done by variable resistors off-chip and/or by physical modification of MEMS sensors, i.e. laser ablation of resistor material.

Sensors: Change in Impedance

- Furthermore, the Wheatstone Bridge ain’t just for resistors anymore … phasor analysis:



$$\hat{\mathbf{V}}_{in} = P\{V_{in}\cos(\omega t+\phi)\} = V_{in}e^{\phi j}$$

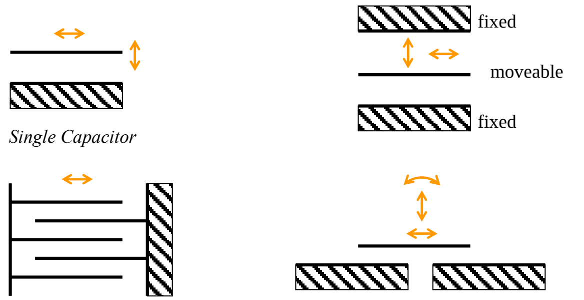
$$\mathbf{Z}_{cap} = 1/C\omega j$$

$$\mathbf{Z}_{ind} = L\omega j$$

$$\mathbf{Z}_{res} = R$$

Sensors: Capacitive

- MEMS structures can be viewed as arrangements of capacitors:



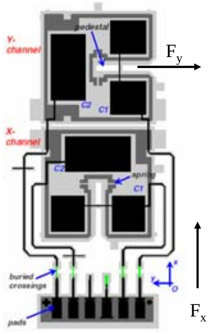
Single Capacitor

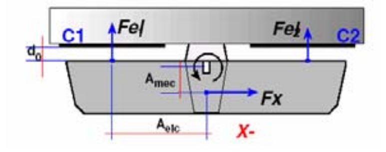
Interdigitated

Differential Sensing and/or Feedback Control of moveable structure

Sensors: Capacitive

- Ex. Accelerometer
  - D. Lapadatu et al., “Dual-axes Capacitive Inclinometer / Low-g Accelerometer for Automotive Applications,” 2001.

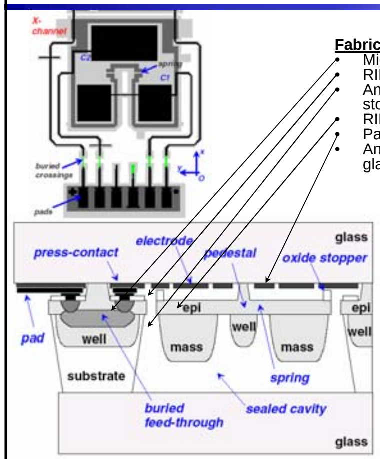


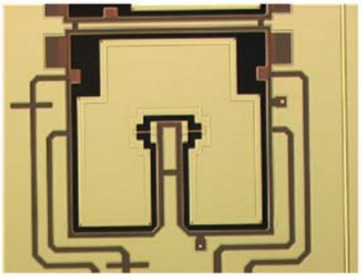


Sensors: Capacitive

Fabrication

- Microelectronics fab device wafer (Top)
- RIE Etch epi-layers (Top)
- Anisotropic TMAH wet etch with electrochemical etch stop (Back)
- RIE Etch epi-layers (Back)
- Pattern wires on top glass plate
- Anodic bond top glass plate – device wafer – bottom glass plate





Sensors: Other

- Inductive
- Magnetic

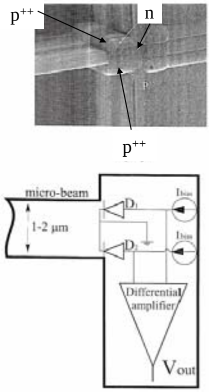
Microelectronics and MEMS

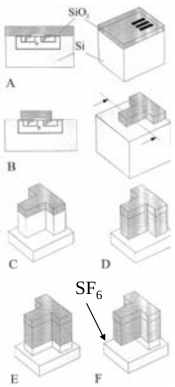
- For the most part, MEMS are fabricated using the same techniques, materials, and chemicals as microelectronics.
- Can MEMS and Microelectronics be integrated?
  - Major characteristics of microelectronic structures:
    - Crystalline semiconductor substrates; p or n-wells; and crystalline, polycrystalline, or amorphous thin films
  - Major characteristics of MEMS structures:
    - Crystalline semiconductor materials - *Bulk Micromachining*
    - Polycrystalline and Amorphous semiconductor and non-semiconductor materials - *Surface Micromachining*
    - Electroplated metals, polymers, etc. - *Micromolding*
- The combination of MEMS and Microelectronics is usually referred to as:

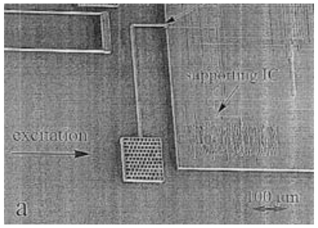
“INTEGRATION”

Integration: Bulk Etched CMOS

- Post RIE patterning and isotropic Si etch to release bulk structures:







D. Haronianr, “A low-cost micromechanical accelerometer with integrated solid-state sensor,” Sensors and Actuators A, vol. 84, pp. 149–155, 2000.

Integration: Bulk Etched CMOS

- Si bulk etch from “back” of CMOS chip: ex. Motorola

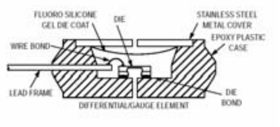
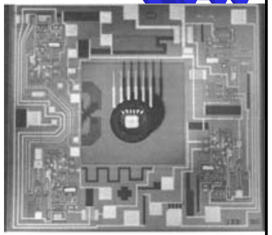
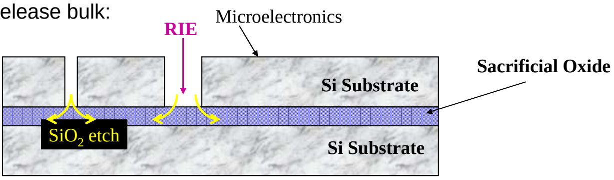


Figure 3. Cross-Sectional Diagrams (Not to Scale)

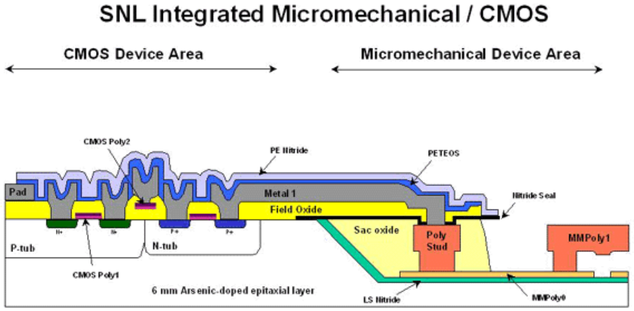


- Post RIE patterning and SiO_2 etch of SOI to release bulk:



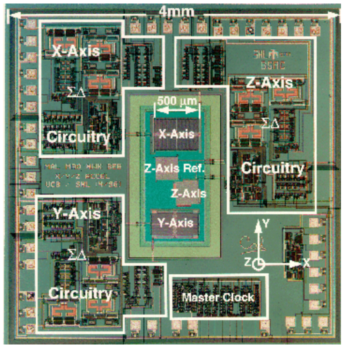
Integration: Trench Integration

- Sandia's Integrated MicroElectroMechanical Systems (IMEMS)
  - A fabrication process that enables both CMOS circuitry and surface micromachined MEMS to be created on the same chip.



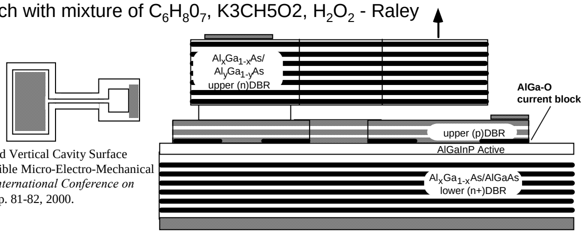
Integration: Trench Integration

- Ex. Three-axis, force-balanced accelerometer - designed by Berkely Sensor and Actuator Center (BSAC) at U.C. Berkeley



Integration: III-V Thin Films

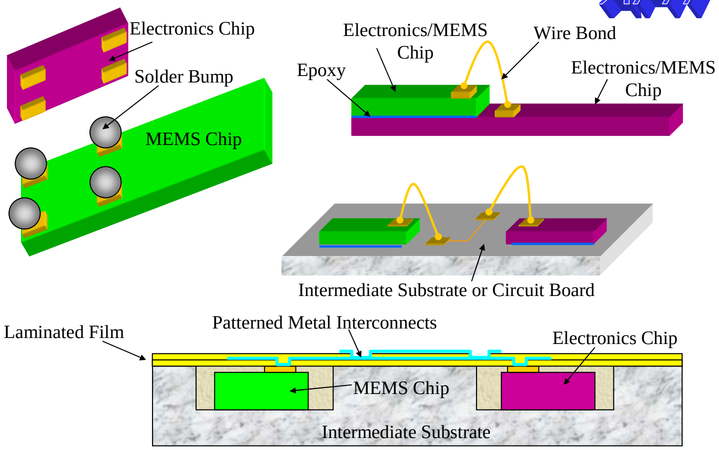
- Sacrificial etching of III-V materials yields inherent combination of electronics and mechanical structures
  - 95:1 GaAs to AlGaAs with 10:1 ratio of citric acid $\{C_6H_80_7\}$ (50%) : hydrogen peroxide $\{H_2O_2\}$ (30%) - Kovacs
  - GaAs etch with mixture of $C_6H_80_7$, K3CH5O2, H_2O_2 - Raley



J. A. Lott et al., "Tunable Red Vertical Cavity Surface Emitting Lasders Using Flexible Micro-Electro-Mechanical Top Mirrors," *IEEE/LEOS International Conference on Optical MEMS*, Kauai, HI, pp. 81-82, 2000.

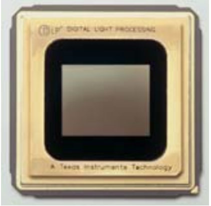
- Sacrificial etch for Epi-Si systems?
- Polysilicon electronic devices?

Integration: Multi-Chip Arrangement



Integration: Surface Micromachining on microelectronics

- Parallel Plate Examples: Texas Instruments Digital Micromirror Device^{TM}



SXGA device with black aperture: 1280x1024; 1,310,720 mirrors