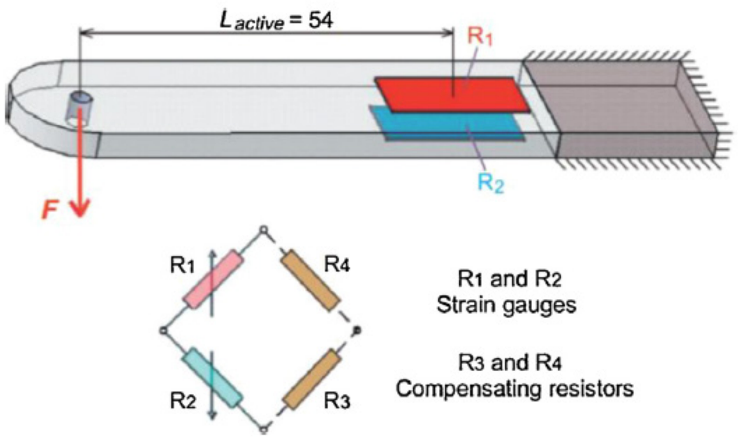
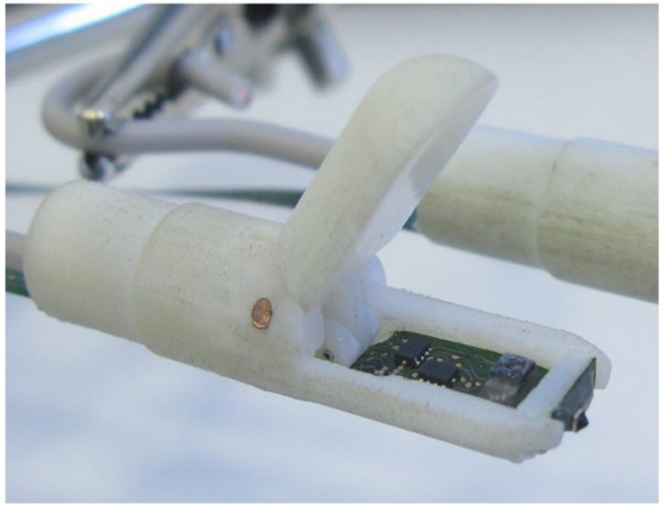
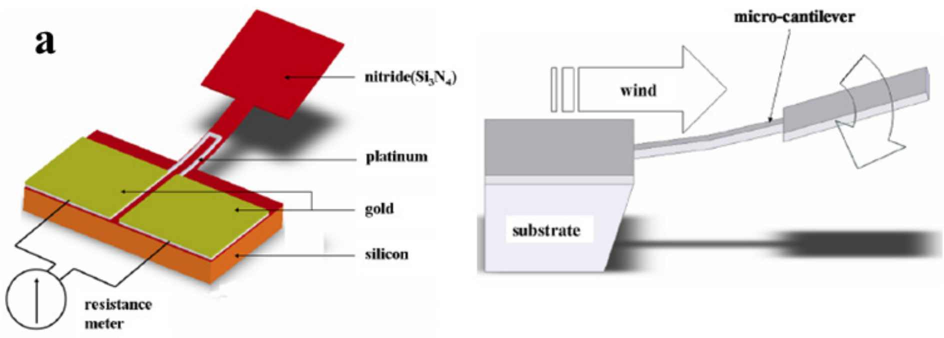
BMEN 2151 *Introductory Medical Device Prototyping*

Sensor Principles

Prof. Steven S. Saliterman, http://saliterman.umn.edu/







Sensor Classification Schemes

- A sensor measures information from the environment (e.g. a blood *analyte*, or *measurand*) and provides an electrical signal in response.
- Sensors may be classified in various ways:
  - Measurand - temperature, pressure, flow etc.
  - Transduction (physical and chemical effects) - SAW, ion selective FETs, optodes (chemical transducer) etc.
  - Materials - resistive, piezoelectric, magnetic, permeable membranes, etc.
  - Technology – MEMS, bioMEMS, plasmon resonance, CMOS imaging, charge coupled devices etc.
  - Energy requirement - active or passive.
  - Applications - industrial, automative, aviation, consumer electronics, biomedical etc.

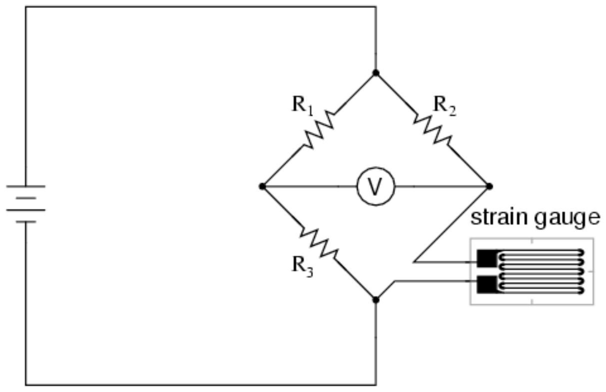
Common Microsensor Types

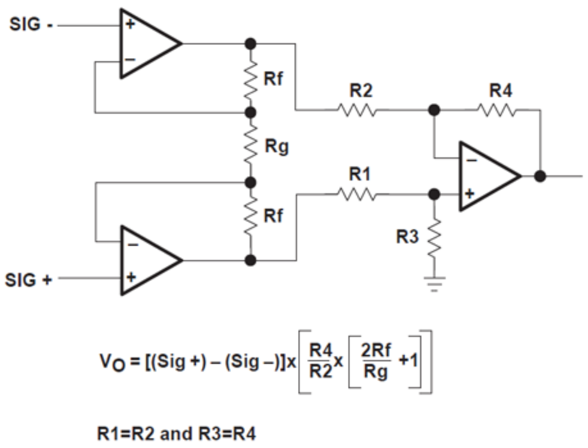
- Thermal sensors – measuring changes in temperature.
  - Thermomechanical
  - Thermoresistive
  - Thermocouples.
- Mechanical sensors – properties of stain, force and displacement.
  - Piezoresistive – strain in a semiconductor changes resistivity.
  - Piezoelectric – strain in a piezoelectric crystal causes a potential.
  - Capacitive – electrostatic, parallel plates and displacement.
  - Resonant – microfabricated beams and bridges.
- Chemical sensors – interaction with solids, liquids and gases.
- Radiant sensors – ionizing radiation, and visible, infrared or UV light.
- *Biosensors - measurement of biological analytes (another lecture).*

Shanbhag PP, Patil NS. BioMEM systems: A novel approach for drug targeting in chronic diseases. *New Horizons in Translational Medicine.* 2017;3(6):265-271.

Wheatstone Bridge Operation

Quarter-bridge strain gauge circuit





- If the bridge resistors have the same value, equal to the strain gauge's resistance at rest, then the voltage is zero.
- The voltage can be amplified to get a higher sensitivity for the complete circuit.
- This can be done with a high gain instrumentation amplifier
- The instrumentation amplifier inputs replace the volt meter in the top circuit.

Karki, J. Texas Instruments: Signal Conditioning Wheatstone Resistive Bridge Sensors. Application Report, SLOA034, September 1999.

Piezoelectric Effects

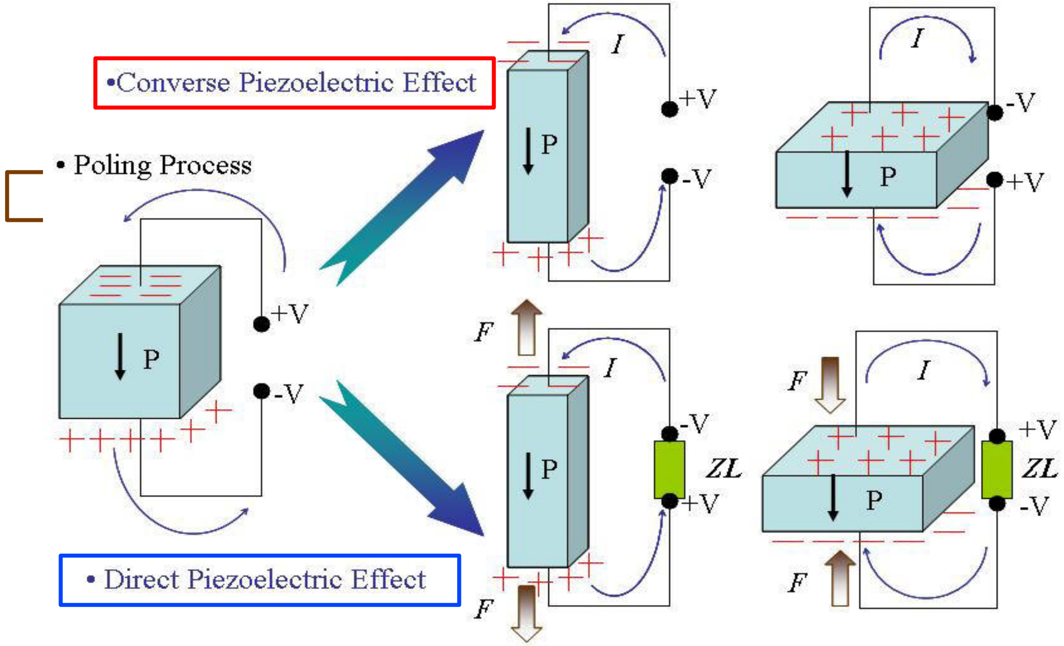
- Direct transduction from mechanical to electrical domains and vice versa. May be used as sensors or actuators.
- The reversible and linear piezoelectric effect manifests as the production of a charge (voltage) upon application of stress (direct effect) and/or as the production of strain (stress) upon application of an electric field (converse effect).
- Three modes of operation depending on how the piezoelectric material is cut: transverse, longitudinal and shear.
- Amplifiers are needed to detect the small voltage.

Tadigadapa, S., and K. Mateti. 2009. Piezoelectric MEMS sensors: state-of-the-art and perspectives. *Measurement Science & Technology* 20, no. 9:092001.

Direct and Converse Piezoelectric Effects…

Converse Piezoelectric Effect **- Application of an electrical field creates mechanical deformation in the crystal.**

Polling **- Random domains are aligned in a strong electric field at an elevated temperature.**



Direct Piezoelectric Effect **- When a mechanical stress (compressive or tensile) is applied a voltage is generated across the material.**

Adopted from bme240.eng.uci.edu

Piezoelectric Relationship…

- The piezoelectric effect is a linear phenomenon where deformation is proportional to an electric field:

Converse Piezoelectric Effect **Direct Piezoelectric Effect**

$$S = dE \quad and \quad D = dT$$

Where

S is the mechanical strain,

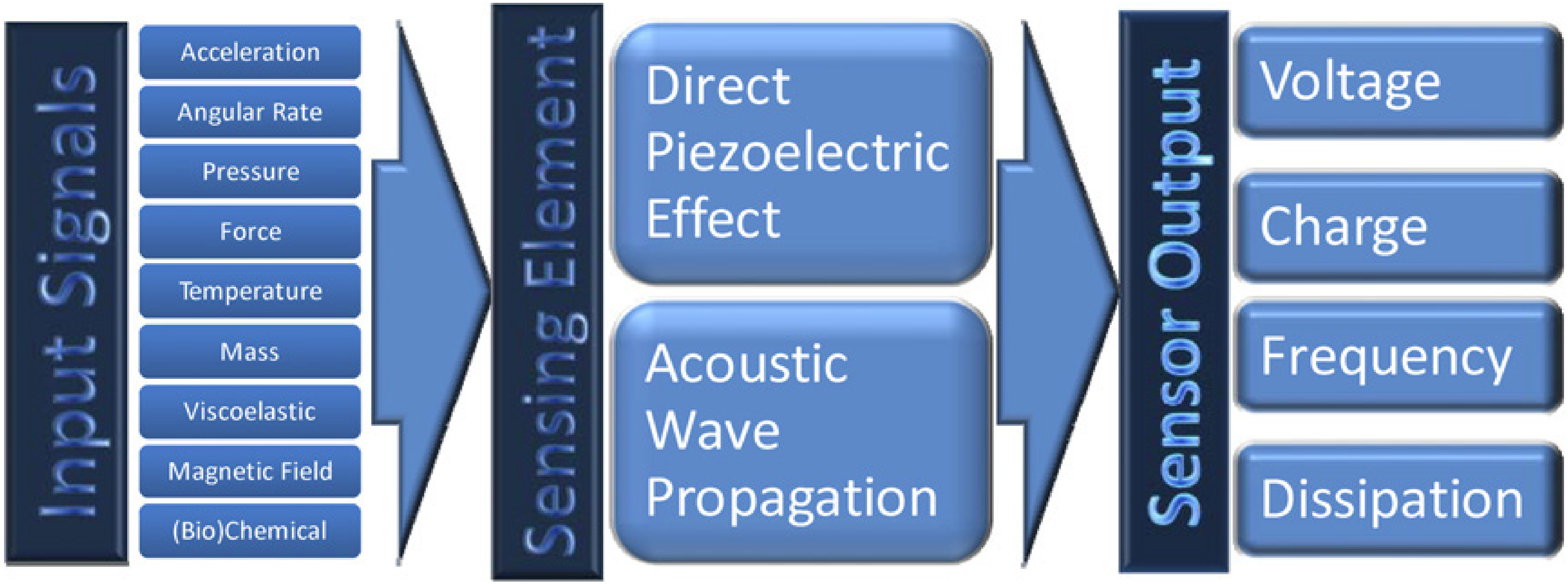
d is the piezoelectric coefficient,

E is the electric field,

D is the displacment (or charge density) linearly, and

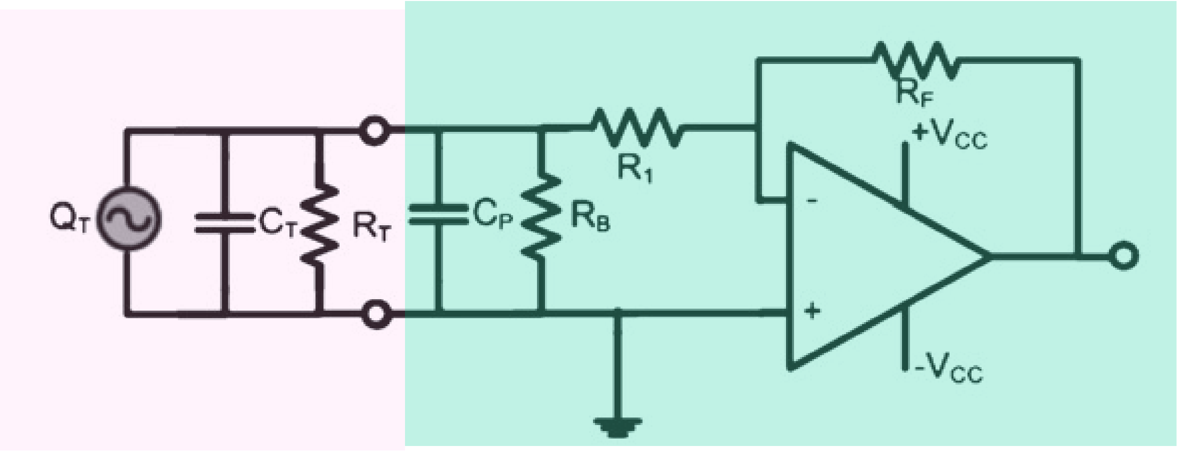
T is the stress.

Two Modes of Operation…



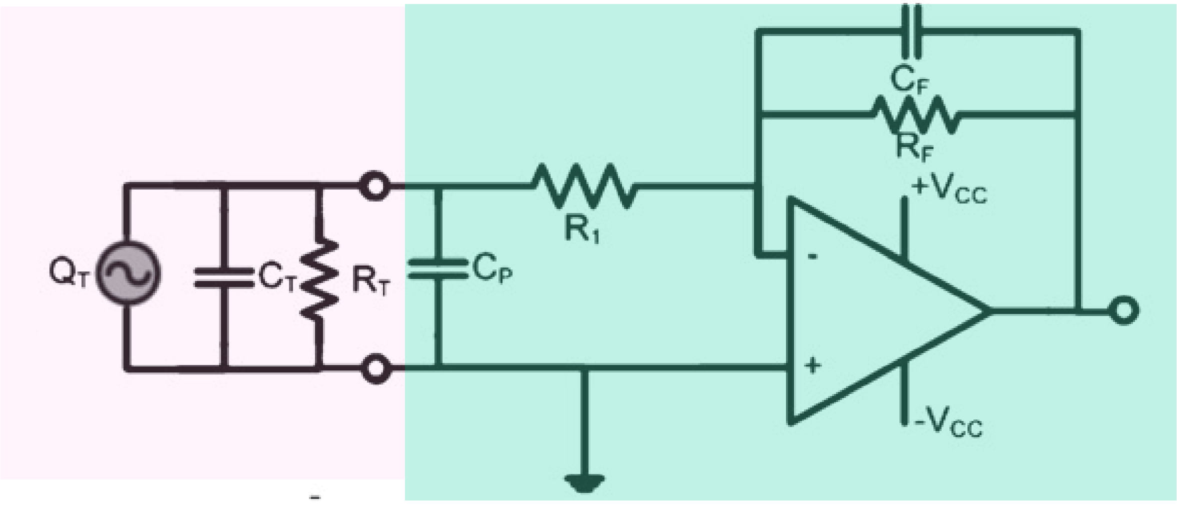
Tadigadapa, S., and K. Mateti. 2009. Piezoelectric MEMS sensors: state-of-the-art and perspectives. *Measurement Science & Technology* 20, no. 9:092001.

Modeling & Harnessing Piezoelectric Sensor…



$$V_{Out} = -\frac{Q_T}{C_T + C_P}\left(\frac{R_F}{R_1}\right)$$

Charge source Q_T with a shunt capacitor C_T and resistor R_T

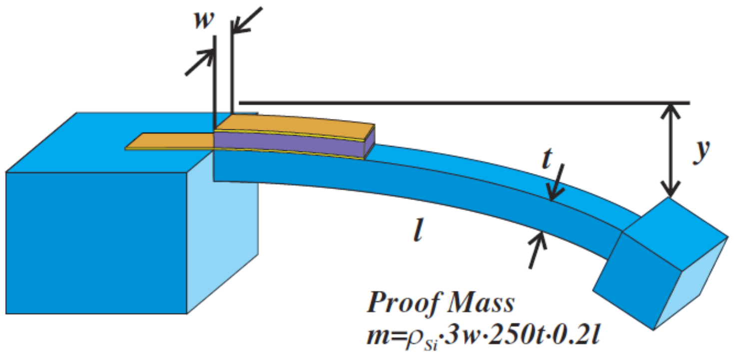


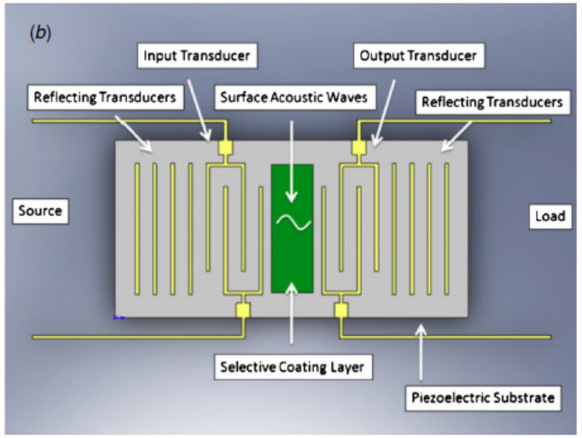
$$V_{Out} = -\frac{Q_T}{C_F}$$

Tadigadapa, S., and K. Mateti. 2009. Piezoelectric MEMS sensors: state-of-the-art and perspectives. *Measurement Science & Technology* 20, no. 9:092001.

Configurations…

- Piezoelectric sensors maybe configured as direct mechanical transducers or as resonators.
- The observed resonance frequency and amplitude are determined by the physical dimensions, material and mechanical and interfacial inputs to the device.





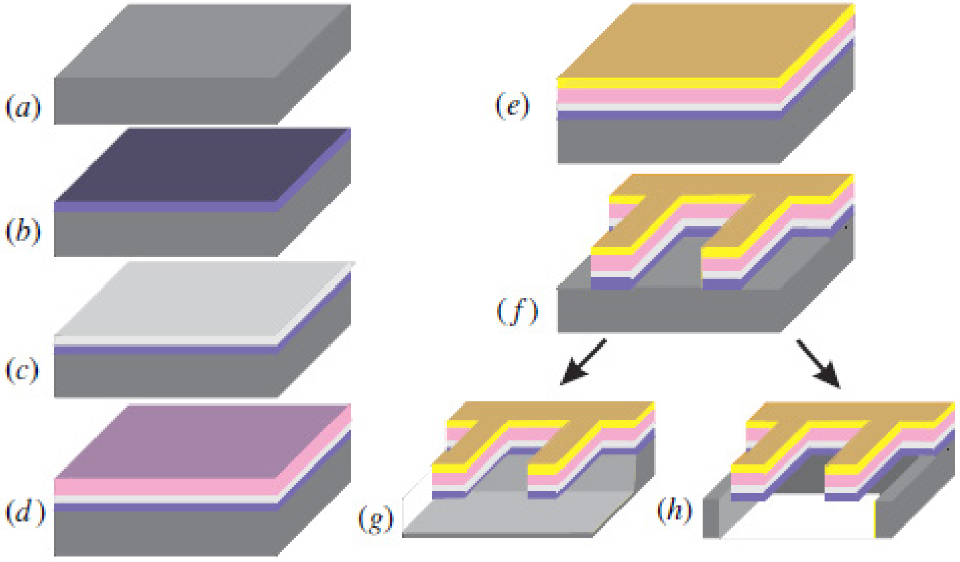
Tadigadapa, S., and K. Mateti. 2009. Piezoelectric MEMS sensors: state-of-the-art and perspectives. *Measurement Science & Technology* 20, no. 9:092001.

Piezoelectric Materials…

- Crystals
  - Quart SiO_2
  - Berlinite $AlPO_4$
  - Gallium
  - Orthophosphate $GaPO_4$
  - Tourmaline (complex chemical structure)
- Ceramics
  - Barium titanate $BaTiO_3$
  - Lead zirconate titanate PZT, Pb [ZrxTi1-x] O3 ; x = 0,52
- Other Materials
  - Zinc oxide ZnO
  - Aluminum nitride AlN
  - Polyvinylidene fluoride PVDF

Adopted from Piezomaterials.com

Micromachining a Piezoelectric Sensor…



(a) Substrate silicon wafer.
(b) Thermally oxide placed.
(c) Bottom platinum electrode is deposited.
(d) The piezoelectric thin film is deposited and annealed.
(e) Top electrode metal such as Cr/Au is deposited.
(f) The entire piezoelectric, electrodes and passive layer stack is patterned and etched.
(g) Substrate silicon is etched from the front side using anisotropic wet etchant or isotropic vapor phase XeF_2 etchant while protecting the transducer stack.
(h) Alternatively, the substrate silicon is anisotropically etched from backside to release the transducer structure.

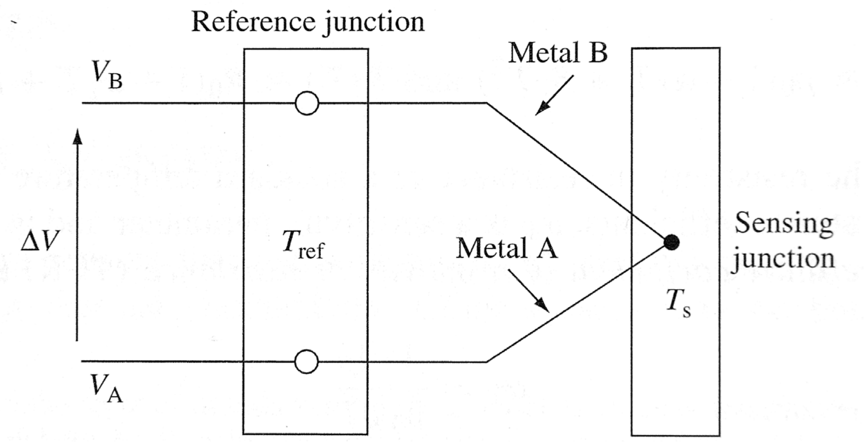
Tadigadapa, S., and K. Mateti. 2009. Piezoelectric MEMS sensors: state-of-the-art and perspectives. *Measurement Science & Technology* 20, no. 9:092001.

Thermosensor Basics

- Platinum resistor:
  - Linear, stable, reproducible.
  - Material property dependency on temperature,
- Thermocouples (e.g. Type K)
- Thermistor: a semiconductor device made of materials whose resistance varies as a function of temperature.
- Thermodiode and Thermotransistor.

Thermocouple…

- Potentiometric devices fabricated by the joining of two different metals forming a sensing junction:
  - Based on the thermoelectric *Seebeck effect* in which a temperature difference in a conductor or semiconductor creates an electric voltage:



$$\Delta V = \alpha_s \Delta T$$

Where

ΔV is the electrical voltage,

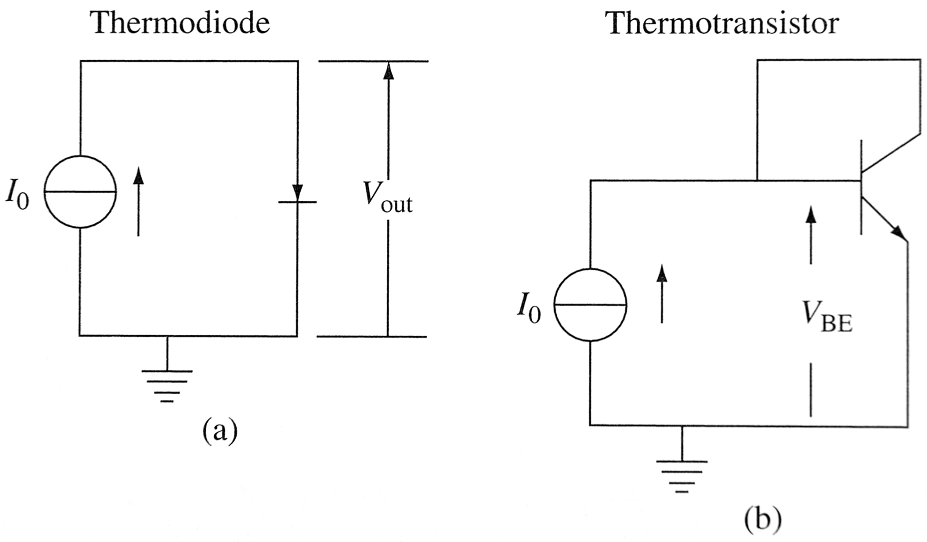
α_s is the Seebeck coefficient expressed in volts/K°, and

ΔT is the temperature difference (T_S - T_{ref}).

Gardner, JW, VK Varadan and OO Awadelkarim, *Microsensors, MEMS and Smart Devices*. John Wiley & Sons, Ltd. W. Sussex (2001).

Thermodiode and Thermotransistor…

- When a p-n diode is operated in a constant current (I_O) circuit, the forward voltage (V_{out}) is *directly proportional to the absolute temperature (PTAT).*



$$V_{out} = \frac{k_B T}{q} \ln\left(\frac{I}{I_S} + 1\right)$$

Where

k_b is the Bolzman constant,

T is temperature,

q is the charge on an electron,

I is the operating current and

I_S is the saturation current.

Gardner, JW, VK Varadan and OO Awadelkarim, *Microsensors, MEMS and Smart Devices*. John Wiley & Sons, Ltd. W. Sussex (2001).

Force Sensing Methods

- Force sensing methods (examples to follow):
  - Strain gauge-based force sensor.
  - Piezoresistive force sensor.
  - Capacitive force sensor.
  - Piezomagnetic force sensor.
- Others
  - Optical force sensor (Raman spectrometer, laser interferometer, AFM, optical tweezers).
  - Vision-based force sensor.
  - Electroactive force sensor (electronic and ionic).
  - PZT force sensor (based on direct piezoelectric effect).
  - PVDF force sensor (polyvinylidene difluoride).

Wei YZ, Xu QS. An overview of micro-force sensing techniques. *Sensors and Actuators a-Physical.* 2015;234:359-374.

Calculating Young's Modulus…

Stress

$$\sigma = \frac{F}{A}$$

Where…
σ stress (Mpa),
F is the force (N),
A is the cross sectional area (mm^2)

Strain

$$\epsilon = \frac{(L - L_o}{L_o}$$

Where…
ϵ is the strain,
L is the stretched length,
L_o is the initial length (mm)

Young's Modulus
(Stress/Strain)

$$E = \sigma/\epsilon$$

Han CJ, Chiang HP, Cheng YC. Using Micro-Molding and Stamping to Fabricate Conductive Polydimethylsiloxane-Based Flexible High-Sensitivity Strain Gauges. *Sensors.* 2018;18(2).

Strain Gauge…

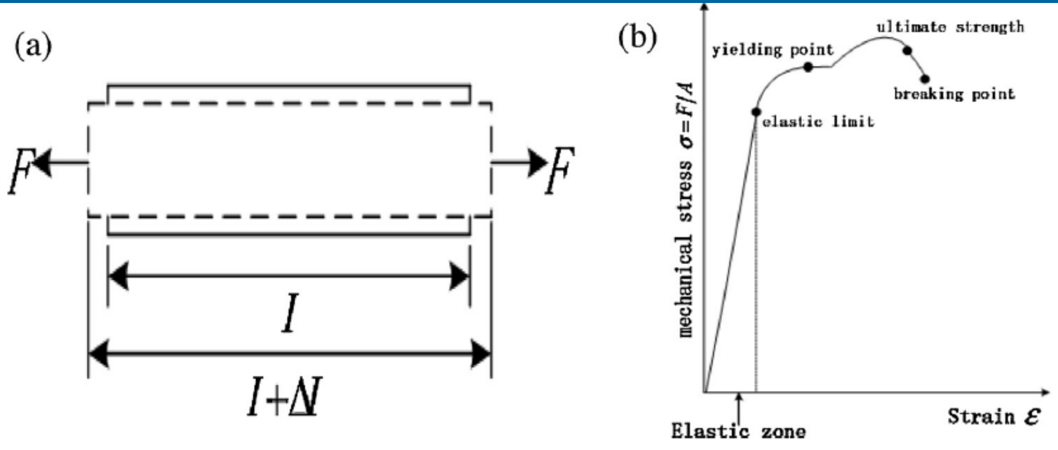
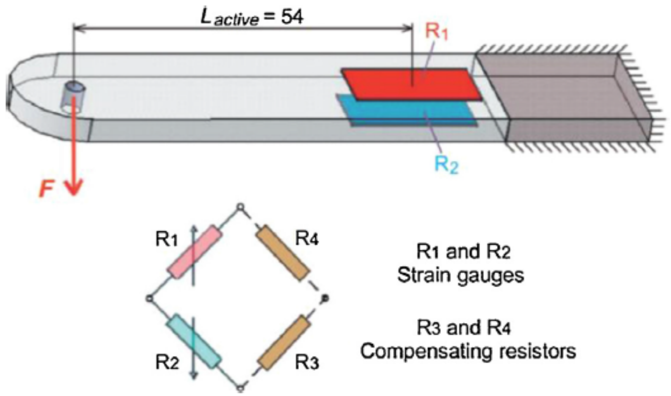


Fig. 1. Working principle of strain-gauge based force sensors. (a) Schematic diagram of strain [6], (b) stress and strain curves [6].



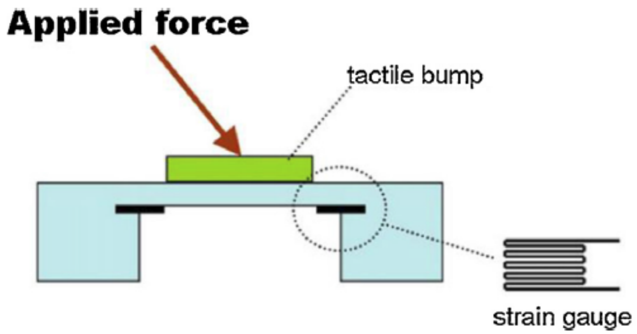
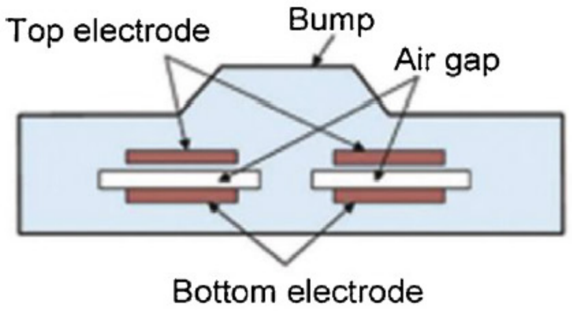
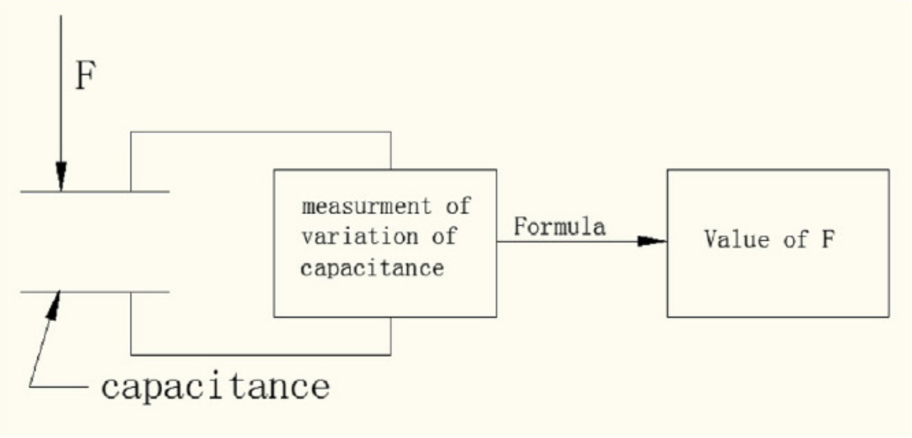


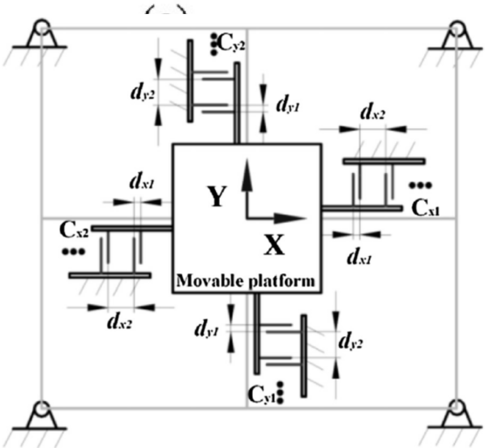
Fig. 3. An application of strain gauge-based force sensors [21].

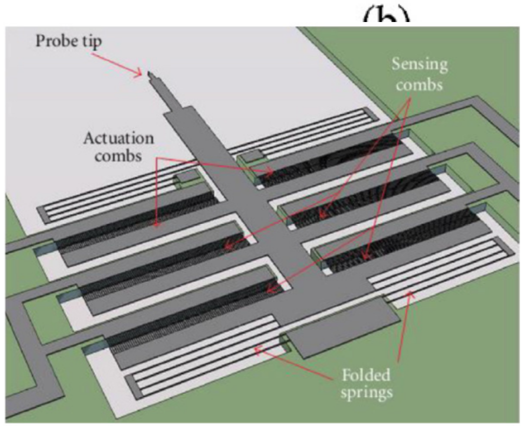
1) C. Ma, J. Du, Y. Liu, Y. Chu, Overview of micro-force sensing methods, in: K.M. Lee, P. Yarlagadda, Y.M. Lu (Eds.), Progress In Mechatronics And Information Technology, 2015, Pts 1 And 22,014, 25–31.
2) D.M. Stefanescu, A.T. Farcasiu, A. Toader, Strain gauge force transducer and virtual instrumentation used in a measurement system for retention forces of palatal plates or removable dentures, Sens. J. IEEE 12 (2012) 2968–2973.
3) H. Yousef, M. Boukallel, K. Althoefer, Tactile sensing for dexterous in-hand manipulation in robotics—a review, Sens. Actuators A: Phys. 167 (2011) 171–187.

Capacitive Force Sensor…





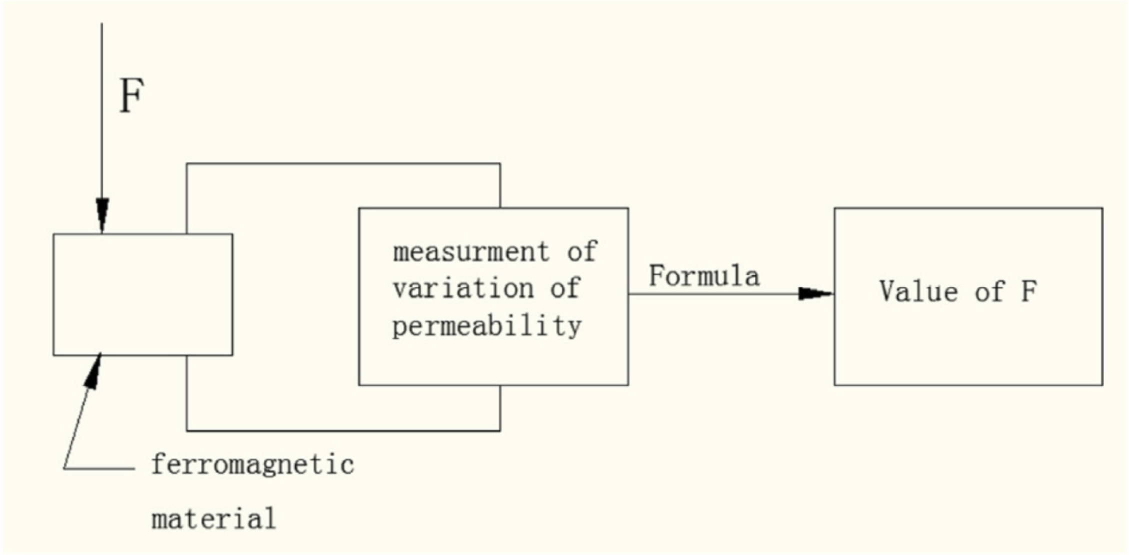




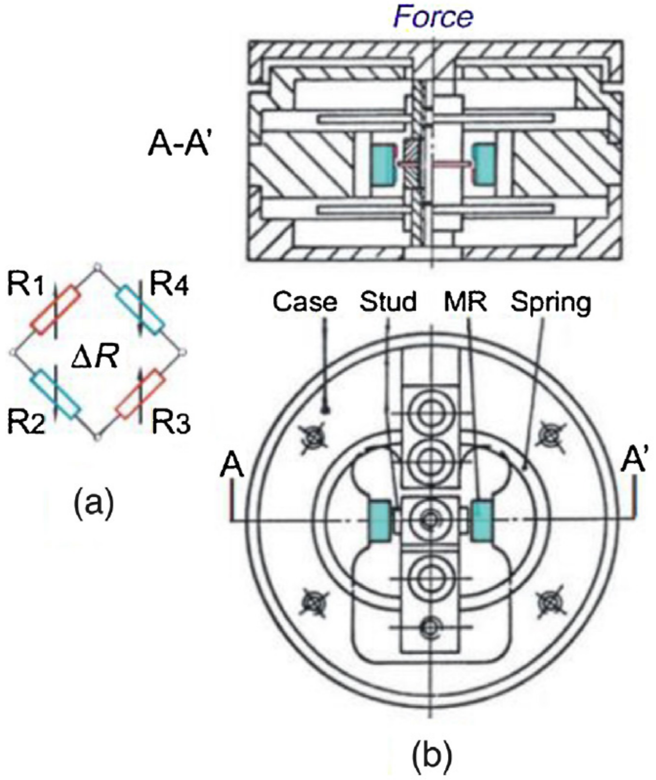
- Functions by measuring force by changes in the distance between plates.
- Able to measure normal and shear stress.
- Range: mN to pN.
- RC circuits may account for up to 30% of sensors.
- Signals are obtained by capacitance to frequency conversion (oscillator), switched capacitor or capacitive AC bridge circuits.

H. Yousef, M. Boukallel, K. Althoefer, Tactile sensing for dexterous in-hand manipulation in robotics—a review, Sens. Actuators A: Phys. 167 (2011) 171–187.
S. Nadvi, D.P. Butler, Z. Celik-Butler, I.E. Goenenli, Micromachined force sensors using thin film nickel-chromium piezoresistors, J. Micromech. Microeng. 22 (2012).
L. Zhang, J. Dong, Design, fabrication, and testing of a SOI-MEMS-Based active microprobe for potential cellular force sensing applications, Adv. Mech. Eng. (2012).

Piezomagnetic Force Sensor…



- *Magnetoelastic effect* - when a ferromagnetic material subjects to mechanical stress, its internal strain leads to the changes in permeability.
- Dynamic and static force measurements.
- Does not need to be glued to the surface.



Wheatstone bridge configuration with magnetoresistive sensors. Resistance varies with magnetic field strength.

D.M. Stefanescu, M.A. Anghel, Electrical methods for force measurement - a brief survey, Measurement 46 (2013) 949–959.

Flow Sensors

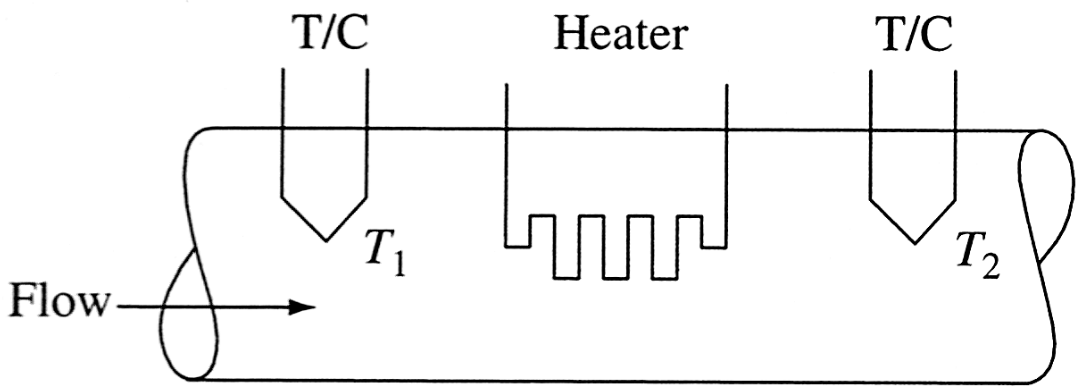
- Measurement of gas and liquid flow rates.
- May be integrated with microfluidics.
- Useful for blood and urine flow, respiratory monitoring and drug delivery devices.
- Advantages of high sensitivity, accuracy and precision, low power consumption and small size.
- Broadly categorized as thermal (thermal exchange) and non-thermal flow sensors.

Thermal Flow Sensing…

- Hot wire or hot element anemometers.
  - Based on convective heat exchange taking place when the fluid flow passes over the sensing element (hot body).
  - Operate in constant temperature mode or in constant current mode.
- Calorimetric sensors.
  - Based on the monitoring of the asymmetry of temperature profile around the hot body which is modulated by the fluid flow.

Example of a Thermal Flow Sensor…

- The heat transferred per unit time from a resistive wire heater to a moving liquid is monitored with a thermocouple:



(a)

Gardner, JW, VK Varadan and OO Awadelkarim, *Microsensors, MEMS and Smart Devices*. John Wiley & Sons, Ltd. W. Sussex (2001).

- In a steady state, the mass flow rate can be determined:

$$Q_m = \frac{dm}{dt} = \frac{P_h}{c_m}(T_2 - T_1)$$

Where

Q_m is the mass flow rate,

P_h is the heat transferred per unit time,

c_m is the specific heat capacity of the fluid and

T_1, T_2 are temperature.

- The volumetric flow rate is calculated as follows:

$$Q_V = \frac{dV}{dt} = \frac{Q_m}{\rho_m}$$

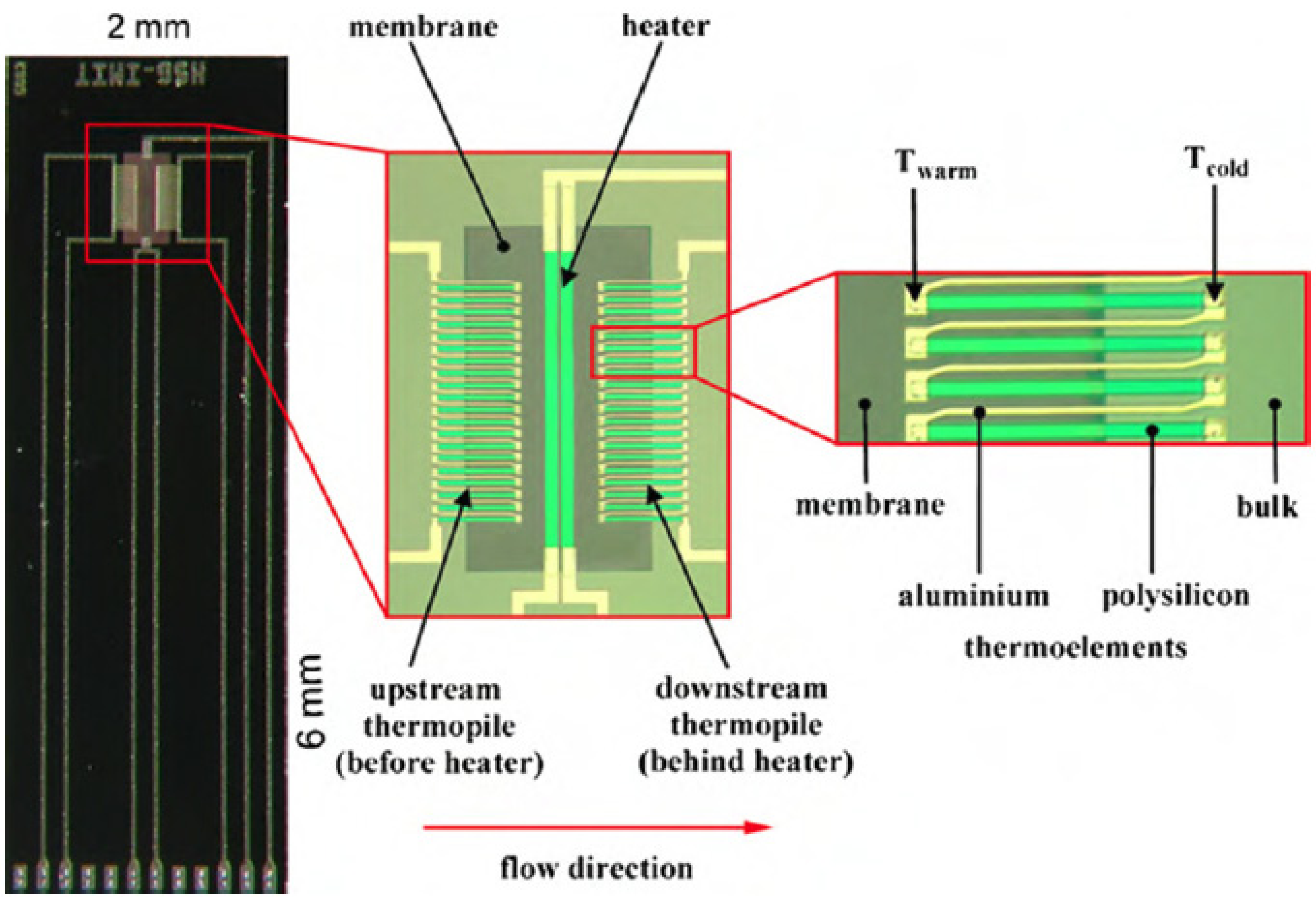
Where

Q_V is the volumetric flow rate,

Q_m is the mass flow rate and

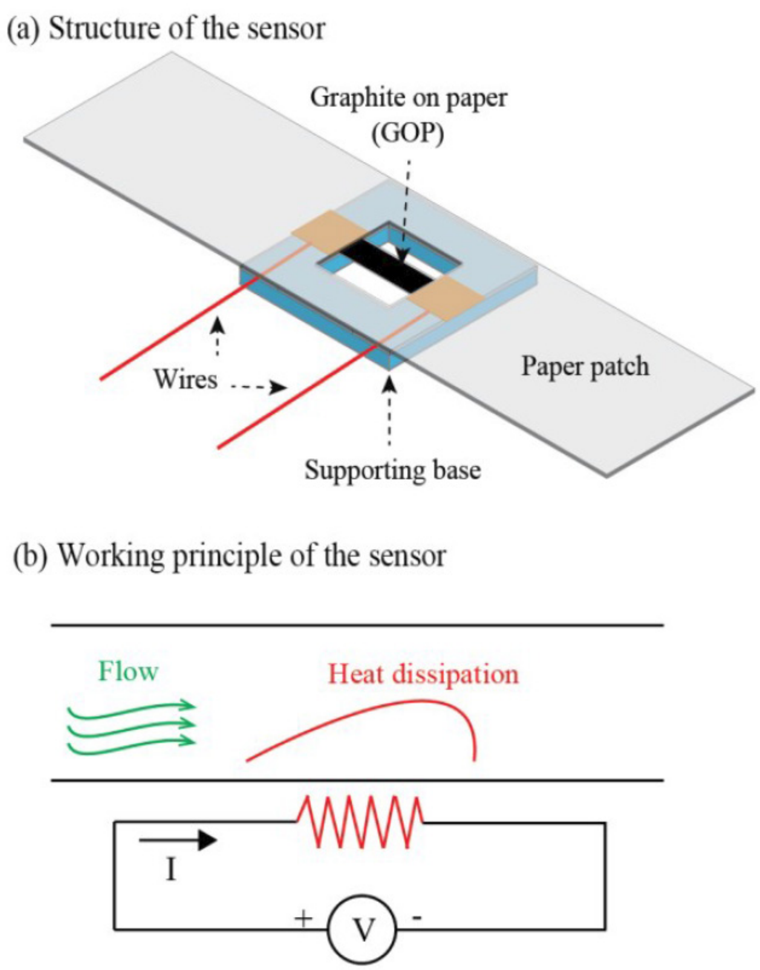
ρ_m is the density.

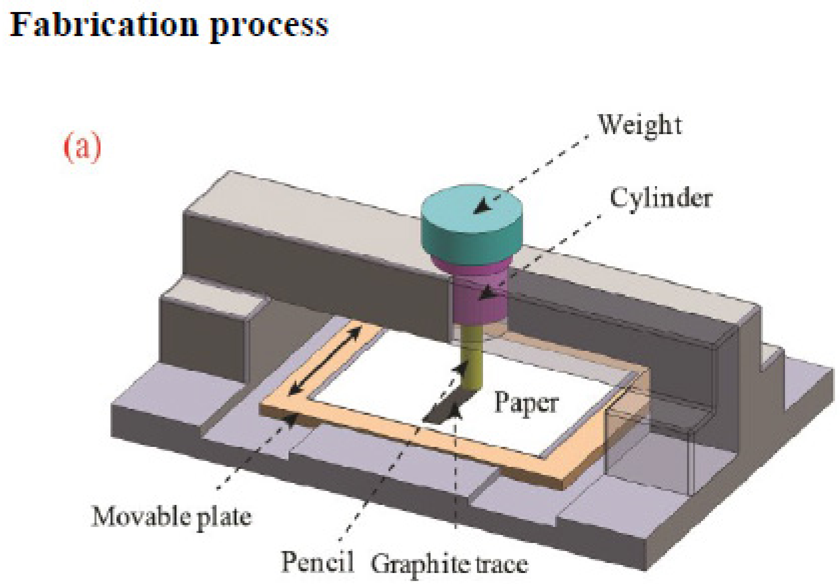
Thermal Flow Sensor with Thermopile…

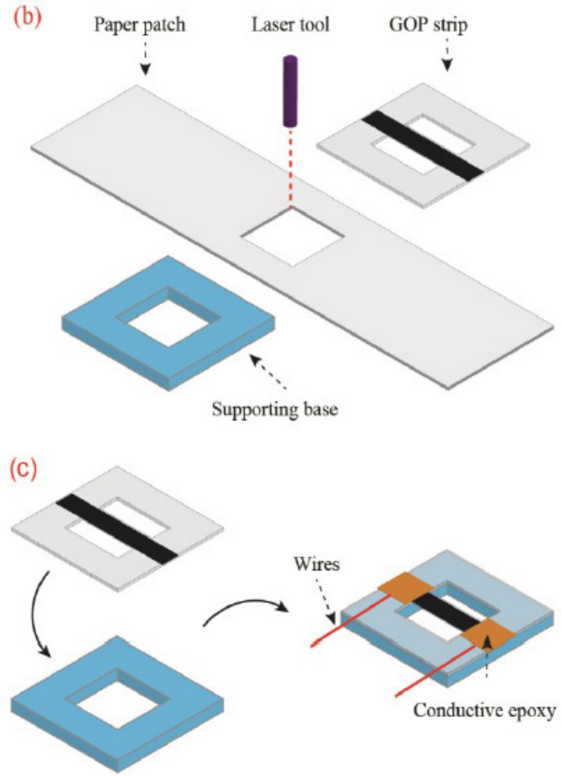


Silvestri, S. and E. Schena Micromachined Flow Sensors in Biomedical Applications. *Micromachines* 2012, 3, 225-243

Pencil Graphite Thermal Flow Sensor…

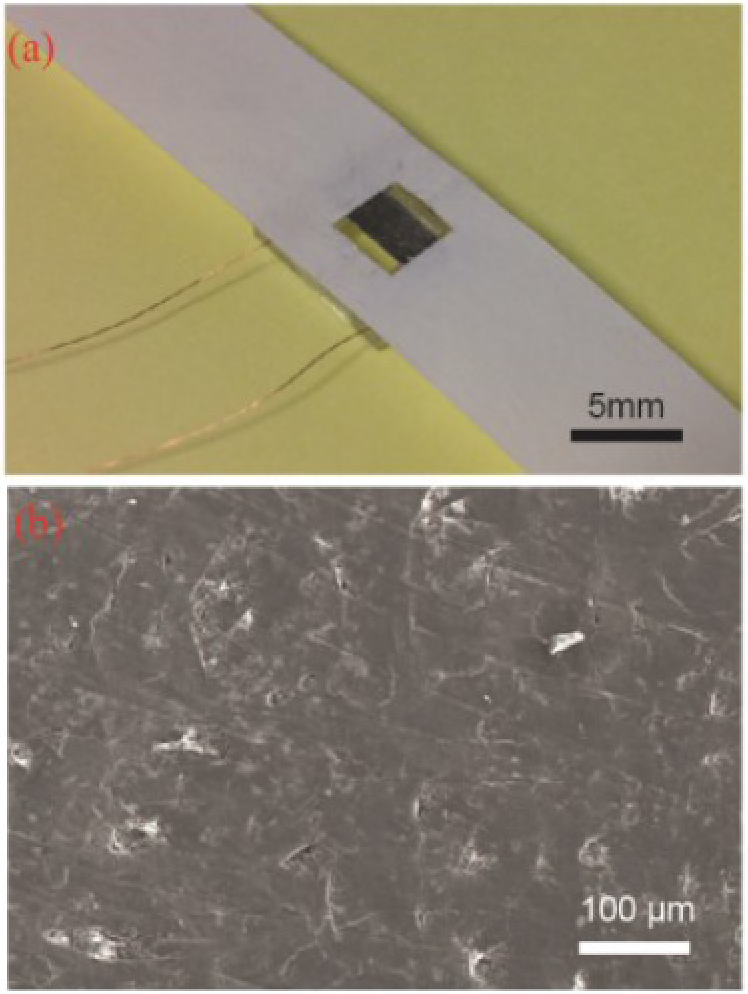


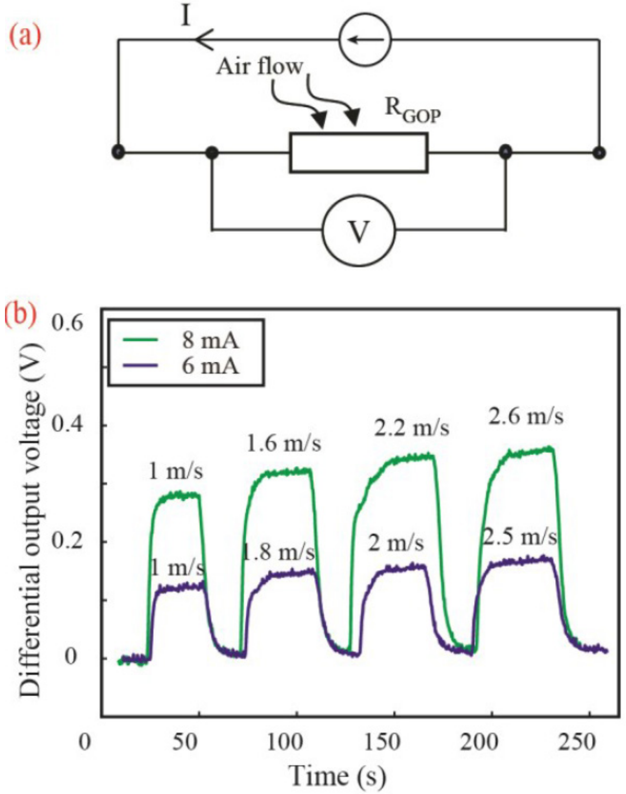


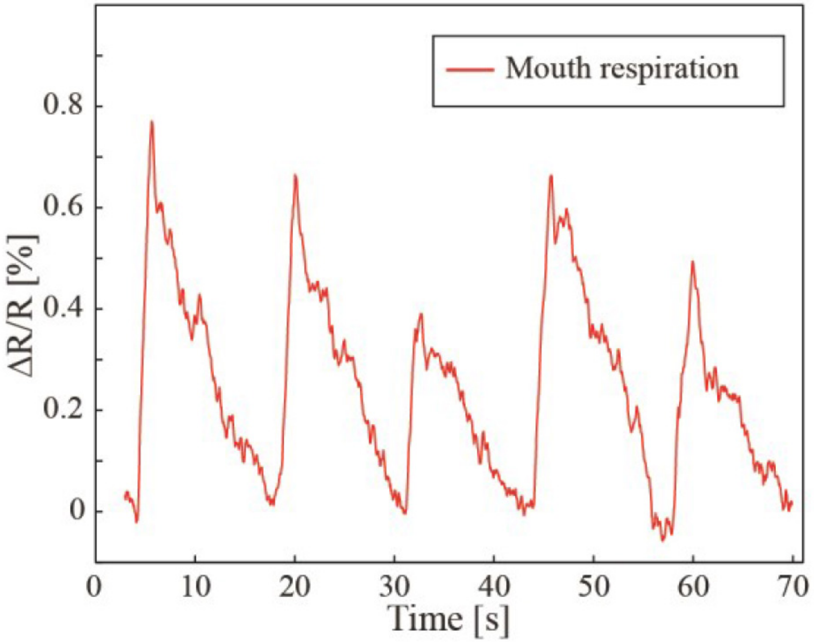


Steven S. Saliterman

Dinh T, Phan H, Qamar A, et al. Environment-friendly wearable thermal flow sensors for noninvasive respiratory monitoring. Paper presented at: 2017 IEEE 30th International Conference on Micro Electro Mechanical Systems (MEMS); 22-26 Jan. 2017, 2017.







- Constant current applied.
- Voltage changes with changes in air flow rate.

Human respirations.

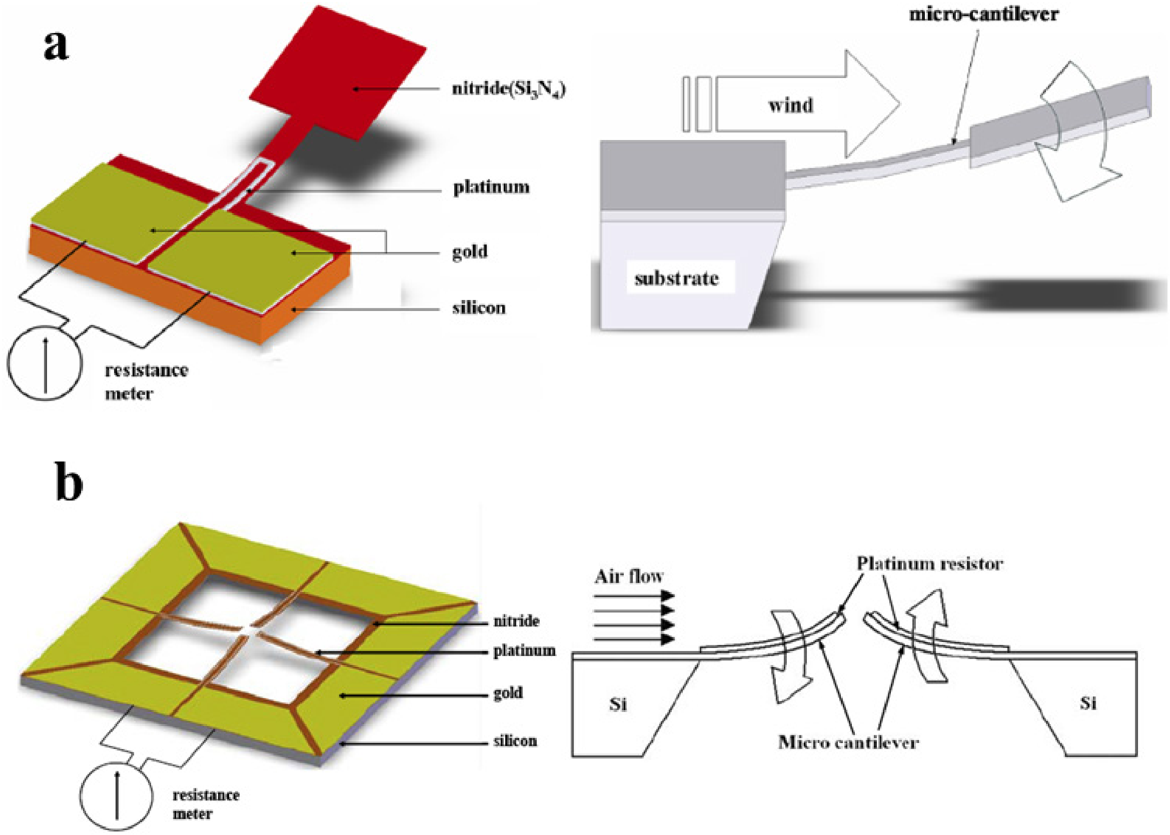
Dinh T, Phan H, Qamar A, et al. Environment-friendly wearable thermal flow sensors for noninvasive respiratory monitoring. Paper presented at: 2017 IEEE 30th International Conference on Micro Electro Mechanical Systems (MEMS); 22-26 Jan. 2017, 2017.

Non-Thermal Flow Sensors

- Cantilever type flow sensors
  - Measuring the drag-force on a cantilever beam.
- Differential pressure-based flow sensors
  - When a fluid flow passes through a duct, or over a surface, it produces a pressure drop depending on the mean velocity of the fluid.
- Electromagnetic
- Laser Doppler flowmeter
  - The phenomenon is due to the interaction between an electromagnetic or acoustic wave and a moving object: the wave is reflected back showing a frequency different from the incident one.
- Lift-force and drag flow sensors
  - Based on the force acting on a body located in a fluid flow.
- Microrotor
  - Rotating turbine
- Resonating flow sensors
  - Temperature effects resonance frequency of a vibrating membrane.

Silvestri, S. and E. Schena Micromachined Flow Sensors in Biomedical Applications. *Micromachines* 2012, 3, 225-243

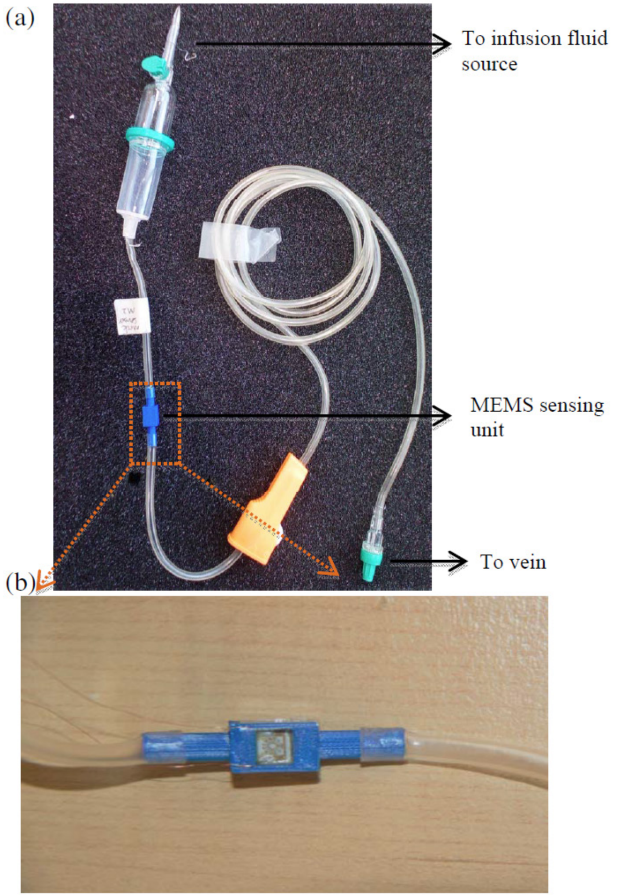
Cantilever Type Sensor…

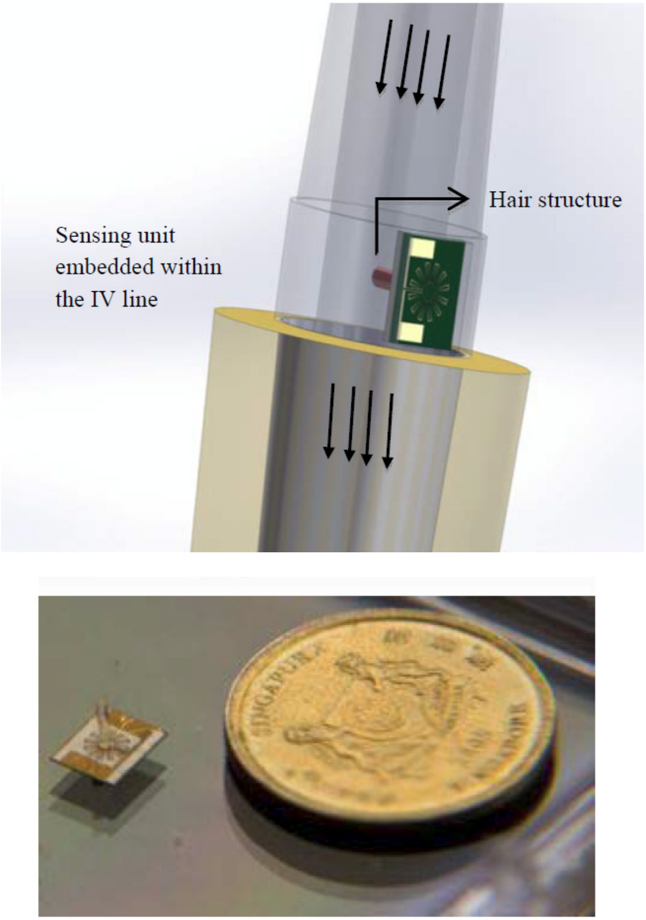


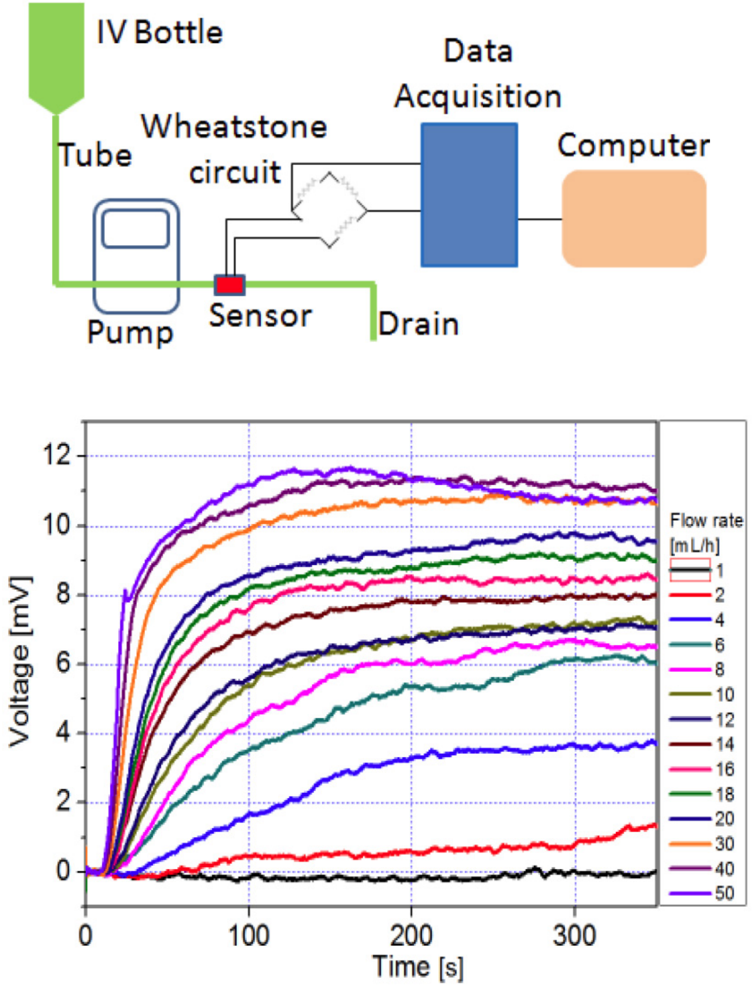
Able to Sense Direction

Silvestri, S. and E. Schena Micromachined Flow Sensors in Biomedical Applications. *Micromachines* 2012, 3, 225-243

Intravenous Infusion Flow Sensor…

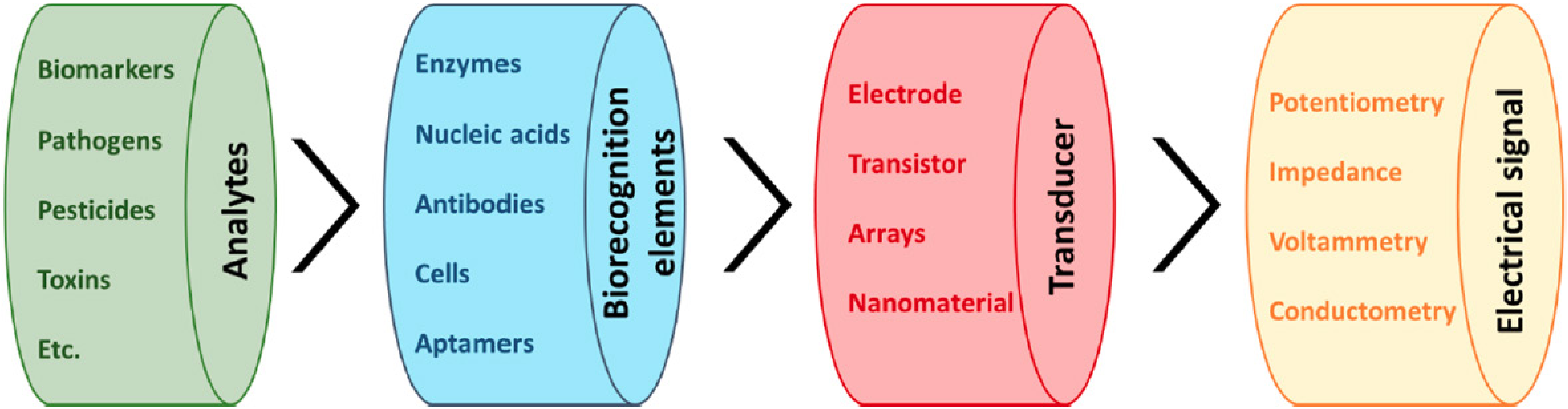






Kottapalli AGP, Shen Z, Asadnia M, et al. Polymer MEMS sensor for flow monitoring in biomedical device applications. 2017 IEEE 30th International Conference on Micro Electro Mechanical Systems (MEMS); 22-26 Jan. 2017, 2017.

Electrochemical Biosensing



Sample preparation – filtration, extraction, purification and enrichment.

Ideally retained in direct contact.
The biomolecules change physical quantities, such as charge, mass or photons.

Measurement of current, potential, or field effect, realized through label-free or labeled approaches.

Analytes are detected with *biological recognition elements*, including enzymes, nucleic acids, antibodies, cells and aptamers.
Electrical signals are derived from *transducers*, including electrodes, field effect transistors (FETs), arrays and nanomaterials.

Wongkaew N, Simsek M, Griesche C, Baeumner AJ. Functional Nanomaterials and Nanostructures Enhancing Electrochemical Biosensors and Lab-on-a-Chip Performances: Recent Progress, Applications, and Future Perspective. *Chemical Reviews.* 2019;119(1):120-194.

Applications in Medicine

- Glucose and anticoagulation monitoring:

Images courtesy of LifeScan, Inc. and HemoSense, Inc.

- Temperature:

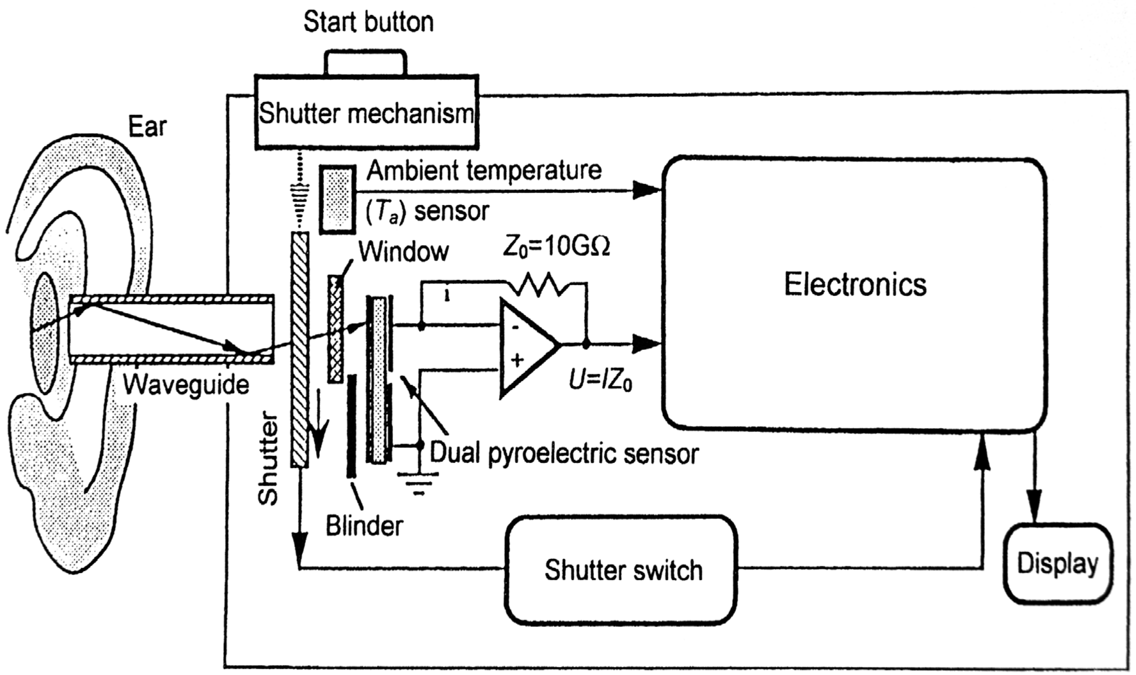
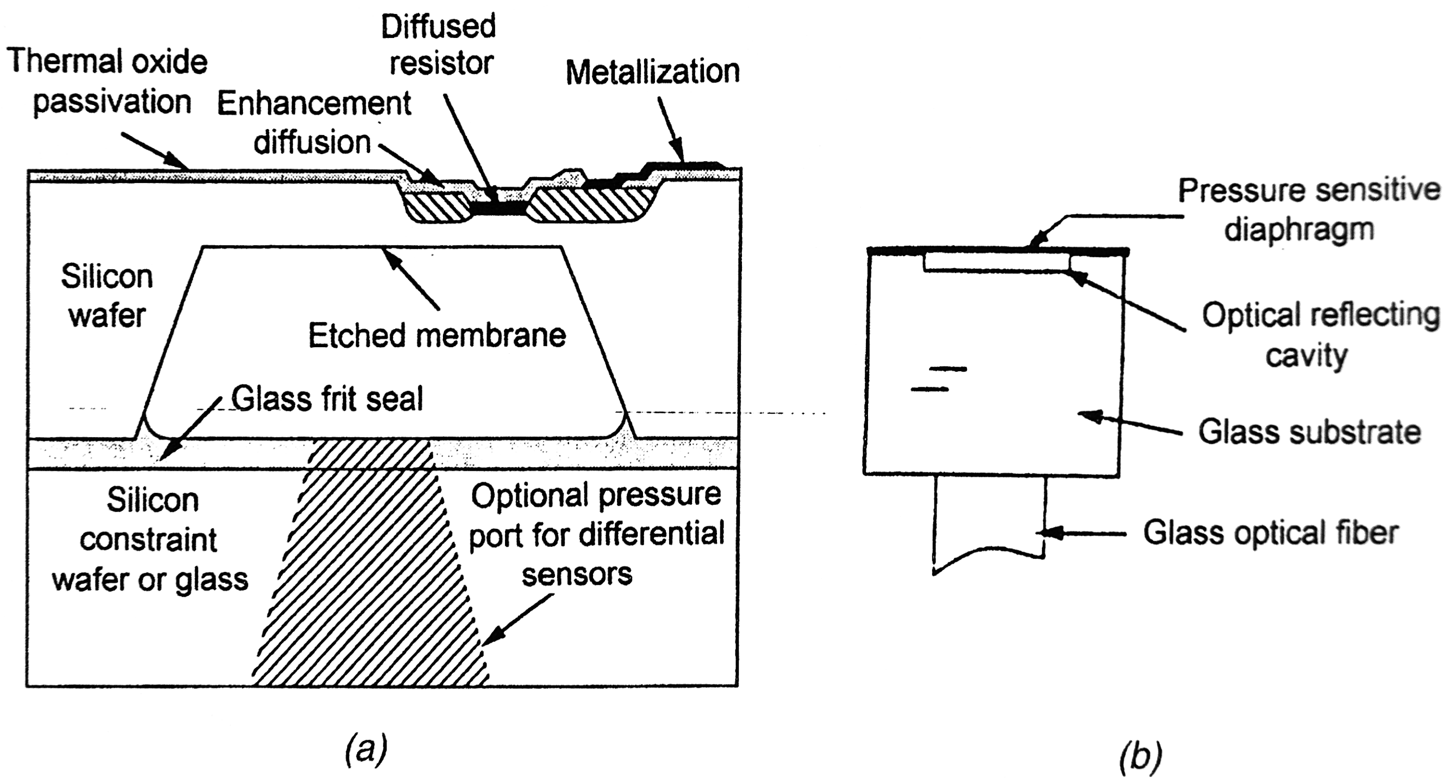


Image courtesy of Braun

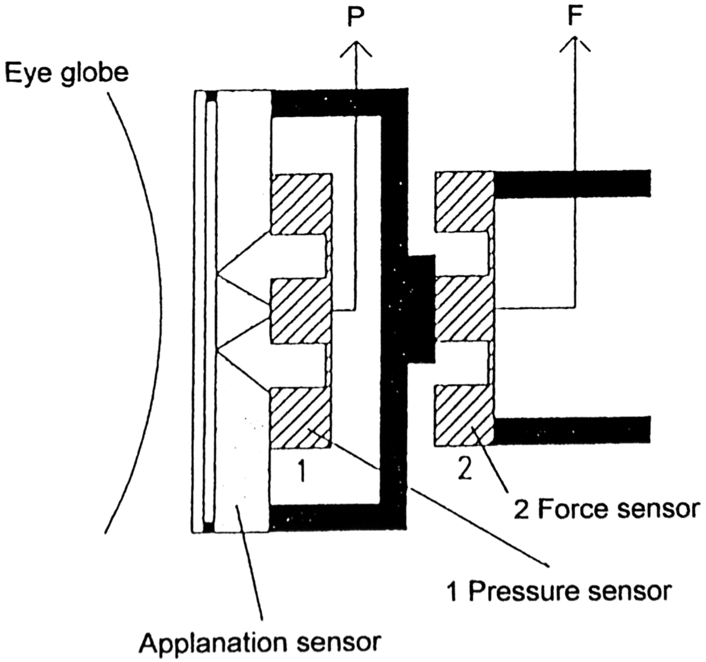
Harsanyi, G., Sensors in Biomedical Applications, Technology and Applications. Technomic Pub. Co., Lancaster, PA (2000)

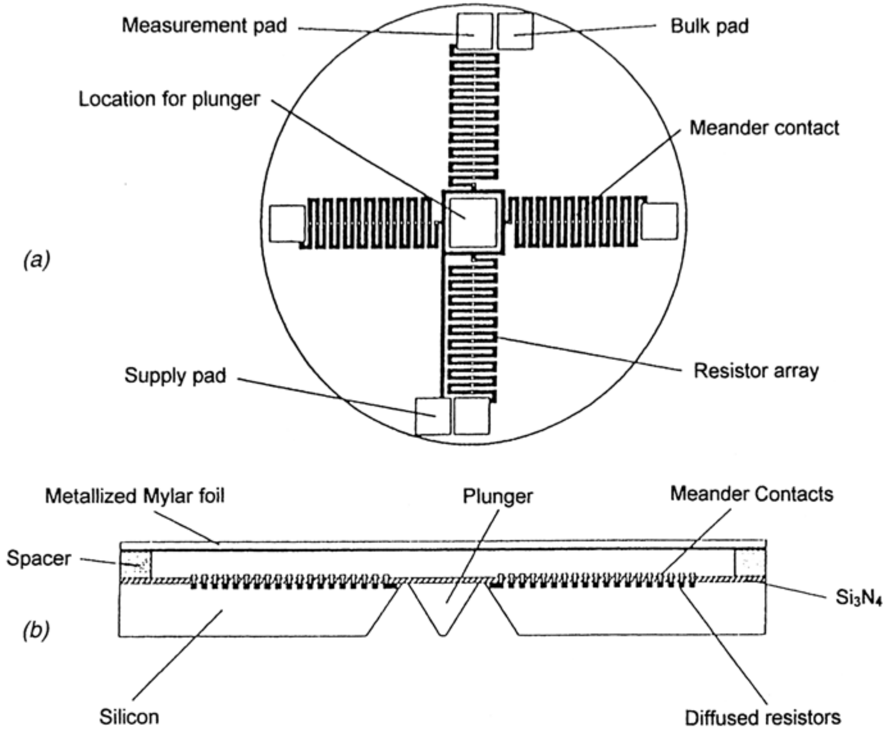
- Pressure:



Fraden, J. “Noncontact temperature measurement in medicine.” *Bioinstrumentation and Biosensors*, D.L. Wise, Ed, Marcel Dekker (1991).

- Intraocular pressure:

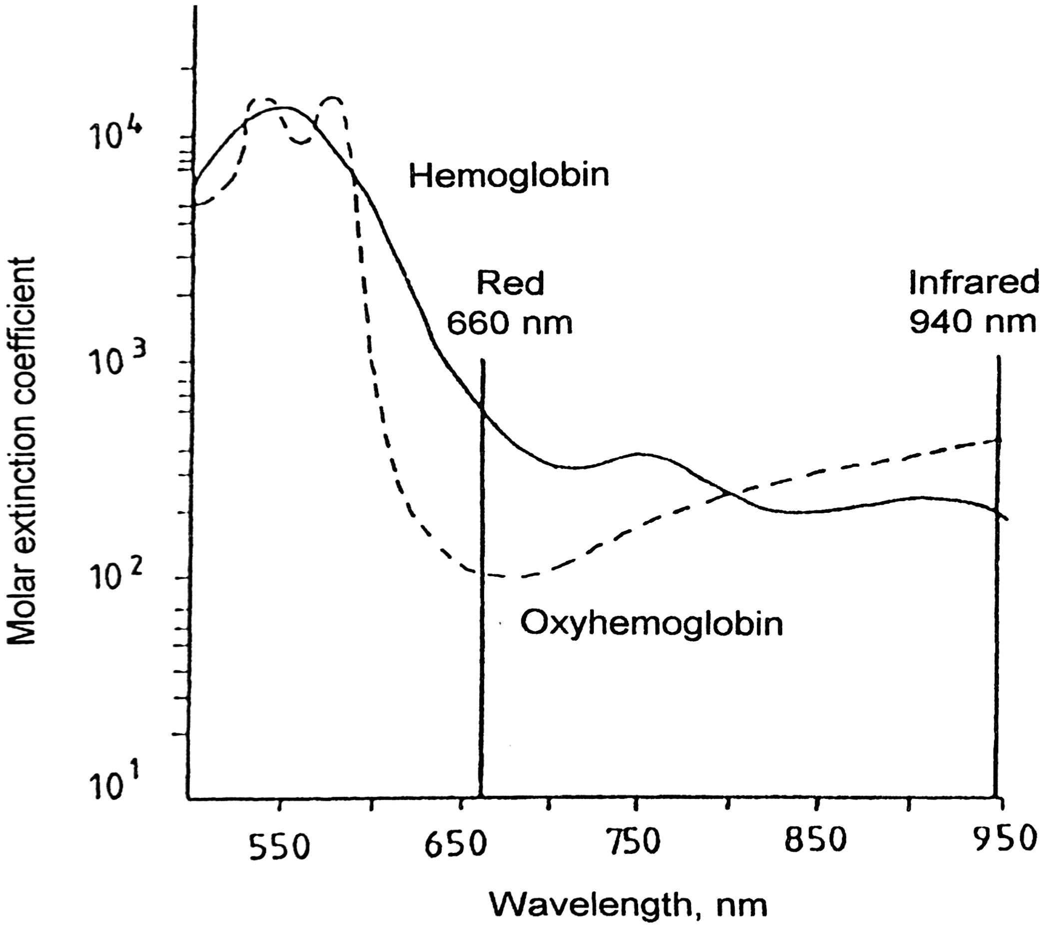




Steven S. Saliterman

Bergveld, A.P., "The merit of using silicon for the development of hearing aid microphones and intraocular pressure sensors." *Senors and Actuators* 41:42, pp. 223-229 (1994)

- Pulse oximetry:



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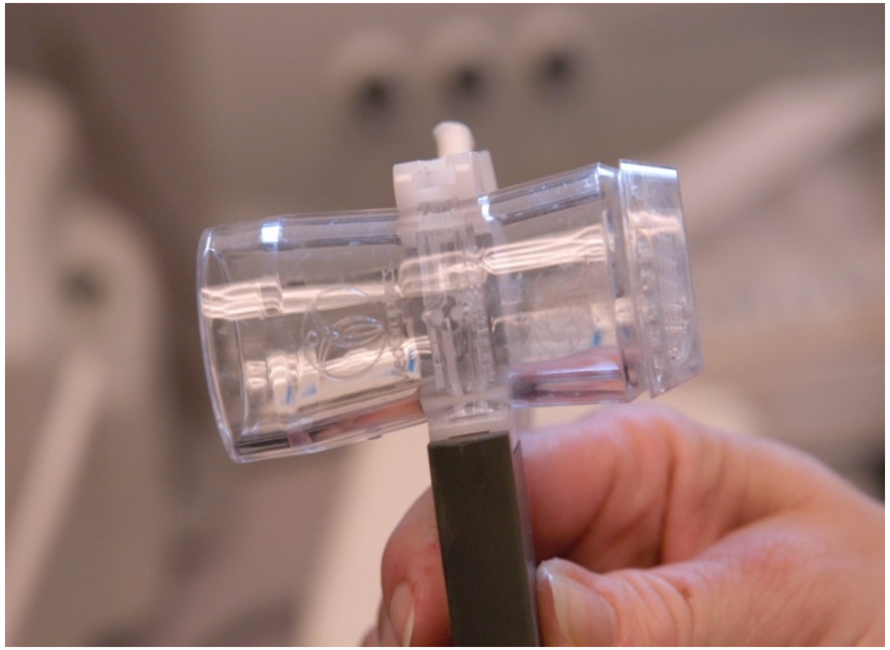
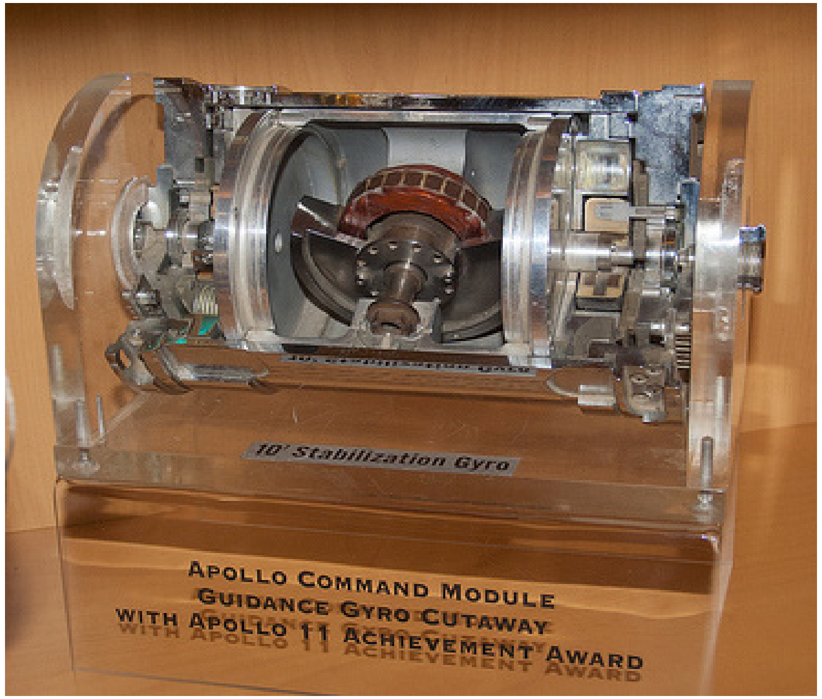
Parker, D. "Sensors for monitoring blood gasses in intensive care." *J Phys. E. Sci. Instrum*. 20, pp. 1103-1112 (1987).

- Respiratory – spirometry and CO_2:



- Implanted pacemaker and rhythm monitor:

Position Sensing – Gyroscope Evolution

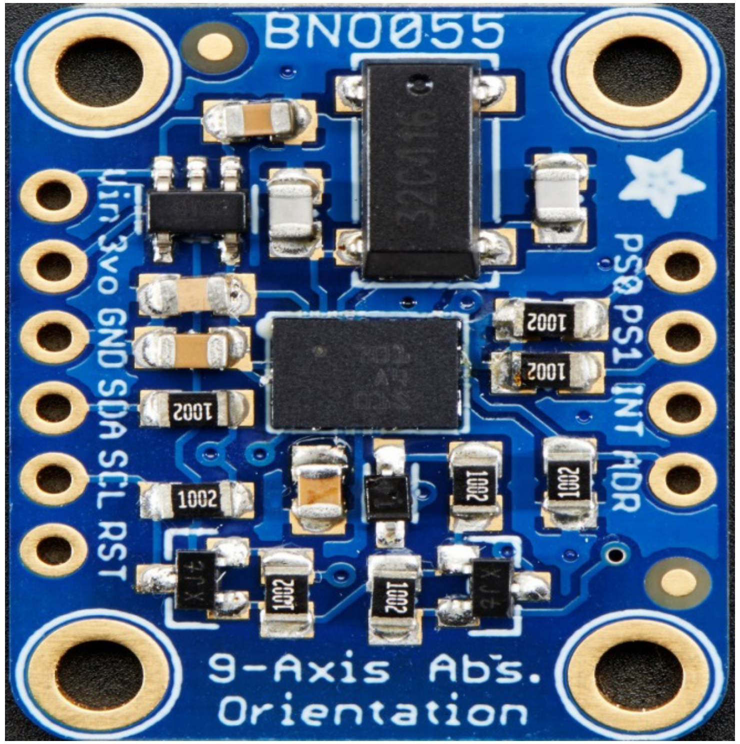


Apollo 11 Gyroscope 1969

Apollo Command Module 1973,
Johnson Space Center, Prof. Saliterman

Gyroscope image courtesy of https://www.flickr.com/photos/blafetra/14524883649

Adafruit BN0055 – Sensor Fusion…



- **Absolute Orientation** (Euler Vector, 100Hz) Three axis orientation data based on a 360° sphere.
- **Absolute Orientation** (Quaterion, 100Hz) Four point quaternion output for more accurate data manipulation.
- **Angular Velocity Vector** (100Hz) Three axis of 'rotation speed' in rad/s.
- **Acceleration Vector** (100Hz) Three axis of acceleration (gravity + linear motion) in m/s^2.
- **Magnetic Field Strength Vector** (20Hz) Three axis of magnetic field sensing in micro Tesla (uT).
- **Linear Acceleration Vector** (100Hz) Three axis of linear acceleration data (acceleration minus gravity) in m/s^2.
- **Gravity Vector** (100Hz) Three axis of gravitational acceleration (minus any movement) in m/s^2.
- **Temperature** (1Hz) Ambient temperature in degrees celsius.

Courtesy of Adafruit

Summary

- A sensor measures information from the environment (e.g. a blood *analyte*, or *measurand*) and provides an electrical signal in response.
- Sensor types introduced today:
  - Wheatstone Bridge
  - Piezoelectric
  - Thermosensors
  - Force & Microforce
  - Flow – Thermal & Non-Thermal Methods
  - Electrochemical Biosensors
  - Position Sensors
- Clinical Applications