Lecture 3: Survey of sensing principles

- Sensor classification
- Mechanical sensors
- Thermal sensors
- Chemical sensors

Sensor classification schemes

- **Sensors can be classified, among others, according to one of the following criteria**
  - **Power supply requirements**
    - Passive and active
  - **Nature of the output signal**
    - Digital and analog
  - **Measurement operational mode**
    - Deflection and null modes
  - Input/output dynamic relationships (covered in Lecture 2)
    - Zero, first, second order, etc.
  - Measurand
    - Mechanical, thermal, magnetic, radiant, chemical
  - Physical measurement variable
    - Resistance, inductance, capacitance, etc.

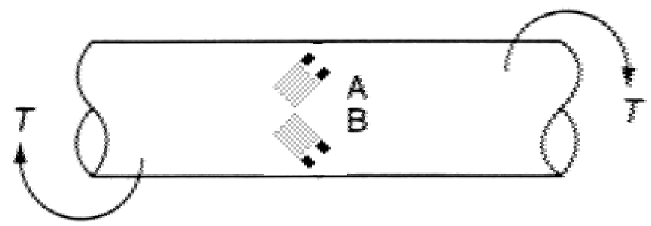
Passive and active sensors

- **Passive or self-generating**
  - Directly generate an electrical signal in response to an external stimuli without the need for an external power supply
    - Output signal power comes from the stimulus
  - Examples
    - Thermocouple
    - Piezoelectric sensors
- **Active or modulating**
  - These sensors require external power supply or an excitation signal for their operation
    - Output signal power comes from the power supply
  - Examples
    - Thermistors
    - Chemo-resistors

Analog and digital sensors

Analog sensors

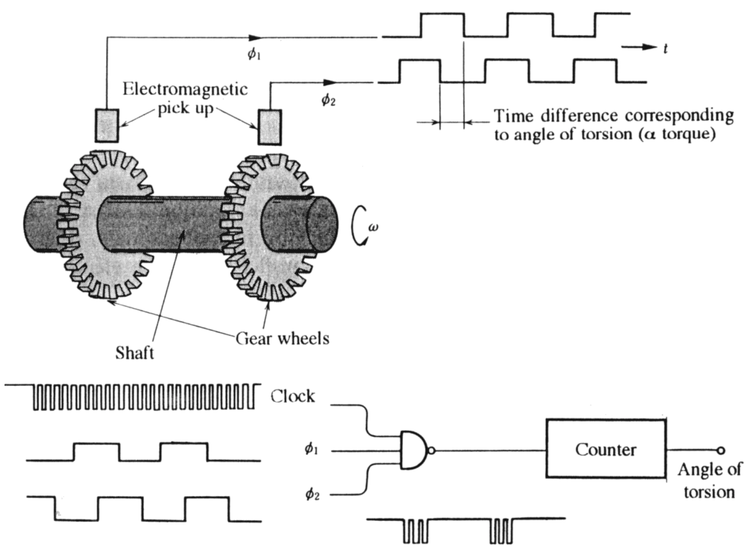
- Provide a signal that is continuous in both its magnitude and temporal or spatial content
  - Most of the physical measurands are analog in nature
- Examples: Temperature, displacement, light intensity



From [Tay97]

Digital sensors

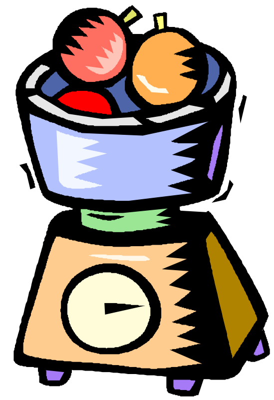
- Their output takes the form of discrete steps or states
  - Digital signals are more repeatable, reliable and easier to transmit
- Examples: Shaft encoder, contact switch



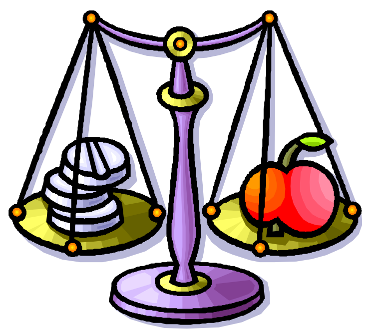
From [Ohb92]

Operational modes

- **Deflection mode**
  - The sensor or instrument generates a response that is a deflection or a deviation from the initial condition of the instrument
    - The deflection is proportional to the measurand of interest



- **Null mode**
  - The sensor or instrument exerts an influence on the measured system so as to oppose the effect of the measurand
    - The influence and measurand are balanced (typically through feedback) until they are equal but opposite in value, yielding a null measurement



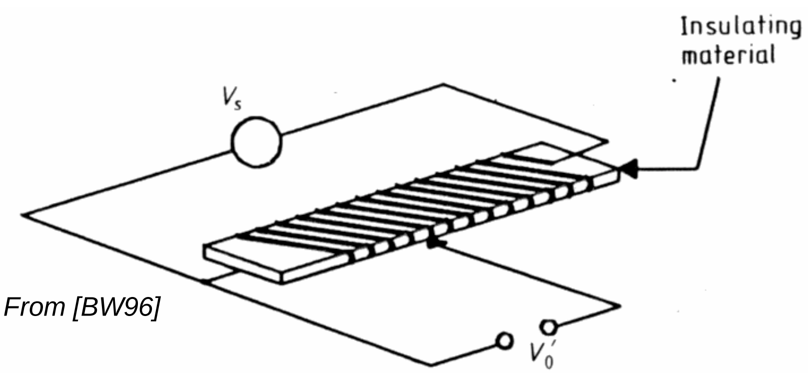
- **Null mode instrumentation can produce very accurate measurements, but are not as fast as deflection instruments**

Mechanical measurands

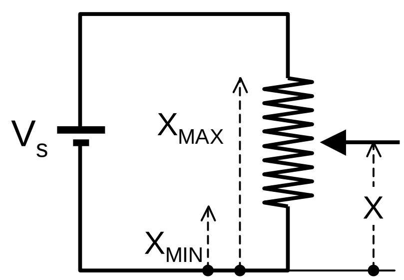
- **Displacement**
  - Resistive sensors
  - Capacitive sensors
  - Inductive sensors
- **Force and acceleration**
  - Strain gauges
  - Cantilever beam-based sensors

Resistive displacement sensors

- **A resistance with a movable contact (a potentiometer) may be used to measure linear or rotational displacements**
  - A known voltage is applied to the resistor ends
  - The contact is attached to the moving object of interest
  - The output voltage at the contact is proportional to the displacement
- **Notes**
  - Non-linearities as a result of loading effects
  - Resolution due to limited number of turns per unit distance
  - Contact wear as a result of frictions



From [BW96]

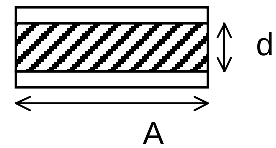


$$V_0 = V_S \frac{X - X_{MIN}}{X_{MAX} - X_{MIN}}$$

Capacitive displacement sensors

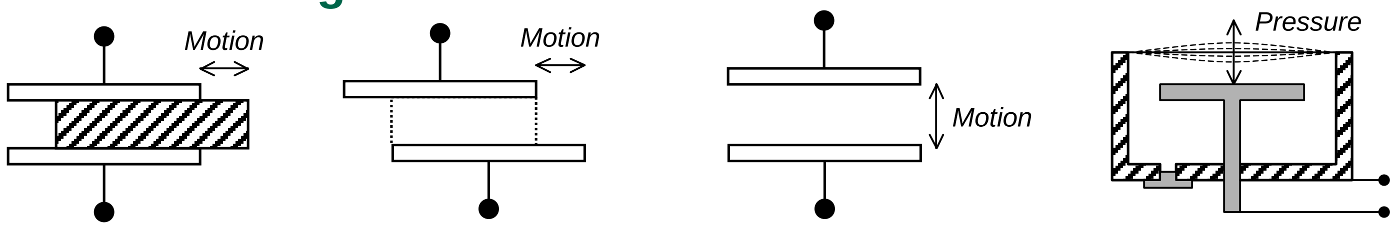
- **The capacitance of a parallel plate capacitor is**

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



  - d is the separation between the plates, A is the area of the plates, ε_0 is the permitivity of air and ε_r is the relative permitivity of the dielectric

- **A moving object is attached to the dielectric or the plates to generate capacitance changes**

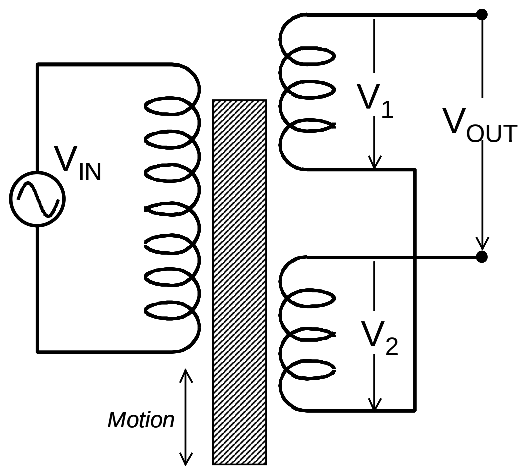


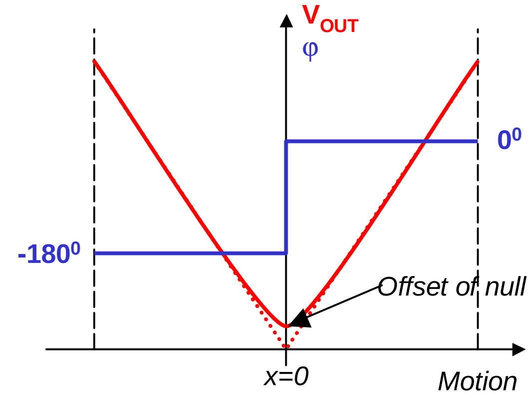
- **Notes**
  - Variable distance (d) sensors operate over a range of a few millimeters
  - Cross-sensitivity to temperature and humidity (specially if the dielectric is air)
  - Capacitive sensors are also commonly used to measure pressure
    - “Condenser” microphones measure changes in air pressure of incoming sound waves

Inductive displacement sensors

Linear Variable Differential Transformer (LVDT)

- Motion of a magnetic core changes the mutual inductance of two secondary coils relative to a primary coil





  - Primary coil voltage: $V_S\sin(\omega t)$
  - Secondary coil induced emf: $V_1=k_1\sin(\omega t+\varphi)$ and $V_2=k_2\sin(\omega t+\varphi)$
    - k_1 and k_2 depend on the amount of coupling between the primary and the secondary coils, which is proportional to the position of the coil
      - When the coil is in the central position, $k_1=k_2 \Rightarrow V_{OUT}=V_1-V_2=0$
      - When the coil is is displaced x units, $k_1\neq k_2 \Rightarrow V_{OUT}=(k_1-k_2)\sin(\omega t+\varphi)$
      - Positive or negative displacements are determined from the phase of V_{OUT}

Inductive displacement sensors (cont)

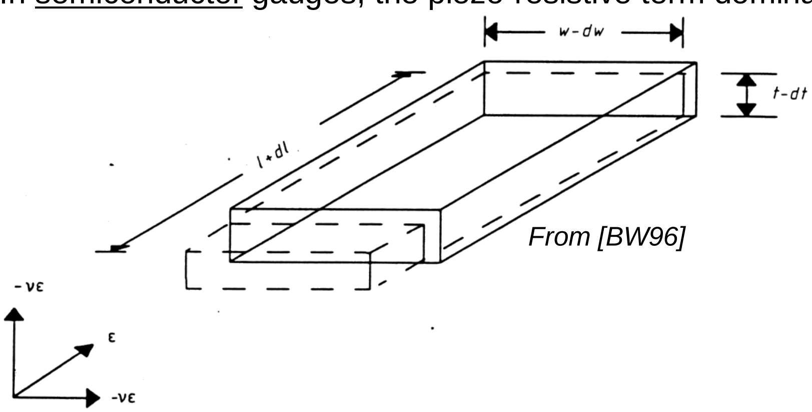
- **LVDT Characteristics**
  - Typical LVDTs run at 5V, 2kHz
  - LVDTs can measure from mm down to μm
  - Due to small variations in the windings, a small residual voltage appears at the output when the coil is in the central position
- **Advantages of the LVDT over other displacement sensors**
  - No mechanical wear ensures a long life
  - Complete electrical isolation
  - DC versions with integrated oscillators are available

Strain gauges

- **Strain gauges are devices whose resistance changes with stress (piezo-resistive effect)**
  - Strain is a fractional change ($\Delta L/L$) in the dimensions of an object as a result of mechanical stress (force/area)
  - The resistance R of a strip of material of length L, cross-section A and resistivity ρ is $R=\rho L/A$
  - Differentiating, the gauge factor G becomes

$$\frac{\Delta R}{R}=\frac{\Delta L}{L}-\frac{\Delta A}{A}+\frac{\Delta\rho}{\rho}\cong(1+2\nu)\frac{\Delta L}{L}+\frac{\Delta\rho}{\rho}\Rightarrow G=\frac{\Delta R/R}{\Delta L/L}=\underbrace{(1+2\nu)}_{\text{GEOMETRIC EFFECT}}+\underbrace{\frac{\Delta\rho}{\rho\Delta L}}_{\text{PIEZO-RESISTIVE EFFECT}}$$

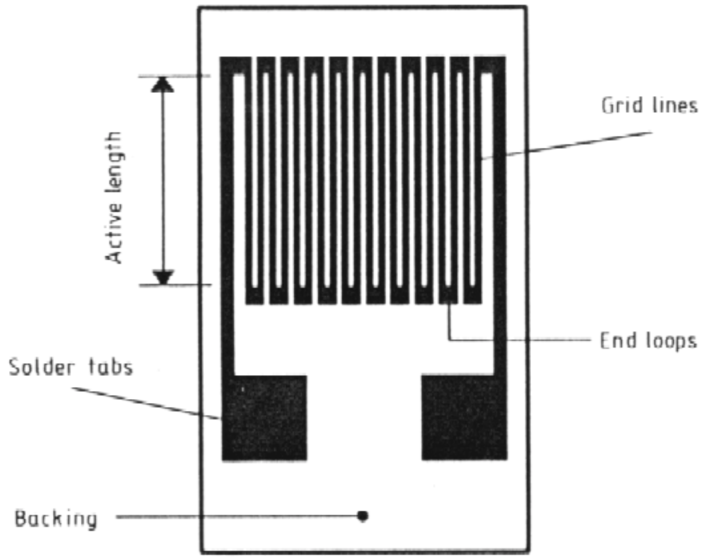
- Where ν is the Poisson's ratio ($\nu\cong0.3$), which determines the strain in directions normal to L
  - In <u>metal</u> foil gauges, the geometric term dominates ($G\cong2$)
  - In <u>semiconductor</u> gauges, the piezo-resistive term dominates ($G\cong100$)



From [BW96]

Strain gauges

- **Fabrication and use**
  - Typical strain gauges consist of a foil or wire grid covered by two sheets of insulation (polyimide)
  - The gauge is attached to the desired object with an adhesive
  - Longitudinal segments are aligned with the direction of stress
  - Sensitivity to traverse stress can be neglected

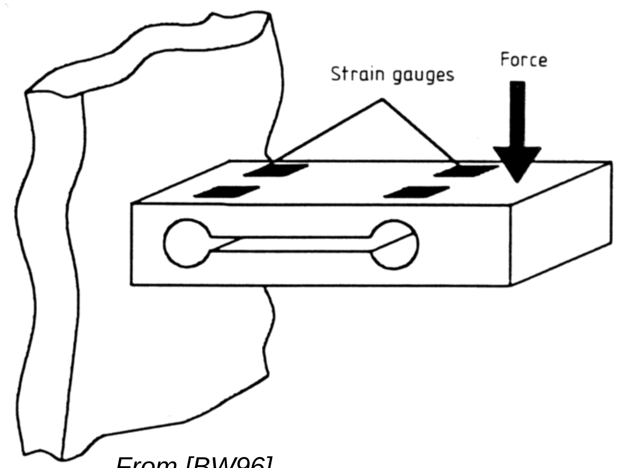


From [BW96]

- **Notes**
  - Temperature effects are quite pronounced in semiconductor gauges
    - To compensate it is common to place “dummy” gauges that are subject to the same temperature changes but no mechanical stress
  - Resistance changes are typically very small
    - Strain gauges are almost invariable used in a Wheatstone bridge (to be covered in lectures 4-6)

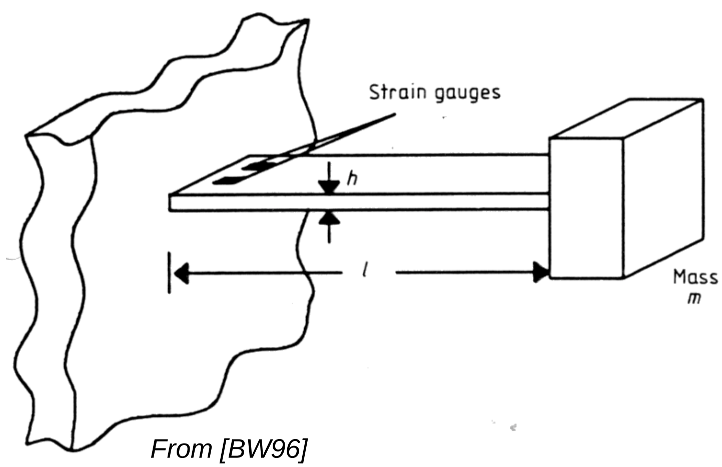
Force and acceleration sensors

- **Force sensors**
  - The coupled-double-beam load cell
    - Dumb-bell cut-out provides areas of maximum strain for the gauges
    - Cantilever beam bends in an S-shape
      - This induces both compressive and tensile strains that can be easily measured in a bridge arrangement



From [BW96]

- **Acceleration sensors**
  - Spring-mass-damper accelerometer
    - Covered in the previous lecture
  - Cantilever-beam with strain gauges
    - A seismic mass is attached to the end of the cantilever
    - Dampening is usually performed with viscous fluids or permanent magnets



From [BW96]

Temperature sensors

- **Thermoresistive sensors**
  - Resistive Temperature Devices (RTD)
  - Thermistors
- **Thermoelectric sensors**
  - The Seebeck effect
  - The Peltier effect
  - Thermocouples
- **p-n junction sensors**
  - Covered in the Lab

Thermoresistive sensors

- **Based on materials whose resistance changes in accordance with temperature**
  - Resistance Temperature Detectors (RTDs)
    - The material is a metal
      - Platinum, Nickel, Copper are typically used
    - Positive temperature coefficients

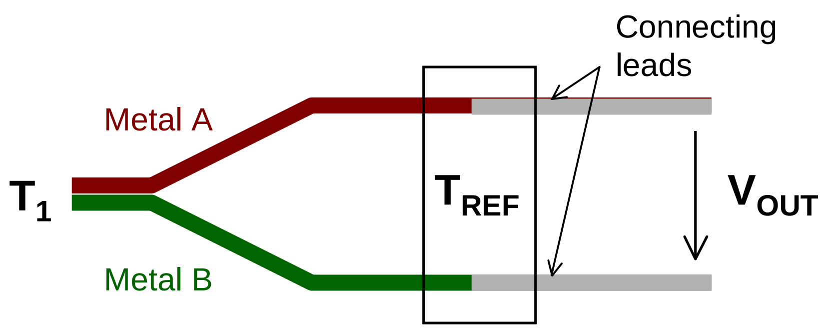
$$R_T = R_0\left[1 + \alpha_1 T + \alpha_2 T^2 + \cdots \alpha_n T^n + \right] \cong R_0\left[1 + \alpha_1 T\right]$$

  - Thermistors (“thermally sensitive resistor”)
    - The material is a semiconductor
      - A composite of a ceramic and a metallic oxide (Mn, Co, Cu or Fe)
    - Typically have negative temperature coefficients (NTC thermistors)

$$R_T = R_0 \exp\left[B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

Thermoelectric sensors

- **The Seebeck effect**
  - When a pair of dissimilar metals are joined at one end, and there is a temperature difference between the joined ends and the open ends, thermal emf is generated, which can be measured in the open ends
- **The Peltier effect**
  - When a current passes through the junction of two different conductors, heat can be either absorbed or released depending on the direction of current flow
- **Thermocouples**
  - Based on the Seebeck effect
  - Open ends must be kept at a constant reference temperature T_{REF}
  - A number of standard TCs are used
    - These are denominated with different letter codes: T, J, K, S, R…
      - i..e, type J (the most popular) is made of Iron and Constantan (Cu/Ni alloy: 57/43)



RTDs vs. thermocouples vs. IC sensors

	THERMOCOUPLES	RTD	IC
ACCURACY	Limits of error wider than RTD or IC Sensor	Better accuracy than thermocouple	Best accuracy
RUGGEDNESS	Excellent	Sensitive to strain and shock	Sensitive to shock
TEMPERATURE	-400 to 4200° F	-200 to 1475° F	-70 to 300° F
DRIFT	Higher than RTD	Lower than TC	
LINEARITY	Very non-linear	Slightly non-linear	Very linear
RESPONSE	Fast dependent on size	Slow due to thermal mass	Faster than RTD
COST	Rather inexpensive except for noble metals TCs, which are very expensive	More expensive	Low cost

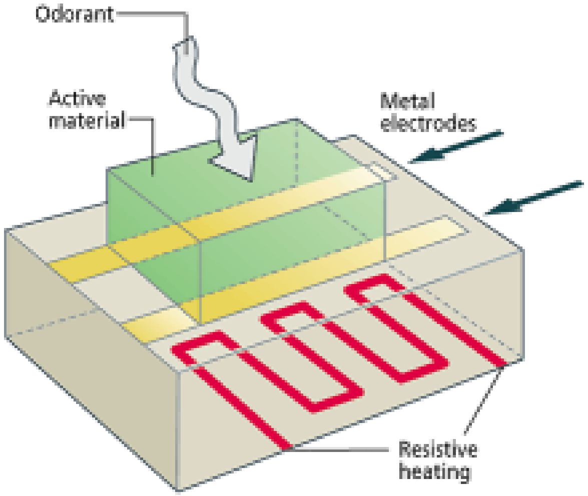
from http://www.wici.com/technote/table2.htm

Chemical sensors

- **Conductivity**
  - Metal-oxides
  - Conducting polymers
- **Piezo-electric**
  - Surface Acoustic Wave
  - Quartz Crystal Microbalance

Conductivity sensors

- **Absorption of gases modifies the conductivity of sensing layer**
- **Sensing layer types**
  - Metal Oxide
    - Typically SnO_2 doped with Pt or Pd
    - Operate a high temperatures (300-500^{0}C)
      - Temperature-selectivity dependency
    - Broad selectivity
      - Particularly suitable for combustible gases
  - Conducting Polymers
    - Based on pyrrole, aniline or thiophene
    - Operate at room temperature

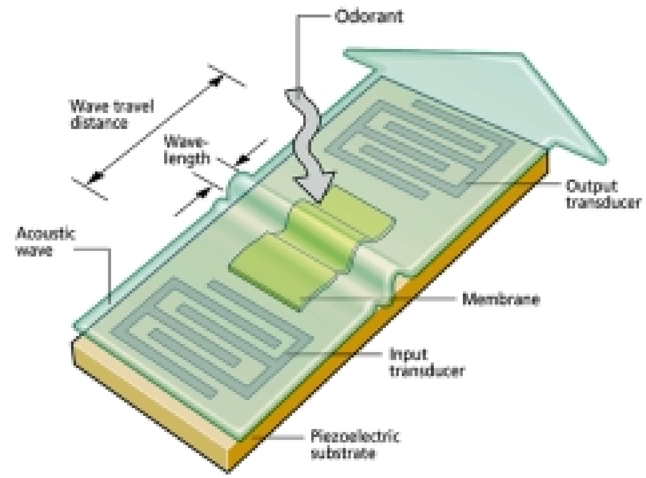


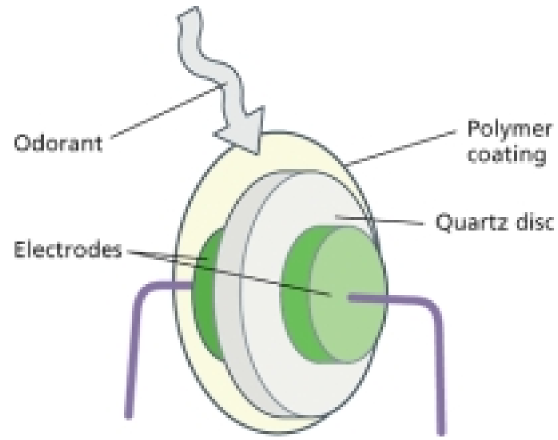
- **CPs vs MOXs**
  - CP advantages
    - Large number of polymers available with various selectivities
    - Sensitivity* to wide number of VOCs
    - Low power consumption
    - Faster response and recovery times
  - CP Limitations
    - Cross-sensitivity* to humidity
    - Lower sensitivity* than MOXs

**By sensitivity here we mean the ability to detect certain VOCs, not the slope of the calibration curve*

Piezo-electric chemical sensors

- **Piezo-electric effect**
  - The generation of an electric charge by a crystalline material upon subjecting it to stress (or the opposite)
    - A typical piezo-electric material is Quartz (SiO_2)
  - Piezo-electric sensors
    - Thin, rubbery polymer layer on a piezo-electric substrate
    - Sensing principle: mass and viscosity changes in the sensing membrane with sorption of VOCs
- **Surface Acoustic Wave (SAW)**
  - AC signal (30-300MHz) applied to interdigitated input electrode generates a surface (Rayleigh) wave
  - Propagation delays to output electrode are affected by changes in the surface properties
  - Phase shifts of the output electrode signal are used as a response
- **Quartz Crystal Microbalance (QMB)**
  - Also known as Bulk Acoustic Wave (BAW) devices
  - Device is operated in an oscillator circuit
  - Changes in the sensing membrane affect the resonant frequency (5-20MHz) of the device





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