Micro Electro Mechanical Systems for mechanical engineering applications

Lecture 6:
Device examples (1): piezoresistivity transduction

Kahp-Yang Suh

Assistant Professor
SNU MAE
sky4u@snu.ac.kr

Generalized Classifications

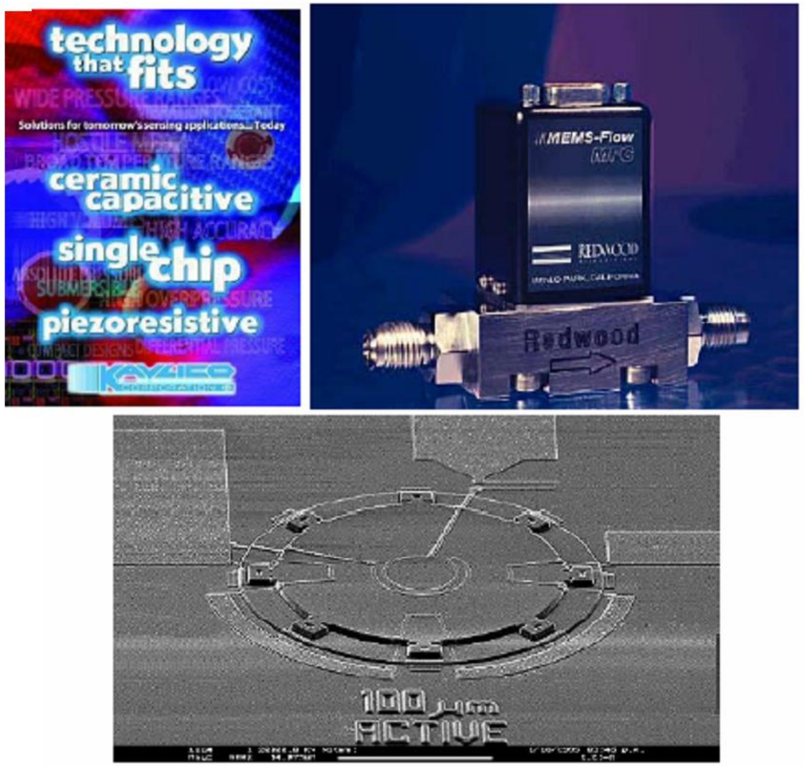
Input \ Output	Mechinical (mechano-)	Thermal (thermo-)	Electrical (electro-)	Magnetic (magneto-)	Radiant (photo- or Radio-)	Chemical (chemo-)
Mechanical	Acoustics fluidics	Cooling Effects	Piezoelectric Piezoresistor	Piezomagnetic	Photo Elasticity	
Thermal	Bi-metallic		Seebeck effect (TC's)			
Electrical	Piezoelectric	Peltier effect (TC's)			Electro-luminescence	
Magnetic	Magnetometer	Thermo-Magnetic				Electrolysis
Radiant		Thermo-Pile	Photo-electric			
Chemical		Calorimeter		Nuclear Magnetic resistance		

Madou, Fundamentals of Microfabrication, 2003

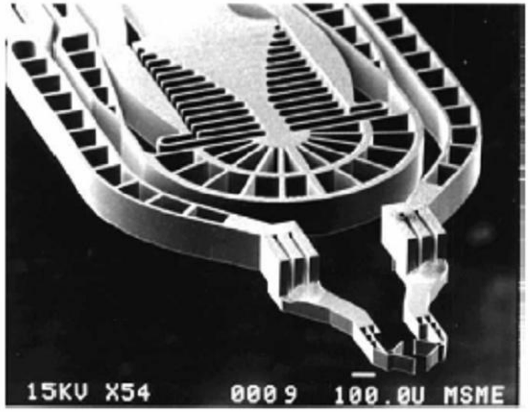
Piezoresistive Transduction

- Applied stress/strain affects resistance in piezoresistive materials
- Discovered in Si in 1954 (Bell labs)
- Physics: majority carrier mobility affected by stress:
  - In p-type Si, hole mobility decreases: R increases
  - In n-type Si, electron mobility increases: R decreases
- Advantages:
  - Simple fabrication
  - Simple interface circuits: measure change in R using a simple Wheatstone bridge topology
- Disadvantages:
  - Temperature sensitive
  - High thermal noise

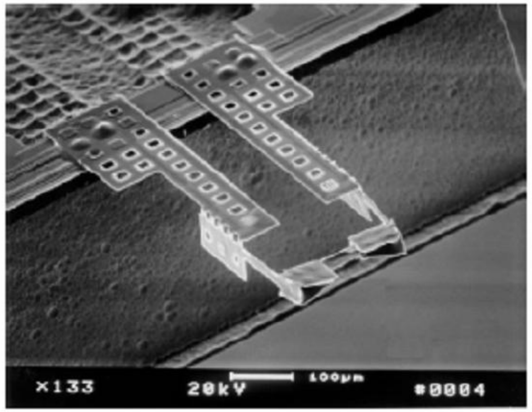
Piezoresistive MEMS Examples (1)



Pressure sensors



Force-feedback microgripper

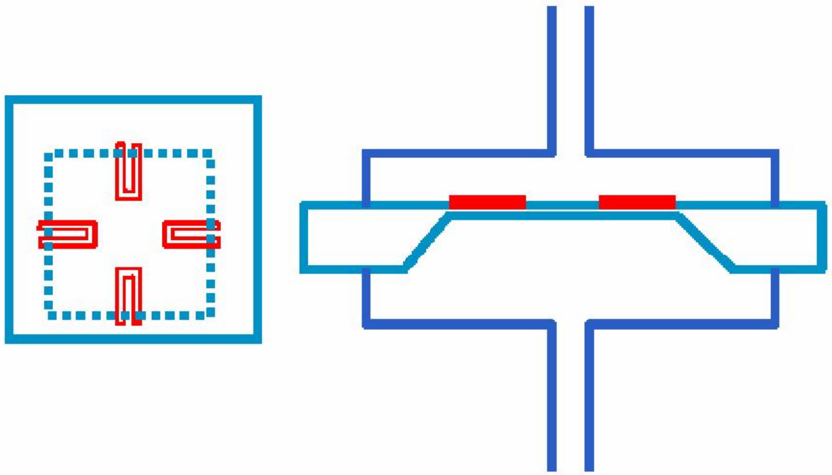


Cell force sensor

Piezoresistive MEMS Examples (2)

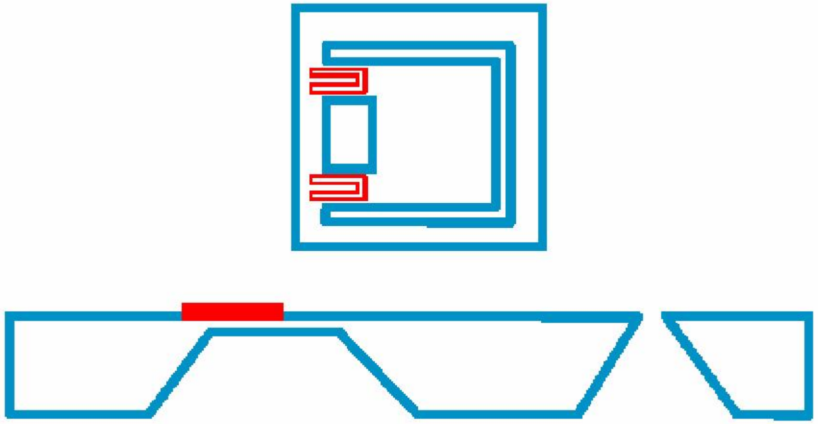
- **Membrane type**

Pressure sensor:



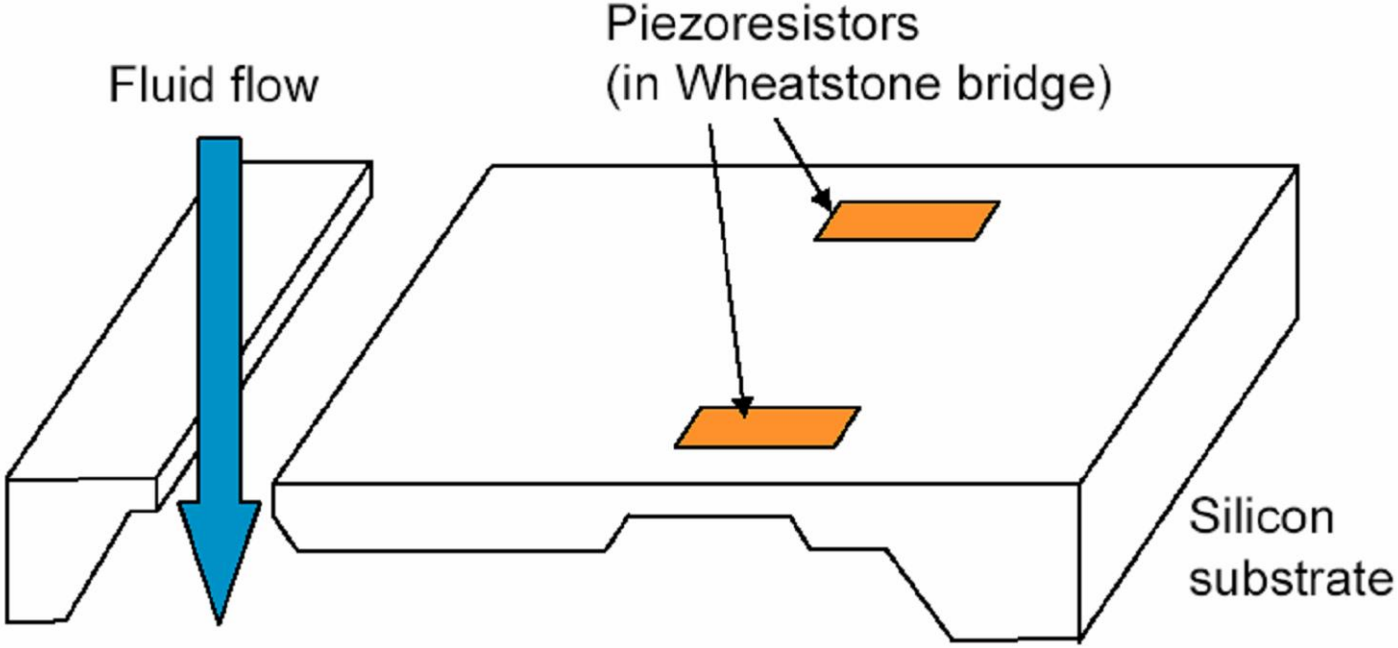
- **Cantilever type**

Acceleromter:



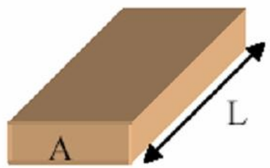
Piezoresistive MEMS Examples (3)

Piezoresistive Flow Sensing



- Cantilever deflection is translated into a voltage signal via the Wheatstone bridge.
- Voltage change is interpreted as flow rate.
- Can sense direction and magnitude of flow.

- Consider the resistance of a rectangular beam with resistivity ρ [Ω cm]:



$$R = \frac{\rho L}{A}$$

$$\ln R = \ln \rho + \ln L - \ln A$$

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dL}{L} - \frac{dA}{A} = \frac{d\rho}{\rho} + \varepsilon(1+\nu)$$

(1+2ν)

piezoresistive effect — gauge effect

- For semiconductor piezoresistors, $d\rho/\rho \gg \varepsilon(1+2\nu)$: $\frac{dR}{R} \approx \frac{d\rho}{\rho}$
- Gauge factor: $GF = \frac{1}{\varepsilon}\frac{dR}{R} \longrightarrow R(\varepsilon) = R_0 + dR = R_0(1 + GF\,\varepsilon)$

Material	Gauge factor (GF)
Metal foil[1]	1-5
Thin-film metals[1]	~2
Doped SCS[1]	80-200
Doped poly-Si[2]	15-27

G. Kovacs, Micromachined Transducers Sourcebook, 1998
Seto, J. Appl. Phys., 1976

Piezoresistivity in Single Crystal Si

$$\frac{dR}{R} = \Pi_{ij}\sigma_{ij}$$

Π_{ij} ← piezoresistive coefficient tenor

σ_{ij} ← stress tensor

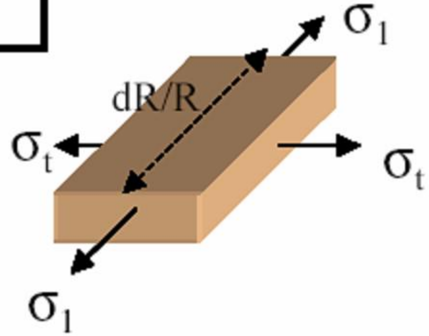
material	ρ [Ωcm]	Π_{11} [$10^{-11}Pa^{-1}$]	Π_{12} [$10^{-11}Pa^{-1}$]	Π_{44} [$10^{-11}Pa^{-1}$]
n-type Si	11.7	-102.2	53.4	-13.6
p-type Si	7.8	6.6	-1.12	138.1
p-type polySi	0.005	dR/R = Πσ, Π = 12 x 10^{-11} Pa^{-1}		

- **For 1-dimensional loading:**

$$\frac{dR}{R} = \Pi_l\sigma_l + \Pi_t\sigma_t$$

Π_l ← Longitudinal direction

Π_t ← Transverse direction



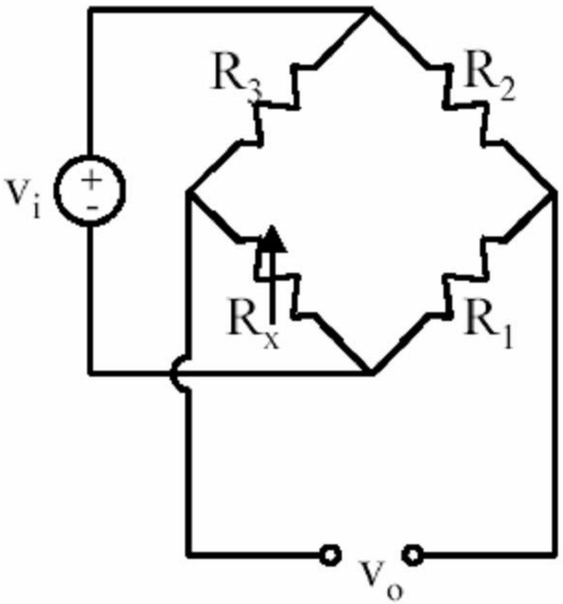
- **For the <110> direction:**

$$\Pi_l = \frac{1}{2}(\Pi_{11} + \Pi_{12} + \Pi_{44})$$

$$\Pi_t = \frac{1}{2}(\Pi_{11} + \Pi_{12} - \Pi_{44})$$

Piezoresistive Sensor Interfacing

- Wheatstone bridge
  - Good sensitivity
  - Temperature independent (to first order)
  - Simple implimentation:



$$v_o = v_i\left(\frac{R_x}{R_x + R_3} - \frac{R_1}{R_1 + R_2}\right)$$

$$@ v_o = 0 :$$

$$\frac{R_x / R_3}{R_x / R_3 + 1} = \frac{R_1 / R_2}{R_1 / R_2 + 1} \Rightarrow \frac{R_x}{R_3} = \frac{R_1}{R_2}$$

Piezoresistive Sensor Interfacing (Con't)

- Simple case:

  let $R_1=R_2=R_3=R_o$, and let $R_x=R_o(1+x)$:

$$v_o = v_i\left(\frac{R_o(1+x)}{R_o(1+x)+R_o} - \frac{R_o}{R_o+R_o}\right)$$

$$= v_i\left(\frac{(1+x)}{(2+x)} - \frac{1}{2}\right)$$

$$= v_i\left(\frac{x}{4+4x}\right) \xrightarrow{\text{for } x<<1} \boxed{v_o \approx v_i \frac{x}{4}}$$

- Output is linear for small strains
- Response in terms of GF, strain:

$$GF = \frac{1}{\varepsilon}\frac{\Delta R}{R} \qquad \Delta R = R - R_o = R_o(1+x) - R_o = x$$

$$\boxed{v_o \approx v_i \frac{GF}{4}\varepsilon}$$

Piezoresistive Sensor Interfacing (Con't)

- 2-R case:

  let R_1=R_3=R_o, and let R_x=R_o(1+x):

$$v_o = v_i\left(\frac{R_o(1+x)}{R_o(1+x)+R_o} - \frac{R_o}{R_o+R_o(1+x)}\right)$$

$$= v_i\left(\frac{x}{(2+x)}\right) \quad \text{for } x<<1$$

$$v_o \approx v_i\frac{x}{2}$$

$$v_o \approx v_i\frac{GF}{2}\varepsilon$$