SENSORS AND TRANSDUCERS

Prof. Katherine Candler

E80 - Spring 2013

(Notes adapted from Prof. Qimin Yang's lecture, Spring 2011)

WHAT COULD YOU FLY WITH YOUR ROCKET?

- http://www.eng.hmc.edu/NewE80/FlightVideos.html

- (just for fun): http://www.youtube.com/watch?v=MQwLmGR6bPA

BRAINSTORM

- What sort of data might you want to collect from your rocket?

BRAINSTORM

- Atmospheric phenomena
  - Temperature
  - Humidity
  - Pressure
  - Trace gas concentration
  - Dust concentration
  - Particle concentration
- Rocket performance data
  - Altitude
  - Velocity
  - Acceleration
  - Vibration
  - Rotation rate
  - Internal temperatures

OUTLINE

- Gas Sensor
- Humidity Sensor
- Pressure Sensor
- Vibration Sensor

IMPORTANT SENSOR SPECIFICATIONS

- What characteristics are important to consider when selecting a sensor?
  - Input range
  - Output range
  - Supply voltage
  - Sensitivity
  - Operating temperature range
  - Response time
  - Accuracy
  - Size
  - Cost

GAS SENSORS

- Solid electrolyte sensors [NO_2, CO_2, O_2]
- Metal oxide sensors [combustible & toxic gases]
- Catalytic bead sensors [combustible gases]
- Electrochemical sensors [toxic gases & oxygen]



http://www.futurlec.com/Gas_Sensors.shtml

http://www.digikey.com/catalog/en/partgroup/gas-sensors/14553

SOLID ELECTROLYTE GAS SENSOR

- Presence of gas (e.g., CO_2) leads to chemical reactions

Cathode:	$2Li^+ + CO_2 + ½O_2 + 2e^- = Li_2CO_3$
Anode:	$2Na^+ + ½O_2 + 2e^- = Na_2O$
Overall chemical reaction:	$Li_2CO_3 + 2Na^+ = Na_2O + 2Li^+ + CO_2$

- Chemical reactions generate an EMF:

$$EMF = E_c - \frac{RT}{2F}\ln(P_{CO2})$$ (Nernst Equation)

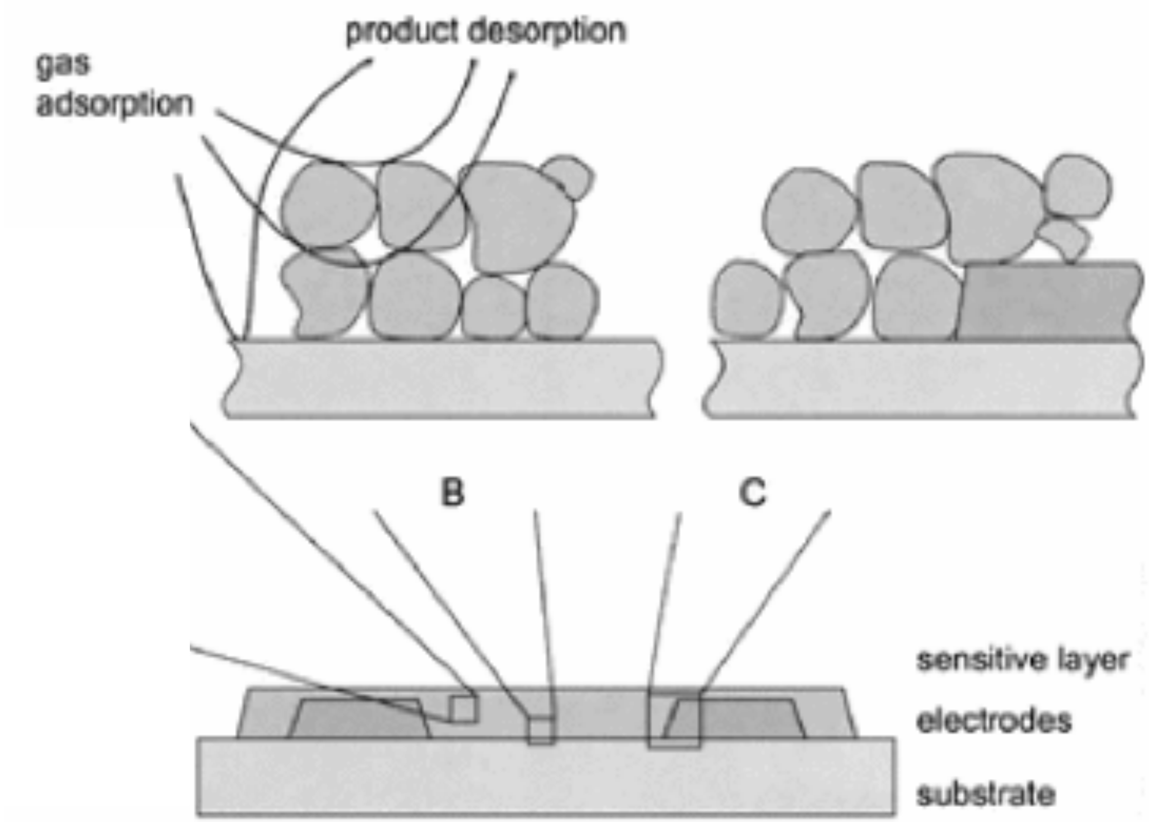
E_c = constant cell potential under standard conditions [V]
R = ideal gas constant = 8.31 J/(mol-K)
T = absolute temperature [K]
F = Faraday constant = 9.65×10^4 C/mol
P_{CO2} = partial pressure of CO_2 gas

http://chemistry.about.com/od/electrochemistry/a/nernstequation.htm

METAL OXIDE GAS SENSOR

- Adsorption of gas increases conductivity of material (e.g., SnO_2)

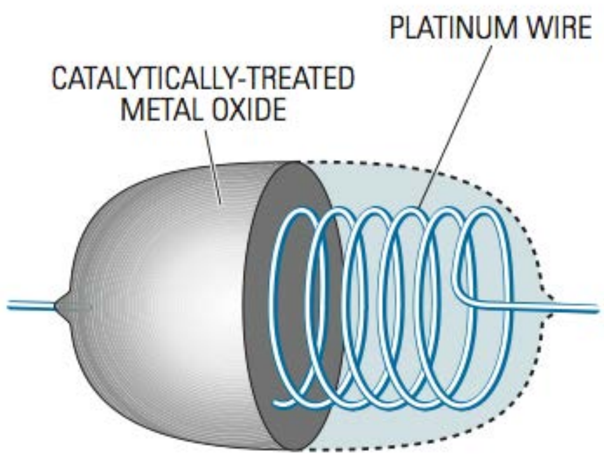
http://intlsensor.com/pdf/solidstate.pdf

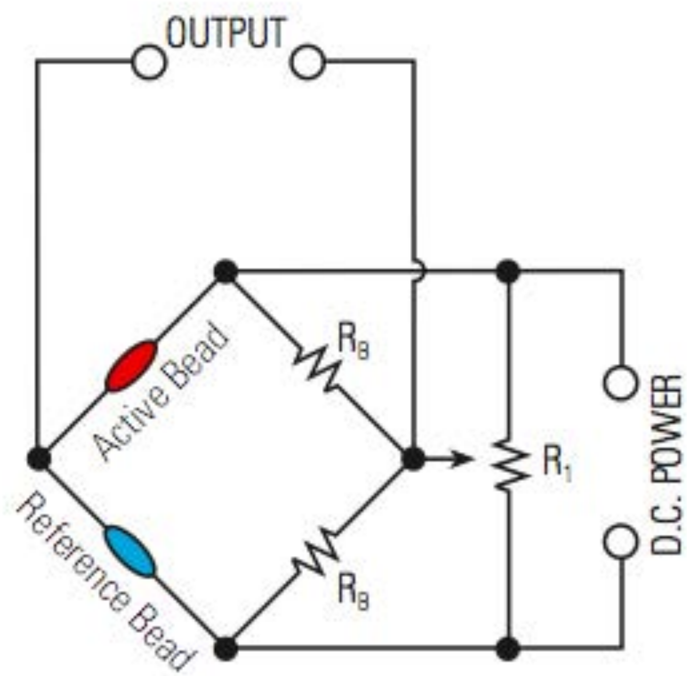


N. Barsan and U. Weimar, Conduction Model of Metal Oxide Gas Sensors, J. Electroceramics, Dec 2001

CATALYTIC BEAD GAS SENSOR

- Presence of combustible gas increases resistance of sensor material (catalytic bead)

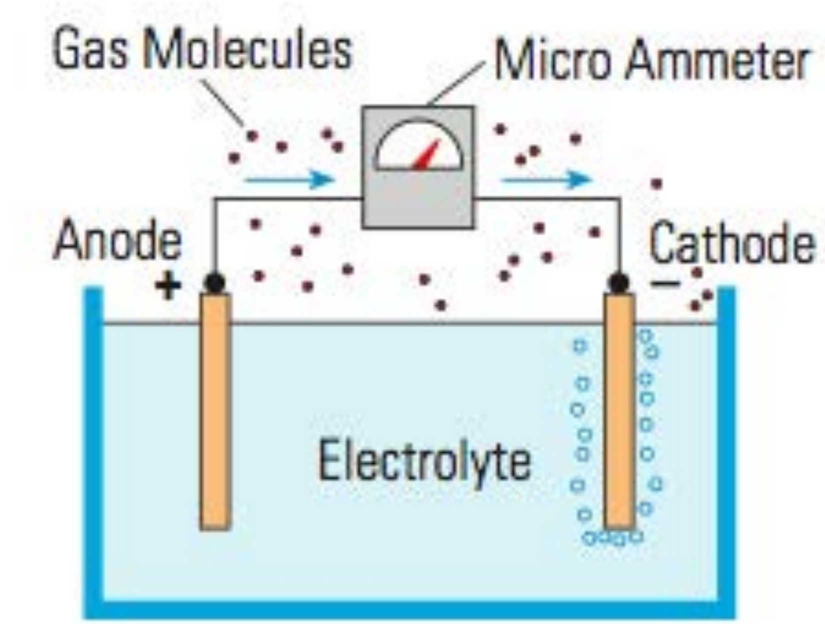




www.intlsensor.com/pdf/catalyticbead.pdf

ELECTROCHEMICAL GAS SENSOR

- Reaction with gas produces a current that is proportional to the gas concentration



http://www.intlsensor.com/pdf/electrochemical.pdf

WHAT IS PARTIAL PRESSURE?

- Partial pressure is a way to express the concentration of a gas:

Partial pressure = (total absolute pressure) x (volume fraction of gas component)

- For low concentrations, we often use ppm or ppb:
  - 1 ppm means 1 molecule (e.g., of CO_2) for 1 million molecules of gas
  - 1 ppb means 1 molecule (e.g., of CO_2) for 1 billion molecules of gas
- Alternate form of ideal gas law: $PV = nRT = \left(\frac{m}{M}\right)RT$
  - Mass per volume: $\frac{m}{V} = \frac{PM}{RT}$

m: mass

M: molar mass

EXAMPLE

Given 1% CO_2 at atmospheric pressure (101.325 kPa) and 25°C (298.15 K), calculate the following:

Hint: Molar mass of CO_2 = 44 g/mol; R = 8.31447 $\frac{m^3 \cdot Pa}{K \cdot mol}$

- ppm = $(0.01) * 10^6 = 10^4$
- Partial pressure of CO_2 = 0.01*101.325 kPa = 1013.25 Pa
- Mass per volume = $\frac{PM}{RT} = \frac{(1013.25 \text{ Pa})(44 \text{ g/mol})}{\left(8.31447 \frac{m^3 \cdot Pa}{K \cdot mol}\right)(298.15 \text{ K})} = 18 \text{ g/m}^3$

GAS COMPOSITION OF DRY AIR

- Nitrogen (N_2): 780,840 PPM
- Oxygen (O_2): 209,460 PPM
- Argon (Ar): 9,340 PPM

- Carbon dioxide (CO_2): 394 PPM
- Methane (CH_4): 1.79 PPM
- Hydrogen (H_2): 0.55 PPM
- Carbon monoxide (CO): 0.1 PPM
- Ozone (O_3): 0 – 0.07 PPM

* See the full list here: http://en.wikipedia.org/wiki/Atmosphere_of_Earth

LET'S LOOK AT SOME DATASHEETS

- Could you use any of the gas sensors for your rocket?

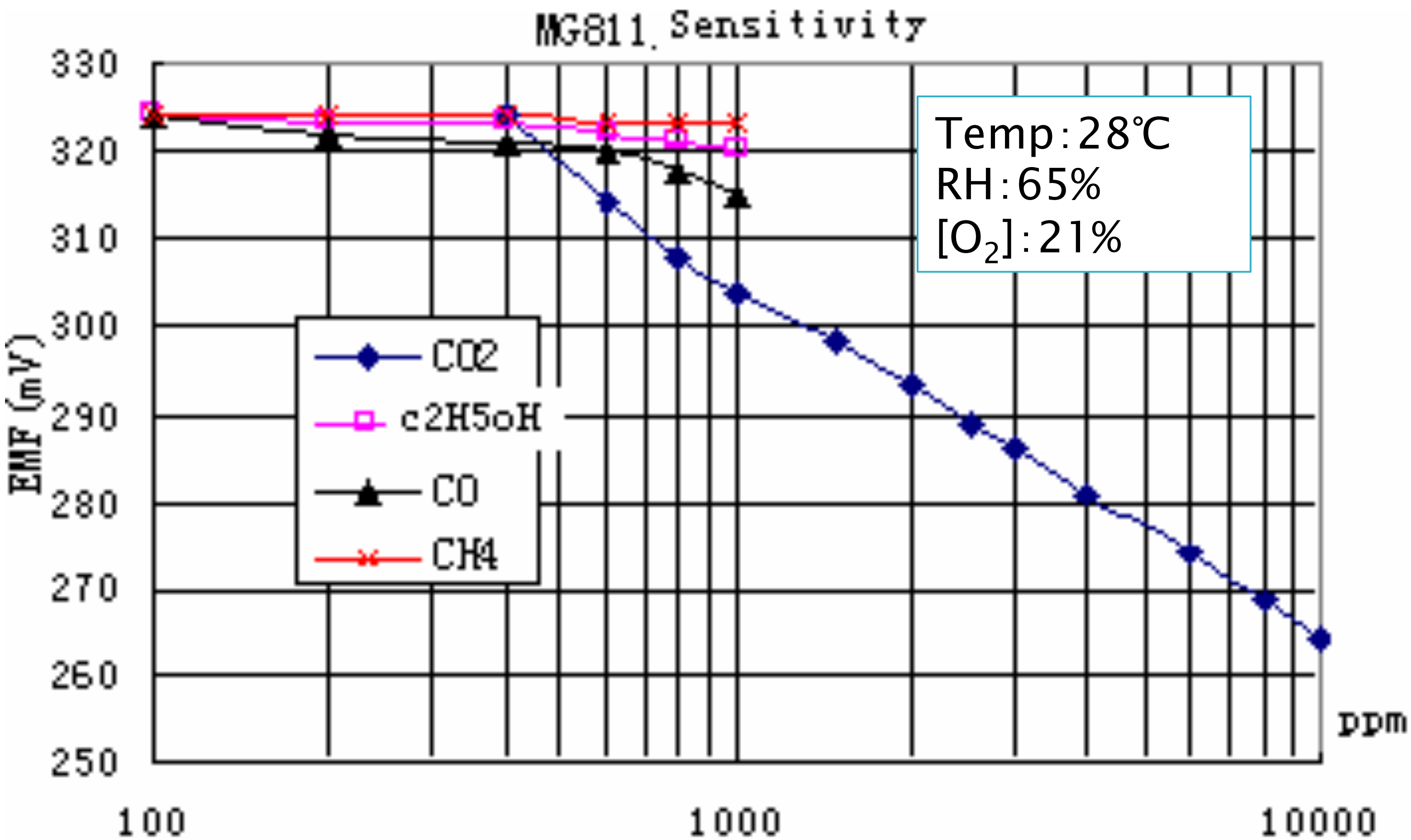
Consider:

- Minimum detection level
- Response time
  - How could you compensate for long response times?
- Heater voltage
- Sensitivity ratio between gases

Recall in dry air:
CO_2: 394 PPM
O_3: 0 – 0.07 PPM

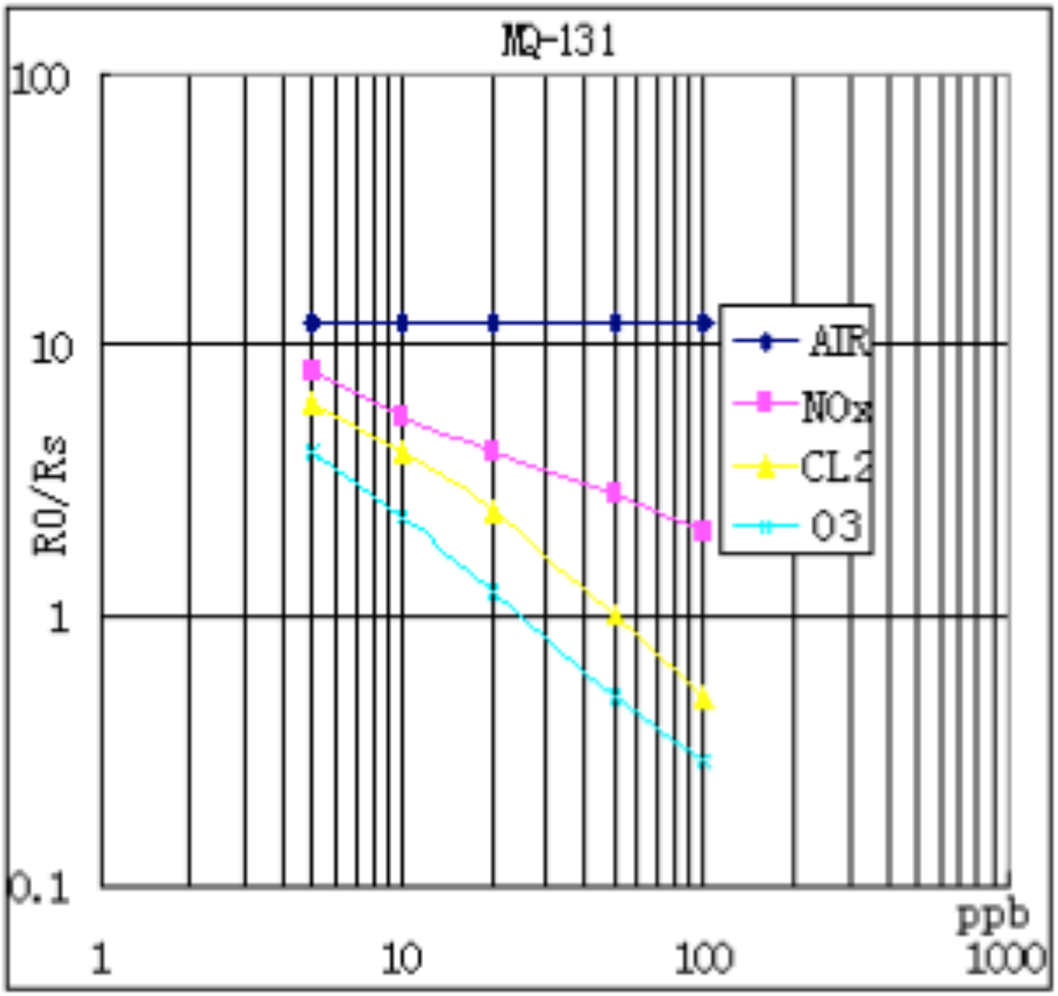
http://www.futurlec.com/Ozone_Gas_Sensor.shtml
http://www.futurlec.com/CO2_Sensor.shtml

EXAMPLE: MG811 CO_2 SENSOR



http://www.futurlec.com/CO2_Sensor.shtml

EXAMPLE: MQ131 O_3 SENSOR



Temp: 20℃
RH: 65%
$[O_2]$: 21%
R_L: 20 kΩ

http://www.futurlec.com/Ozone_Gas_Sensor.shtml

GAS SENSOR APPLICATIONS

- Air quality monitoring (CO_2, O_3, CO)
- Smoke alarms (CO_2)
- Mine and tunnel warning systems (CO_2, combustible gas)
- Greenhouses (CO_2)
- Breathalyzer (Alcohol)
- Automotive applications (O_2, CO_2)

http://www.boschautoparts.com/OxygenSensors/Pages/OxygenSensorDesign.aspx

http://www.bosch.com/en/com/sustainability/issues/products_customers/sustainable_mobility/co2_sensor_1.html

OUTLINE

- Gas Sensor
- **Humidity Sensor**
- Pressure Sensor
- Vibration Sensor

HUMIDITY SENSOR

Relative humidity (RH) describes the amount of water vapor in a mixture of air and water vapor.

$$\mathrm{RH} = \frac{e_{\mathrm{w}}}{e_{\mathrm{w}}^{*}} \times 100\% = \frac{\text{partial pressure of water vapor}}{\text{saturated vapor pressure of water at the given temp}}$$

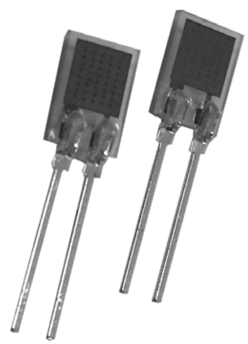
e_{w}^{*} is the maximum water vapor that the air can hold without condensing and is $f\left(T,P\right)$

http://en.wikipedia.org/wiki/Relative_humidity
http://en.wikipedia.org/wiki/Hygrometer


C
F
50 40 30 20 10 0 10 20
120 100 80 60 40 20 0
http://en.wikipedia.org/wiki/Weather_house

ELECTRONIC HUMIDITY SENSORS

- Capacitive
- Resistive



Honeywell HCH-1000

HIH-4010

EMD-4000

- http://media.digikey.com/pdf/Data%20Sheets/Honeywell%20Sensing%20&%20Control%20PDFs/HCH-1000%20Series.pdf
- http://www.digikey.com/product-detail/en/HIH-4010-001/480-3536-ND/2503902?cur=USD
- http://veronics.com/products/Relative_humidity-sensors/emd_4000.pdf

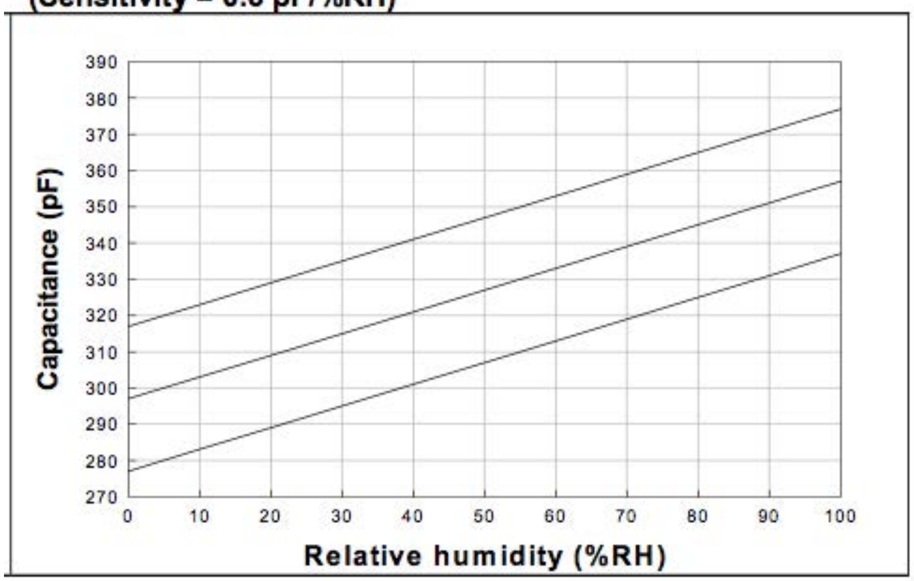
HUMIDITY SENSOR

Capacitive RH sensor:

- Dielectric constant of a polymer or inorganic material changes as it absorbs water vapor
- Dielectric constants: 80 (water) vs. 3.4 (polyimide)
- More water → higher capacitance

$$C = \frac{\varepsilon A}{d}$$

FIGURE 2: TYPICAL HUMIDITY RESPONSE
(Sensitivity = 0.6 pF/%RH)

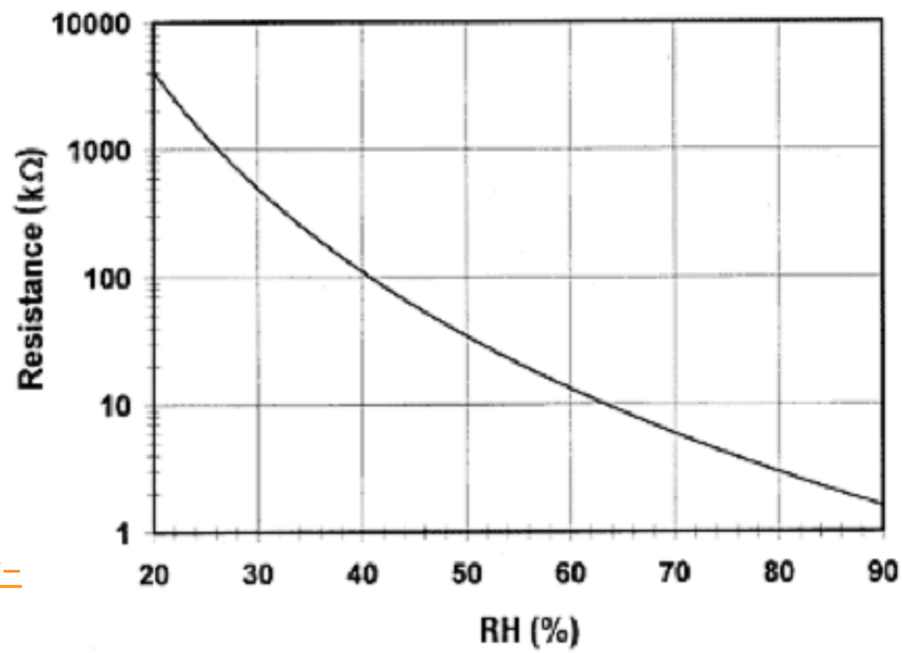


http://media.digikey.com/pdf/Data%20Sheets/Honeywell%20Sensing%20&%20Control%20PDFs/HCH-1000%20Series.pdf

HUMIDITY SENSOR

Resistive RH sensor:

- Electrical resistance of a material changes as it absorbs water vapor
- Typical materials: salts, conductive polymers
- Less sensitive than capacitive RH sensors
- Material properties also tend to depend both on humidity and temperature (in practice, must be combined with temperature sensor)



http://veronics.com/products/Relative_humidity-sensors/emd_4000.pdf

LET'S LOOK AT A DATASHEET

- What is the input range?
- What is the output range?
- What is the sensitivity?
- What is the response time?

OUTLINE

- Gas Sensor
- Humidity Sensor
- **Pressure Sensor**
- Vibration Sensor

PRESSURE SENSORS

- Force-based
  - Piezoresistive: ΔR
  - Piezoelectric: ΔV
  - Capacitive: ΔC
- Others
  - Resonance: ΔQ (damping)
  - Thermal (Pirani gauge)

Piezoresistive pressure sensor

http://www.maxim-ic.com/app-notes/index.mvp/id/871

PRESSURE SENSORS

- What is pressure?

  e.g. atmospheric pressure at sea level is 101.325 kPa

  e.g. tire pressure gauge reads 0 PSI

  e.g. pressure drop for flow measurement

- What kind of pressure do you want to measure?
  - Absolute pressure sensor (compares to vacuum)
  - Gauge pressure sensor (compares to ambient)
  - Differential pressure sensor

ABSOLUTE PRESSURE SENSORS AS ALTIMETERS

Method #1: $\Delta P = -\rho g \cdot \Delta h$

- Assumes density is constant over all height. Is this accurate?

Method #2:

- Using the ideal gas law, $PV = nRT$

$$\rho = \frac{\text{mass} = nM}{\text{volume} = \frac{nRT}{P}} = \frac{MP}{RT}$$

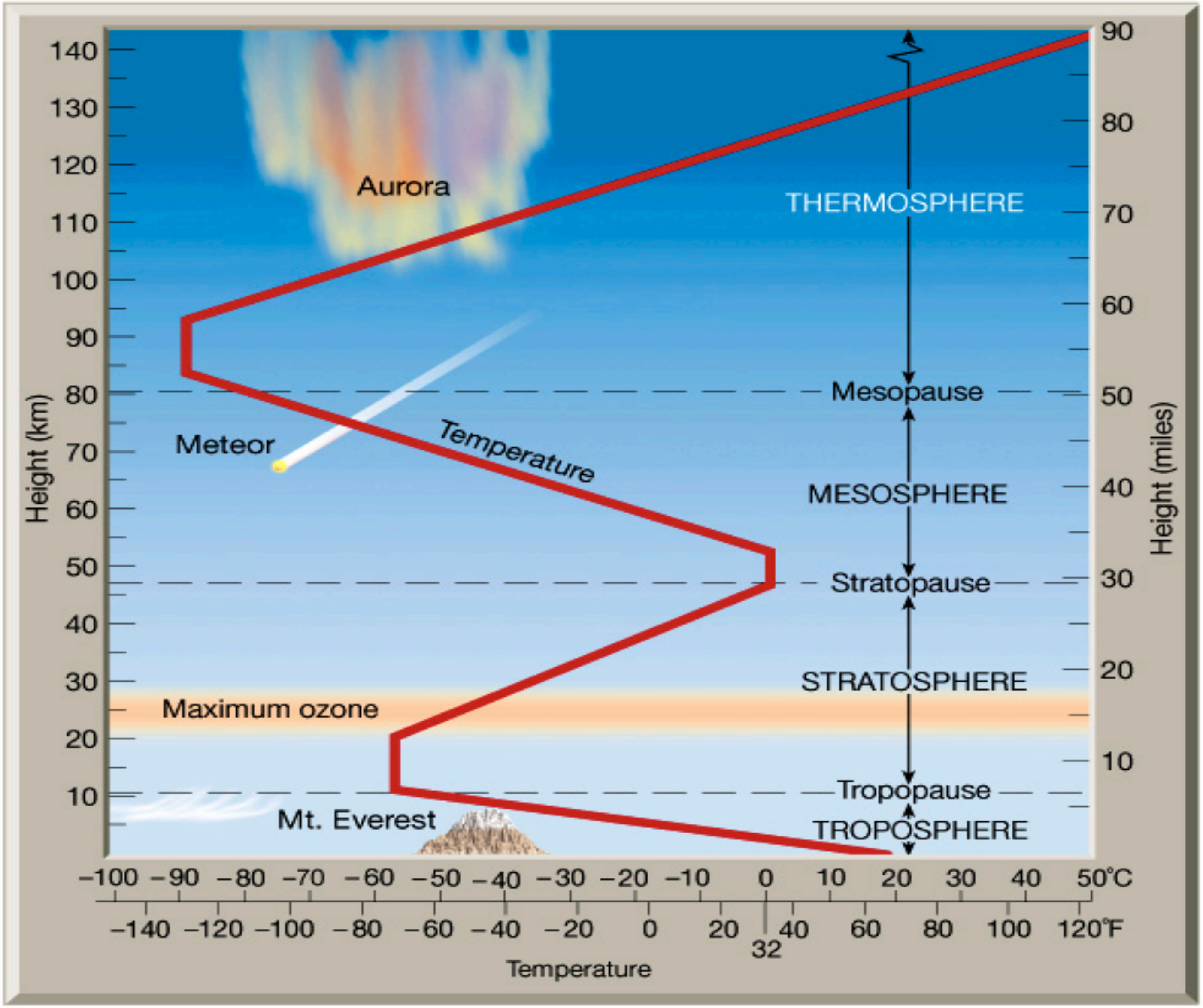
$$P(h) = P_0 \exp\left(-\frac{Mg}{RT}h\right)$$

M: Molar Mass
n: Number of moles
T: Temperature
P: Pressure
h: Altitude

- Accounts for changing density, but not temperature, with height

http://hyperphysics.phy-astr.gsu.edu/hbase/Kinetic/barfor.html

BUT TEMPERATURE CHANGES WITH HEIGHT!



A MORE ACCURATE MODEL…

Method #3:

$$h = \frac{T_0}{-\left(\frac{dT}{dh}\right)} \cdot \left[1 - \left(\frac{P_0}{P}\right)^{\frac{\left(\frac{dT}{dh}\right)R}{gM}}\right]$$

where

- h = altitude (above sea level) **(in meters)**
- P_0 = standard atmosphere pressure= 101.325kPa
- T_0 = 288.15K (+15°C)
- dT/dh= - 0.0065 K/m: thermal gradient or standard temperature lapse rate
- R = gas constant (8.31432 N*m/mol*K)
- g = (9.80665 m/s²)
- M = molar mass of earth's air (0.0289644 kg/mol)

A MORE ACCURATE MODEL…

Plug in all the constants

Method #3:

$$h = 4.43\times10^{4}\times\left(1-\left(\frac{101.325\text{kPa}}{P}\right)^{-0.1902}\right)$$

- h is measured **in meters.**
- Equation calibrated up to 36,090 feet (11,000m).
- Reference: http://en.wikipedia.org/wiki/Atmospheric_pressure
- Different values of dT/dh for different layers of the atmosphere

EXAMPLE

Suppose, **P = 85 kPa** (from Pressure sensor)

Method 1:

$$\Delta h = -\frac{\Delta P}{\rho g} = -\frac{(85-101)kPa}{(1.2\frac{kg}{m^3} * 9.8\frac{m}{s^2})} = 1.36\ km$$

Method 2:

$$h = -\frac{RT}{Mg}\ln(\frac{P}{P_0}) = -8440\ln(\frac{85kPa}{101kPa}) = 1.46km$$

Method 3:

$$h = 4.43 \times 10^4 \times \left(1 - \left(\frac{101.325kPa}{85kPa}\right)^{-0.1902}\right) = 1.43\,km$$

LET'S LOOK AT A DATASHEET

- What is the input range?
- What is the sensitivity?
- What is the supply voltage?
- What is the offset voltage?
- What is the full scale output?
- What is the output range?
- Note: the fully integrated pressure sensor has gain stage and temperature compensation inside (signal conditioning is done already)

MPXA6115AC7U

http://www.mouser.com/ds/2/161/MPXA6115A-66934.pdf

OUTLINE

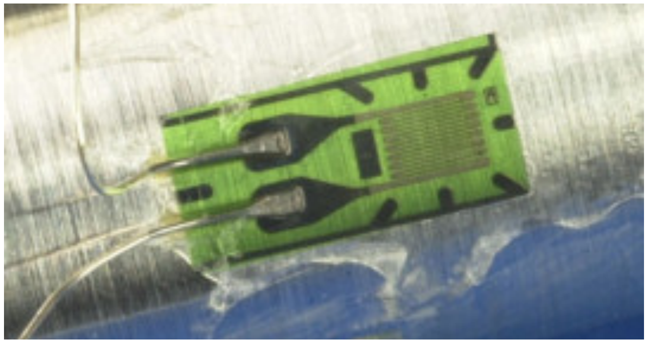
- Gas Sensor
- Humidity Sensor
- Pressure Sensor
- **Vibration Sensor**

VIBRATION SENSORS

Examples:

- Piezoelectric films (ΔV)
- Strain gauges (ΔR)

metal foil strain gauge



What happens when you pull on a piece of metal?

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

- http://www.digikey.com/Scripts/US/DKSUS.dll?Detail&name=MSP1006-ND
- http://www.eng.hmc.edu/NewE80/PDFs/PiezoSensors.pdf
- http://en.wikipedia.org/wiki/Strain_%28physics%29
- http://www.vishaypg.com/micro-measurements/transducer-class-strain-gages/
- http://www.sparkfun.com/datasheets/Sensors/Flex/MSI-techman.pdf

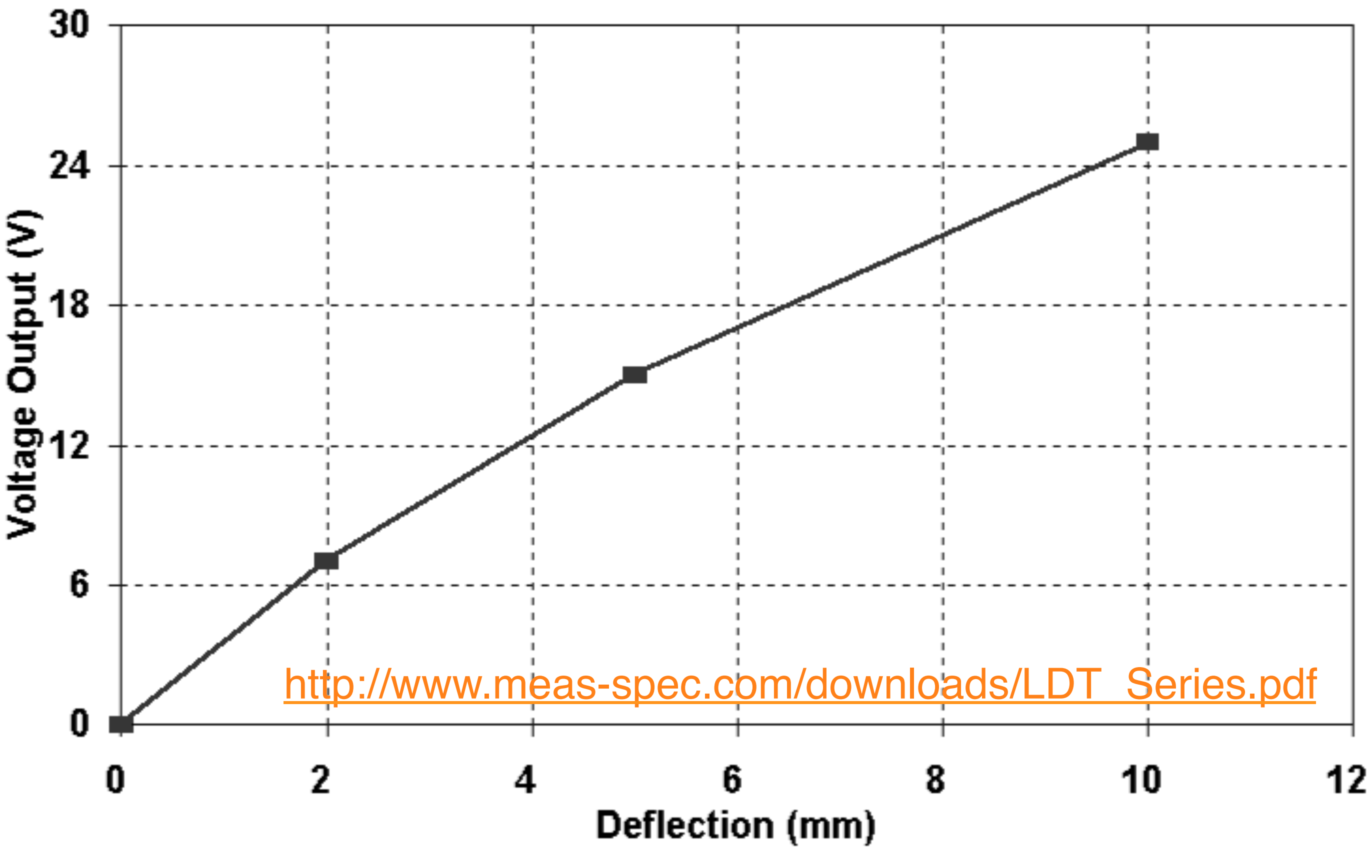
ACCELEROMETERS AS VIBRATION SENSORS

- Full-scale range
- Number of axes
- Interface (analog, digital, pulse output)
- Bandwidth (50-100 Hz)
- Power consumption (supply voltage)

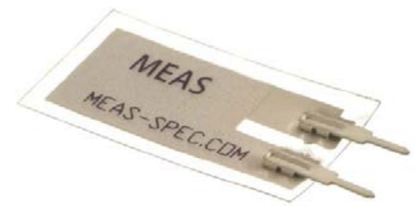
http://www.sparkfun.com/datasheets/Components/General/MMA7361L.pdf

https://www.sparkfun.com/products/9652

EXAMPLE: VIBRATION SENSOR



http://www.meas-spec.com/downloads/LDT_Series.pdf



Suggestion: Use the vibration sensor in the Op Amp Lab for your rocket

VIBRATION SENSOR APPLICATIONS

- Vibration Sensing in Washing Machine
- Low Power Wakeup Switch
- Car Alarms
- Body Movement
- Security Systems
- Digital Cameras
- iPhone

NOW WHAT?

(1) What are your science/engineering goals?

(2) What sensors will you use to achieve your goals?

- E80 website (Final Project) has a list of potential sensors

(3) What circuits will you need?

- Sensors need power
  - Voltage regulators
- Sensor outputs need to interface with the data logger
  - Amplifiers
  - Buffers
  - Anti-aliasing filters

http://www.youtube.com/watch?v=2Ax64jfeVCc