Grab an attendance sheet

# Lecture 12

## March 13, 2025

# TODAY

- Sensors, using temperature as an example
- Sensors for this year

- UPCOMING
  - Lab06 out today or tomorrow – buck converter
  - No EX06 – there will be one more pset on 3DP after spring break
  - Tue – no lecture, will hold OH
  - Thu – 15 min team presentations
  - Next week – DR2

# Why sensors

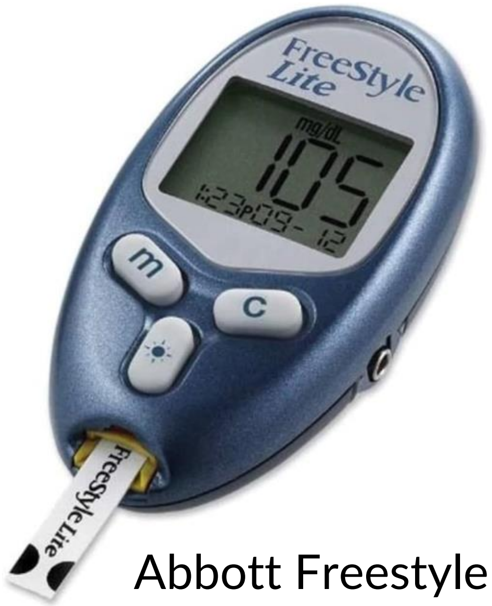
The HW/SW systems we create often/always have to interact with the outside world

- They need to sometimes take in information *aka* **sense**
- Sometimes they need to act on the world *aka* **actuate**
- These are two sides of the same thing – **transducers…**

…but we'll focus on sensors here

# Sensors

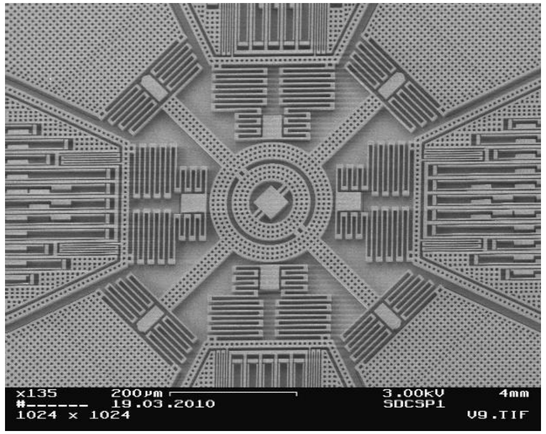
- Pretty much all sensors convert physical quantities into
  - Voltage
  - Time (or frequency)
- Sometimes there's an intermediate step of going to current (charge), magnetic flux, etc.
  - But usually those end up getting converted to voltage or time




Abbott Freestyle

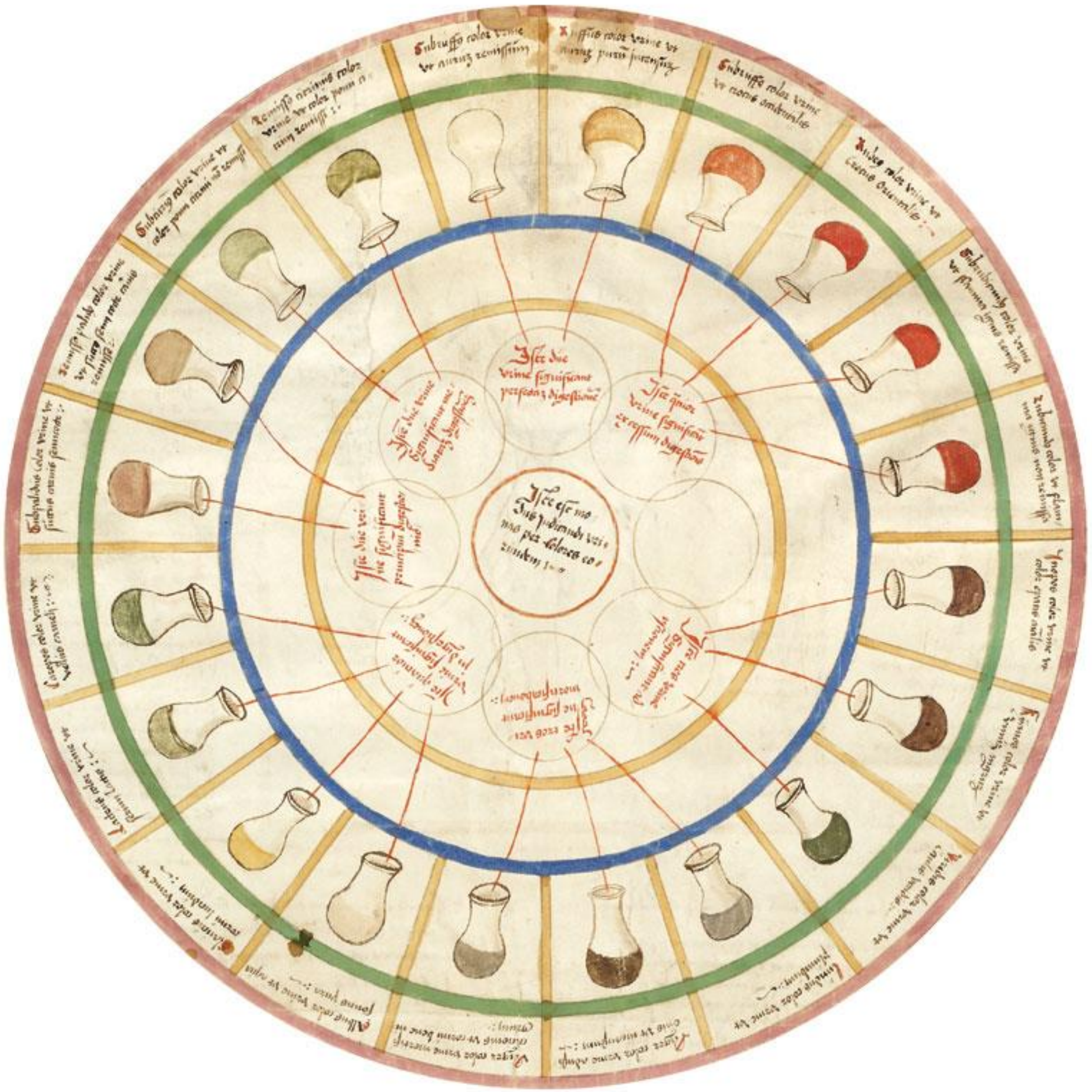

Ultrasonic distance sensor

Plantower PMS series [1003, 3003, etc.]




Invensense MPU6050

# Example: glucose sensing



**Ruffus ut aurum purum intensum**

*(Ruddy as pure intense gold)*

**Subrubicundus color ut crocus occidentalis**

*(Slightly red as occidental saffron)*

**Rubeus ut crocus orientalis**

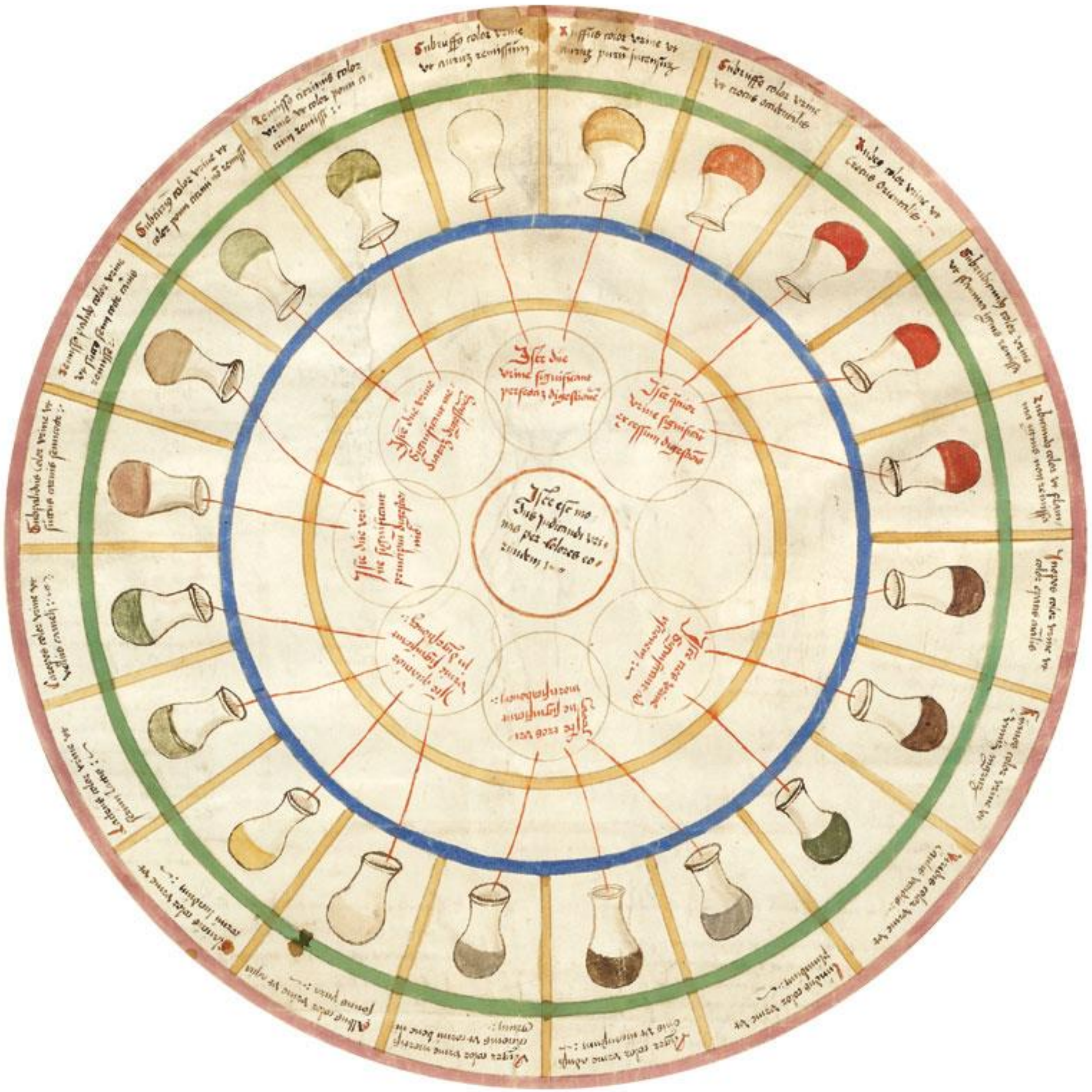
*(Red as oriental saffron)*

**Subrubicundus ut flamma ignis remissa**

*(Slightly red as a lowered flame of fire)*


OHHH...I BET THAT'S YUMMY!

# Example: glucose sensing



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# Example: glucose sensing

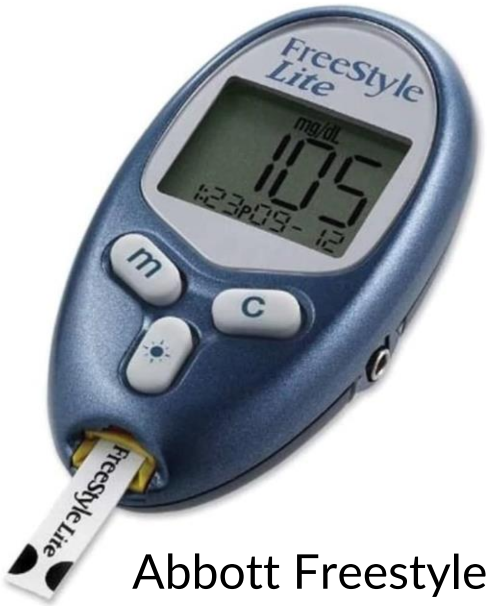
- *Diabetes Mellitus*
    - *Diabetes*: Greek, meaning to urinate excessively
    - *Mellitus*: Latin, meaning sweet like honey
- Type I diabetes, IDDM (insulin-dependent diabetes mellitus)
    - **Symptoms**
        - Hyperglycemia (various long-term cardiovascular diseases)
        - Hypoglycemia (can lead to coma)
    - **Devastating disease until 1923**
        - 1897 life expectancy of 10-yr old after diagnosis: **1.3 yrs**
        - 1945 life expectancy of 10-yr old after diagnosis: **45 yrs**
- Type II diabetes, “adult-onset”
    - Characterized by loss of cell response to insulin

# Example: glucose sensing

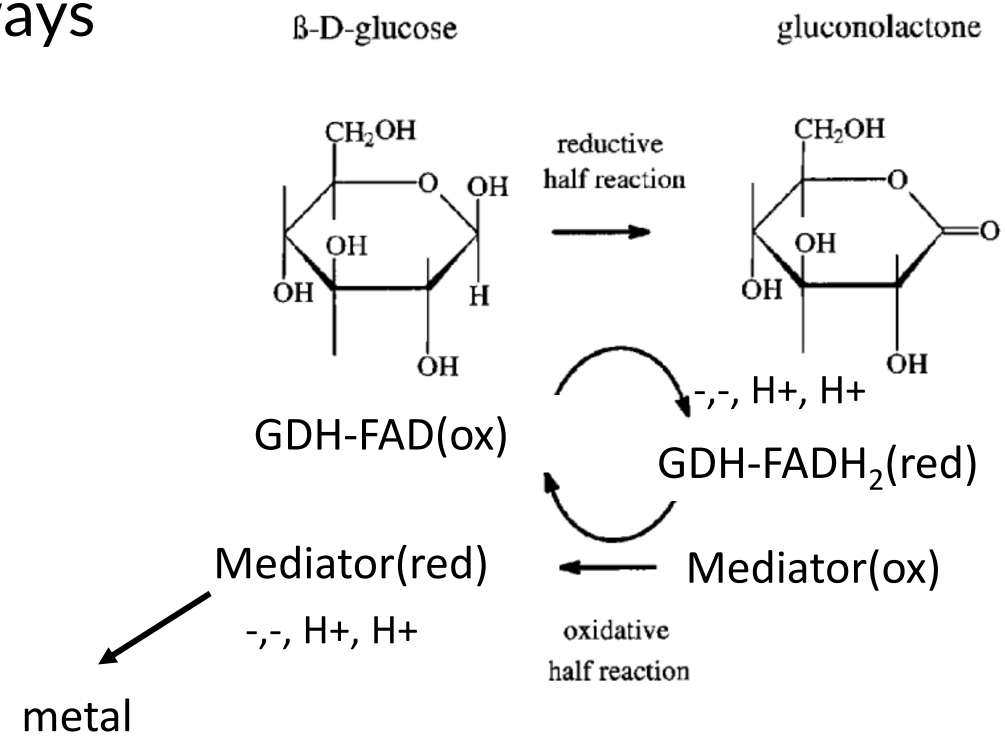
- **Insulin for diabetes**
  - 1921: Banting, Best, and Macleod show that Islets of Langerhans in pancreas produce substance that reverses diabetes ➔ Nobel Prize, 1923
- **Commercialization**
  - First large-scale production by Eli Lilly & Co.  (1922, Britain)
  - Purified from cows (bovine) & then pigs (porcine)
- **First protein ever sequenced (Sanger, 1955)**
  - Nobel Prize 1958
- **First protein ever synthesized (1963)**
- **One of the first proteins whose 3D structure was determined (1971)**
- **First protein synthesized by recombinant DNA technology (1979)**

# Example: glucose sensing

- Need to measure glucose levels to know when to administer insulin
  - If you give insulin and glucose goes too low…coma
- ALL modern glucose meters are electronic
  - Leverage existence of enzymes that act on glucose as part of metabolic pathways
  - Generate electrons

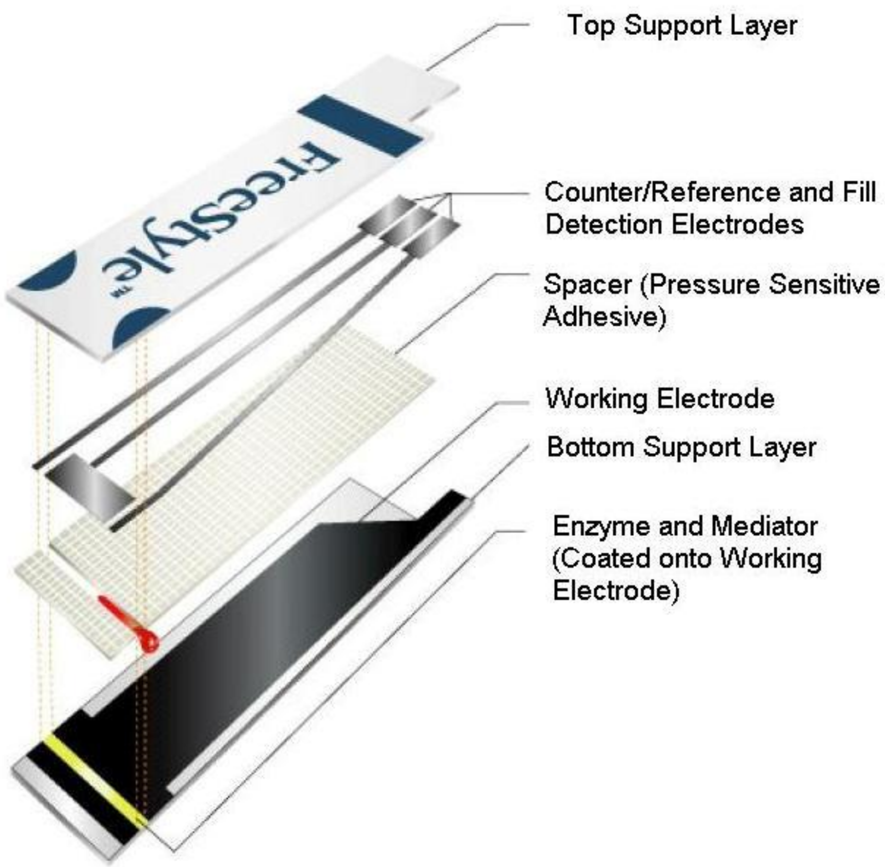



Abbott Freestyle



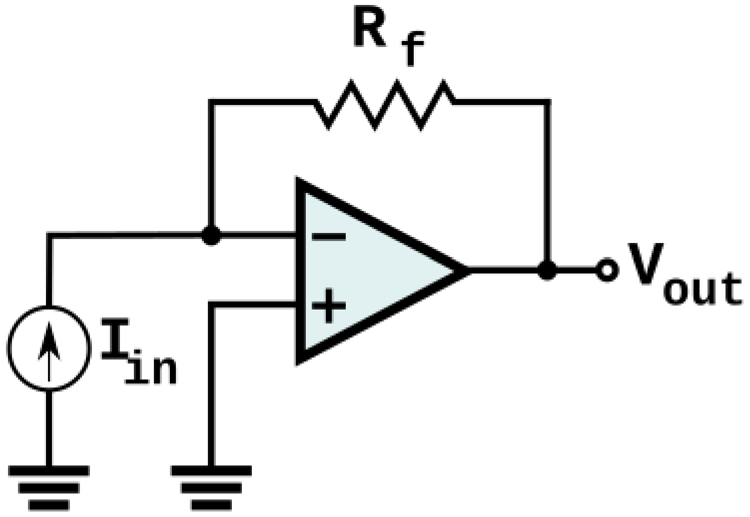
# Example: glucose sensing

- Glucose test strips have the chemistry to do the reaction
- Also, more recently have continuous glucose meters
    - Chemistry is in the needle



# Example: glucose sensing

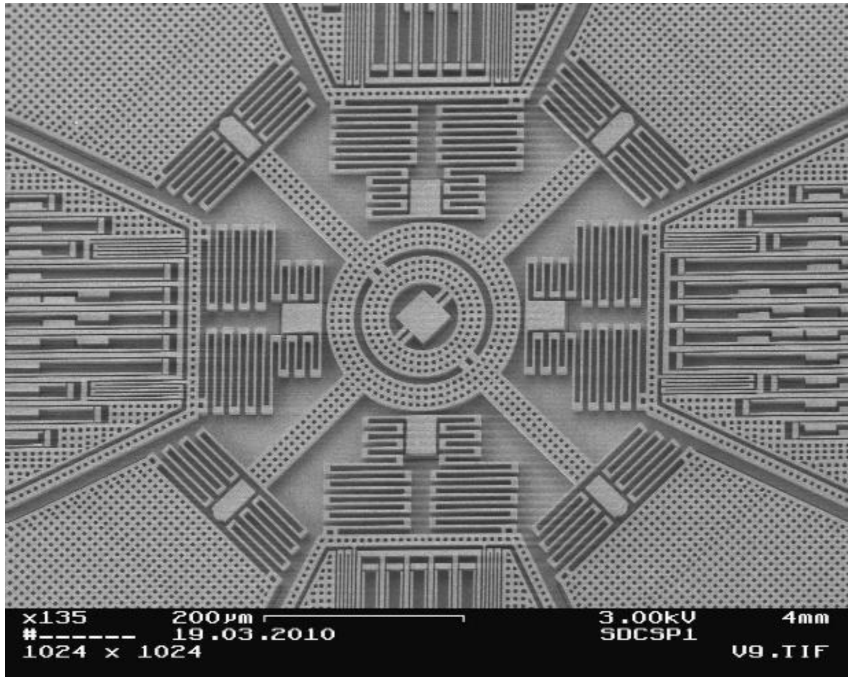
- How to measure charge?
- One common way is to turn current into voltage
  - Transimpedance amplifier




$$V_{out} = -I_{in}R_f$$

# Example: inertial sensing

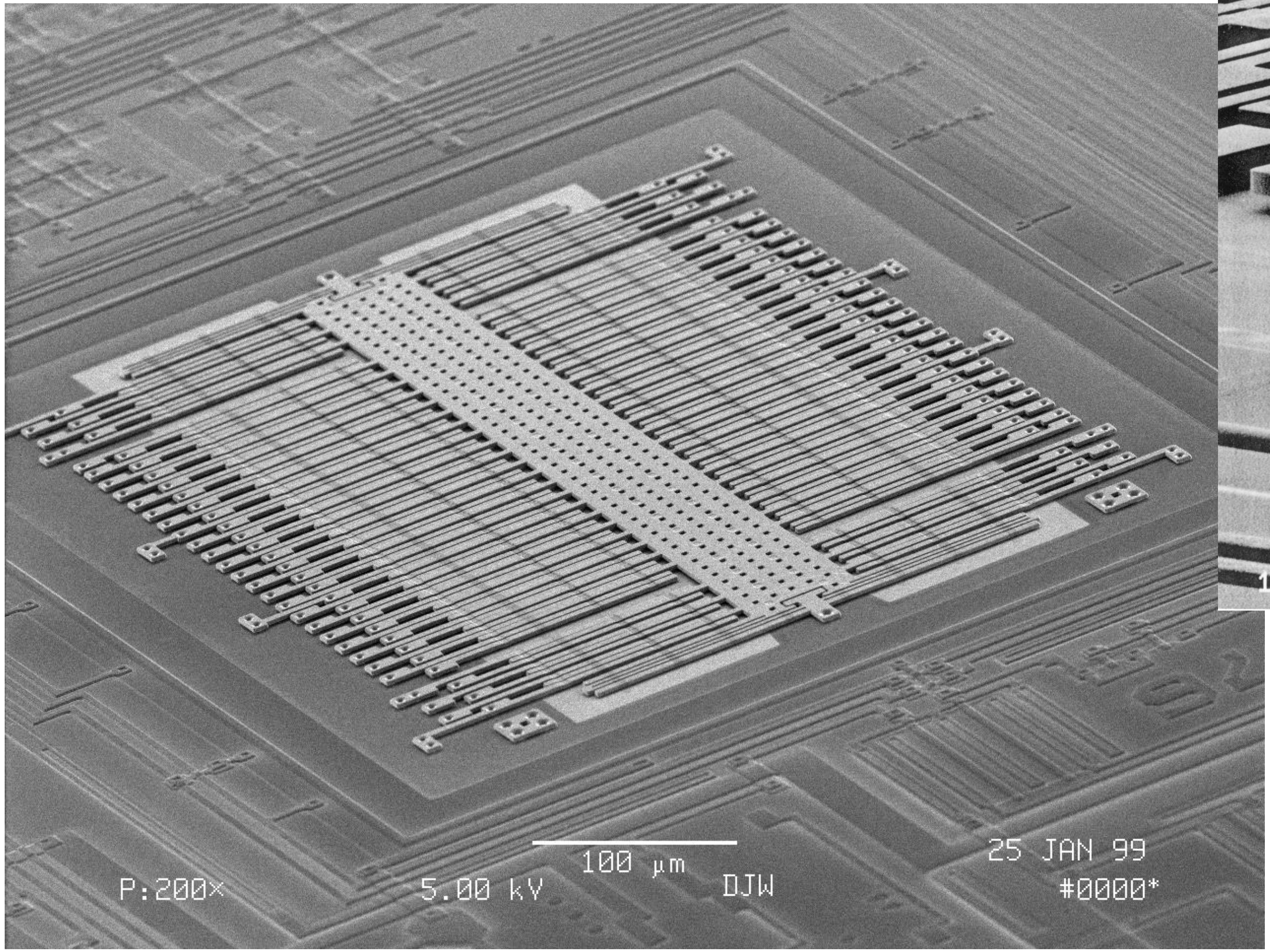
- Genesis: In 1980s, an ADI engineer heard about forming mechanical sensors in silicon
- Market pull was airbag accelerometers (50 g)
  - Current product was $50
  - Auto manufacturers wanted $5 price point
- Team was formed in 1986, first product in 1993
  - Fabrication process was under development since early 80's at Berkeley

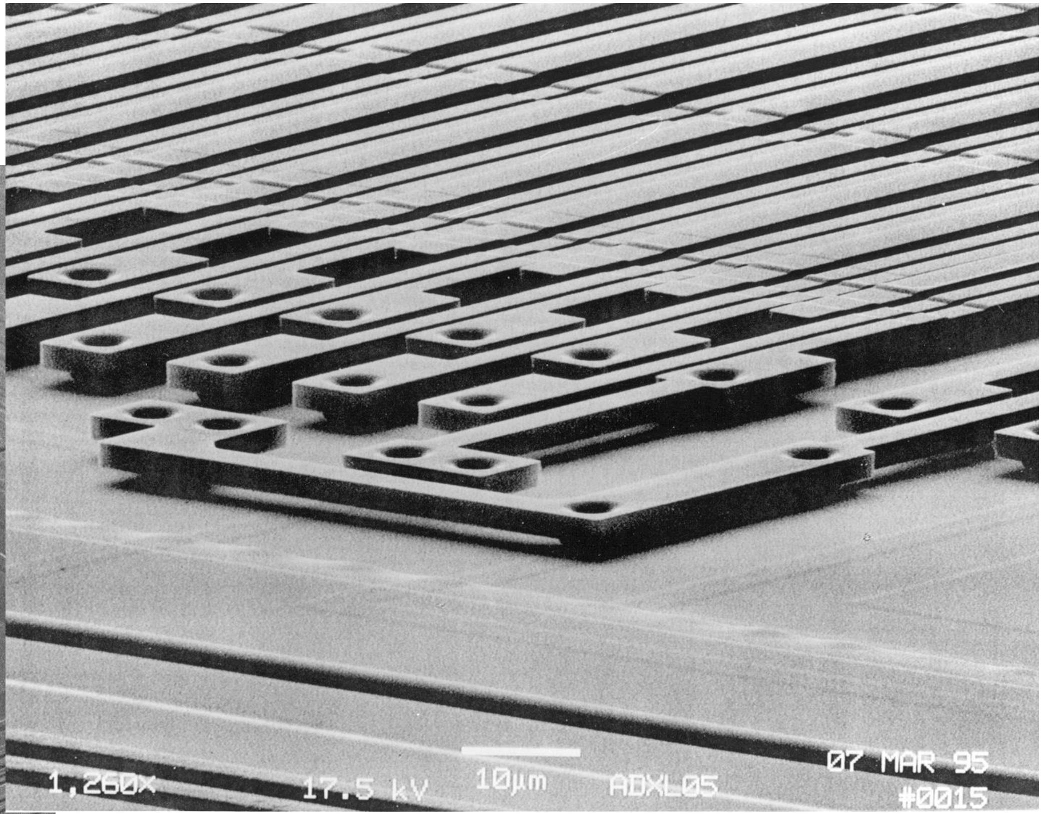



Invensense MPU6050

# Example: inertial sensing

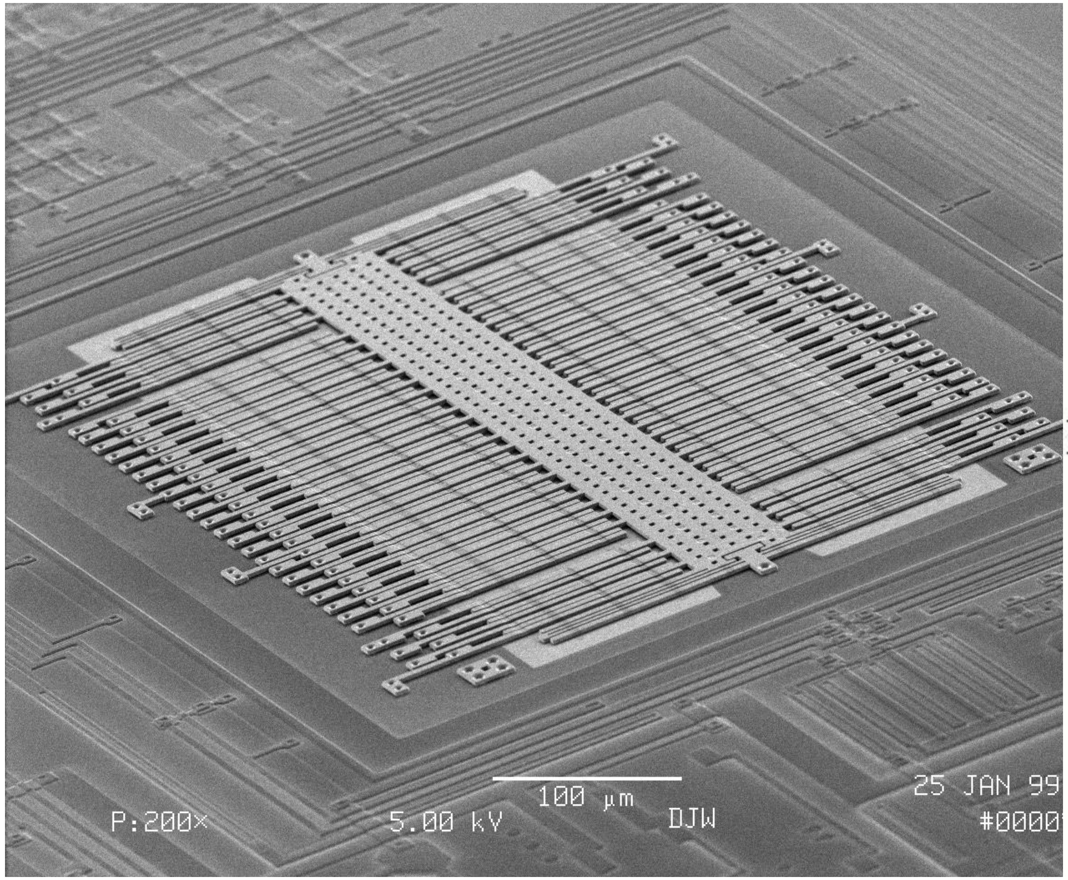
- Original ADXL50

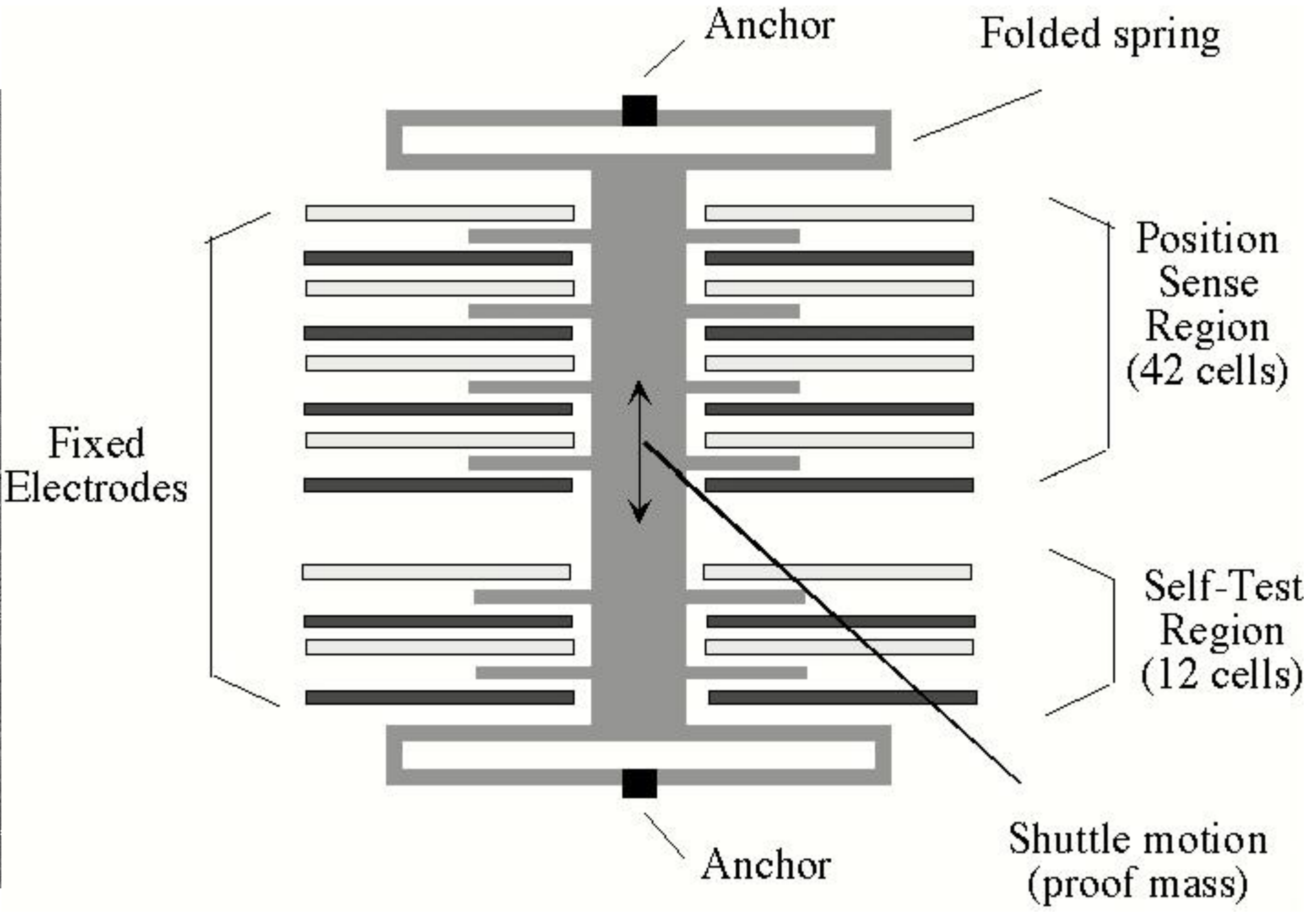


# Example: inertial sensing

- Original ADXL50

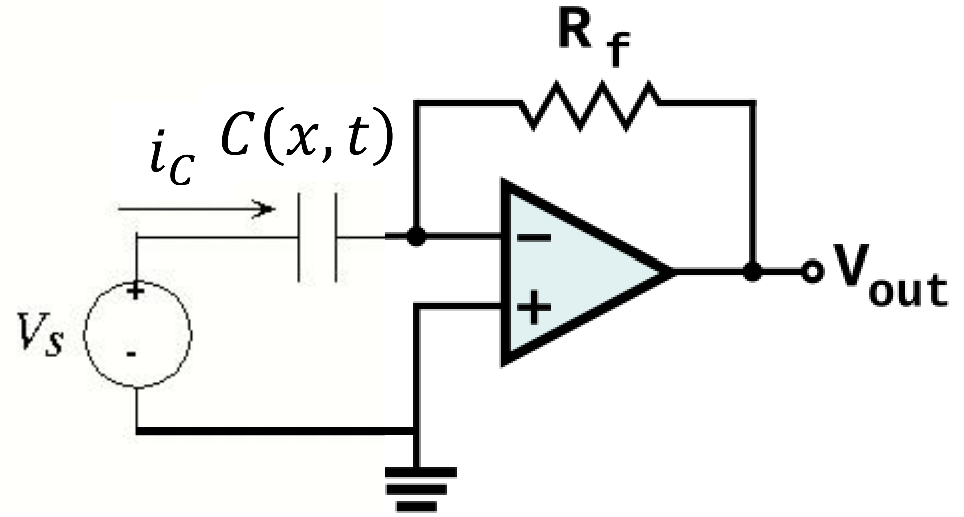



Acceleration ➔ motion of proof mass ➔ change in gap

# Example: inertial sensing

- Original ADXL50




Parallel plate cap $$C(x,t) = \frac{\epsilon A}{g(x,t)}$$

C charge vs. voltage $$Q(x,t) = C(x,t)V$$

DC voltage $V_S$ $$i_C = \frac{dQ}{dt} = C(x,t)\frac{dV_S}{dt} + V_S \left.\frac{\partial C}{\partial x}\right|_{V_S} \frac{dx}{dt}$$

Acceleration ➔ motion of proof mass ➔ change in gap ➔ change in C ➔ change in current ➔ change in voltage

Transimpedance amp $$V_{OUT} = -R_F i_C = -R_F V_S \left.\frac{\partial C}{\partial x}\right|_{V_S} \frac{dx}{dt}$$

Just a constant

# Temperature sensing

**The "hello world" of sensing**

- Very common and very important for many applications…

- Lots of ways to do it – *everything is a temperature sensor*
- Illustrates key sensor selection principles and tradeoffs


HOFFRFE
NEW YORK
NEW YORK

# Temperature sensing

- Like most quantities we care about, several different transduction approaches
- Same with light, presence, etc.

- To select among approaches, it helps to understand how they work
  - To understand tradeoffs

# Temperature sensing

Several common ways to measure temperature

- Most common: via resistance
- Less common: turning temperature directly into voltage
- Coolest: via bandgap sensors

# Temperature sensing

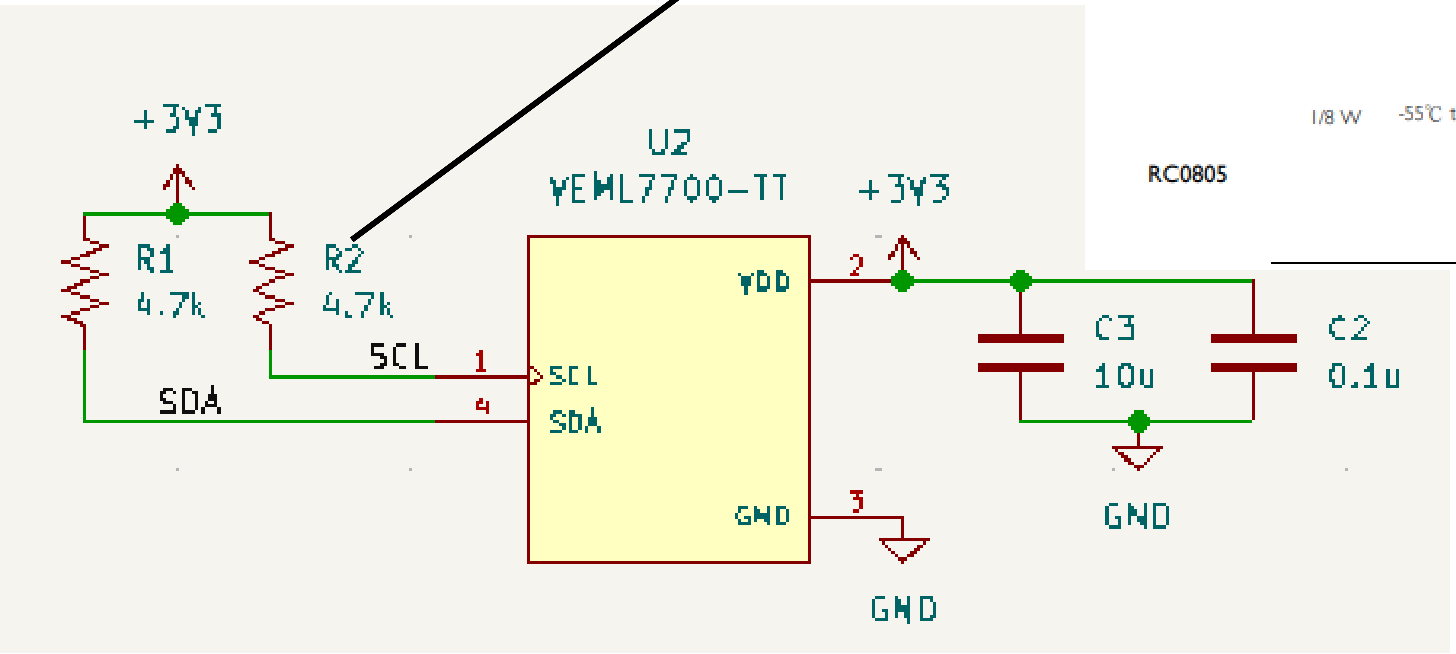
## Temperature-varying resistors

- Every resistor you buy has a resistance that varies with temperature

**Datasheet**

| CHARAC-TERISTICS | POWER | OPERATING TEMPERATURE RANGE | MAXIMUM WORKING VOLTAGE | MAXIMUM OVERLOAD VOLTAGE | DIELECTRIC WITHSTANDING VOLTAGE | RESISTANCE RANGE | TEMPERATURE COEFFICIENT | JUMPER CRITERIA |
|---|---|---|---|---|---|---|---|---|
| RC0805 | 1/8 W | -55℃ to 155℃ | 150V | 300V | 300V | 5% (E24) 1Ω≦R≦100MΩ<br>1% (E24/E96) 1Ω≦R≦10MΩ<br>0.5% (E24/E96) 1Ω≦R≦1MΩ<br>0.1% (E24/E96) 10Ω≦R≦1MΩ<br>10%, 20% (E24) 24MΩ≦R≦100MΩ<br>Jumper<50mΩ | 1Ω≦R≦10Ω ±200ppm℃<br>10Ω<R≦10MΩ ±100ppm℃<br>10MΩ<R≦22MΩ ±200ppm℃<br>24MΩ<R≦100MΩ ±300ppm℃ | Rated Current 2.0A<br>Maximum Current 5.0A |

$R = R(T)$



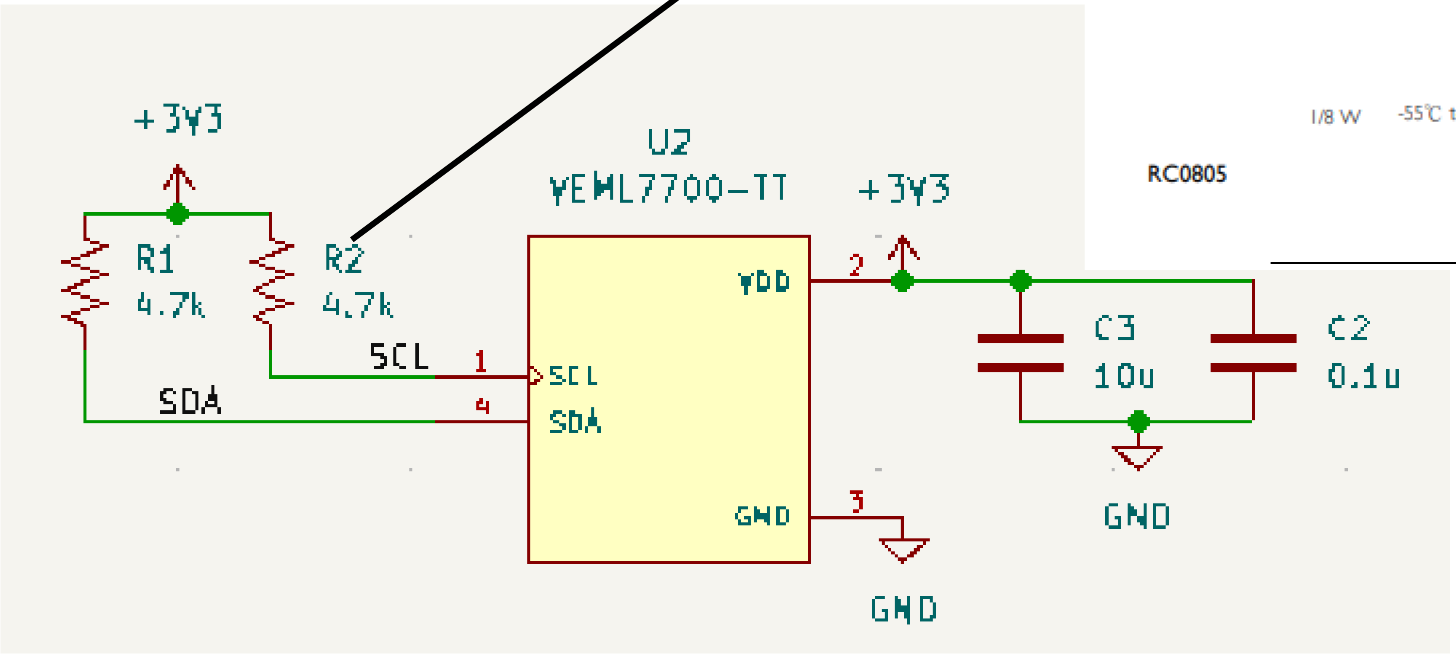

Joel's sensor board

# Temperature sensing

## Temperature-varying resistors

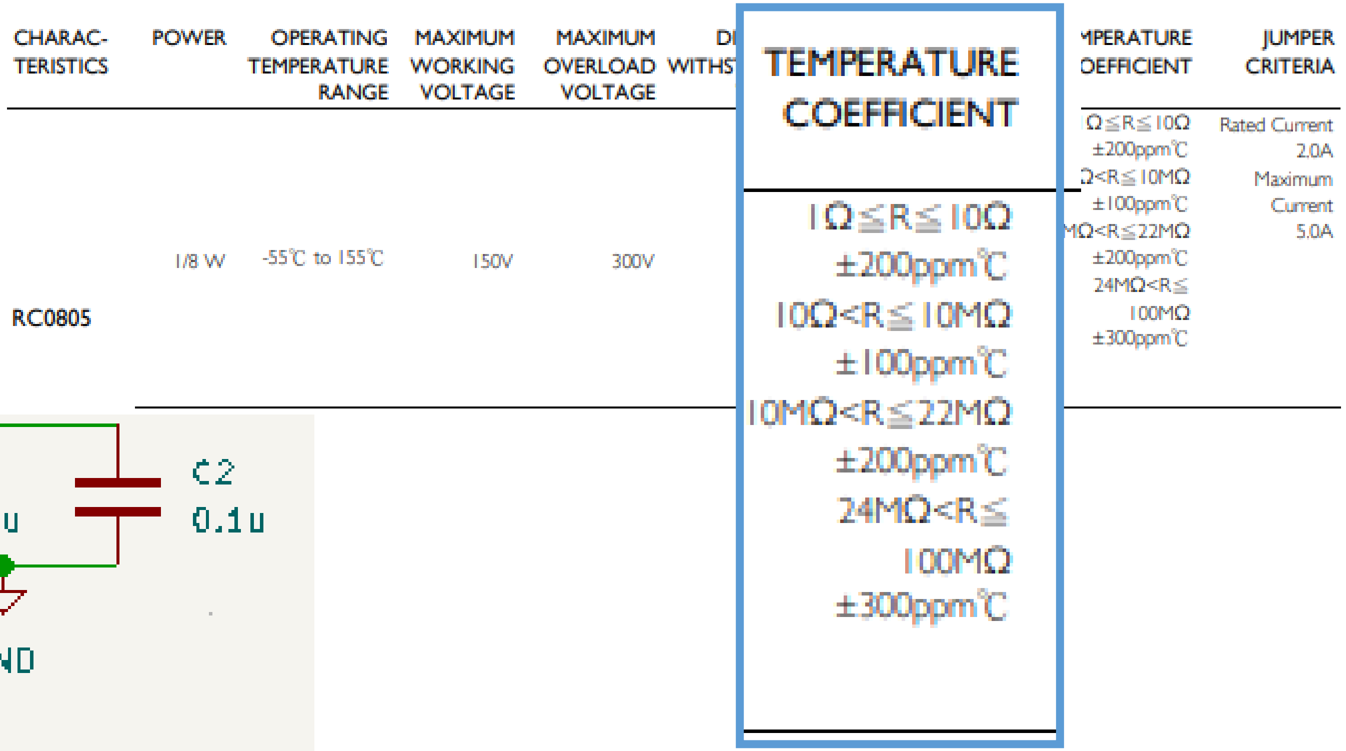
- Every resistor you buy has a resistance that varies with temperature

$$\boldsymbol{R = R(T)}$$




Joel's sensor board

**Datasheet**



| CHARAC-TERISTICS | POWER | OPERATING TEMPERATURE RANGE | MAXIMUM WORKING VOLTAGE | MAXIMUM OVERLOAD VOLTAGE | DI… WITHS… | TEMPERATURE COEFFICIENT | …MPERATURE …OEFFICIENT | JUMPER CRITERIA |
|---|---|---|---|---|---|---|---|---|
| RC0805 | 1/8 W | -55℃ to 155℃ | 150V | 300V | | 1Ω≦R≦10Ω ±200ppm℃ 10Ω<R≦10MΩ ±100ppm℃ 10MΩ<R≦22MΩ ±200ppm℃ 24MΩ<R≦100MΩ ±300ppm℃ | …Ω≦R≦10Ω ±200ppm℃ …Ω<R≦10MΩ ±100ppm℃ …MΩ<R≦22MΩ ±200ppm℃ 24MΩ<R≦100MΩ ±300ppm℃ | Rated Current 2.0A Maximum Current 5.0A |

# Temperature sensing

## Temperature-varying resistors

- Every resistor you buy has a resistance that varies with temperature

$$R = R(T)$$

**Temperature Coefficient of Resistance (TCR)**

$$TCR = \frac{R(T_2)-R(T_1)/_{R(T_1)}}{(T_2-T_1)} \ [\text{ppm}/°C]$$

$T_1$ is typically 25 $°C$

$$R(T_2) = R(T_1)\big(1 + TCR \cdot (T_2 - T_1)\big)$$

For our 4.7k pull-up resistor from sensor board, at $T_2 = 100\ °C$:

$$R(T_2) = 4.7k\big(1 + 100e^{-6} \cdot (75°C)\big)$$

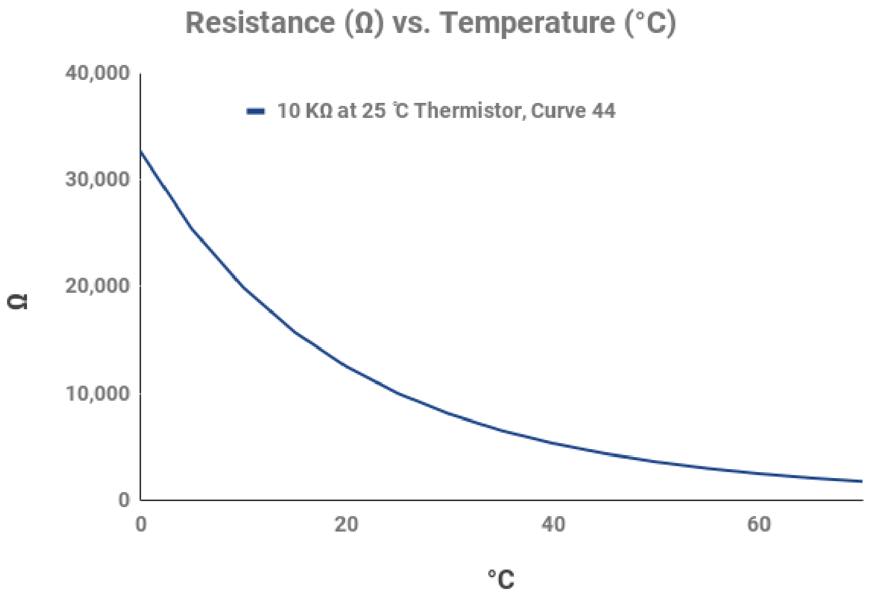
$$R(T_2) = 4.7k(1.0075) = 4.73\text{k}$$

good for us…but not a great sensor

# Thermistor

## Instead…make a resistor with a really large TCR

- Thermistor = temperature-sensitive resistor
- Two-terminal device, avail in small SMT package
- Composite material of metallic oxides
- Inexpensive (~$0.04 @ 1k)
- NTC = negative temperature coefficient [of resistance]
- This is a nonlinear characteristic, so going from $R$ ➔ $T$ requires some work
    - Multiple approaches depending on desired accuracy
    - Though sometimes the absolute temperature doesn’t matter, just trying to keep a system near a reference temperature




$$\beta = \frac{\ln\left(\frac{R(T_1)}{R(T_2)}\right)}{\frac{1}{T_1} - \frac{1}{T_2}}$$

# NTC thermistor

- How to convert resistance (change) into something we can act on?
- Turn into a voltage, of course

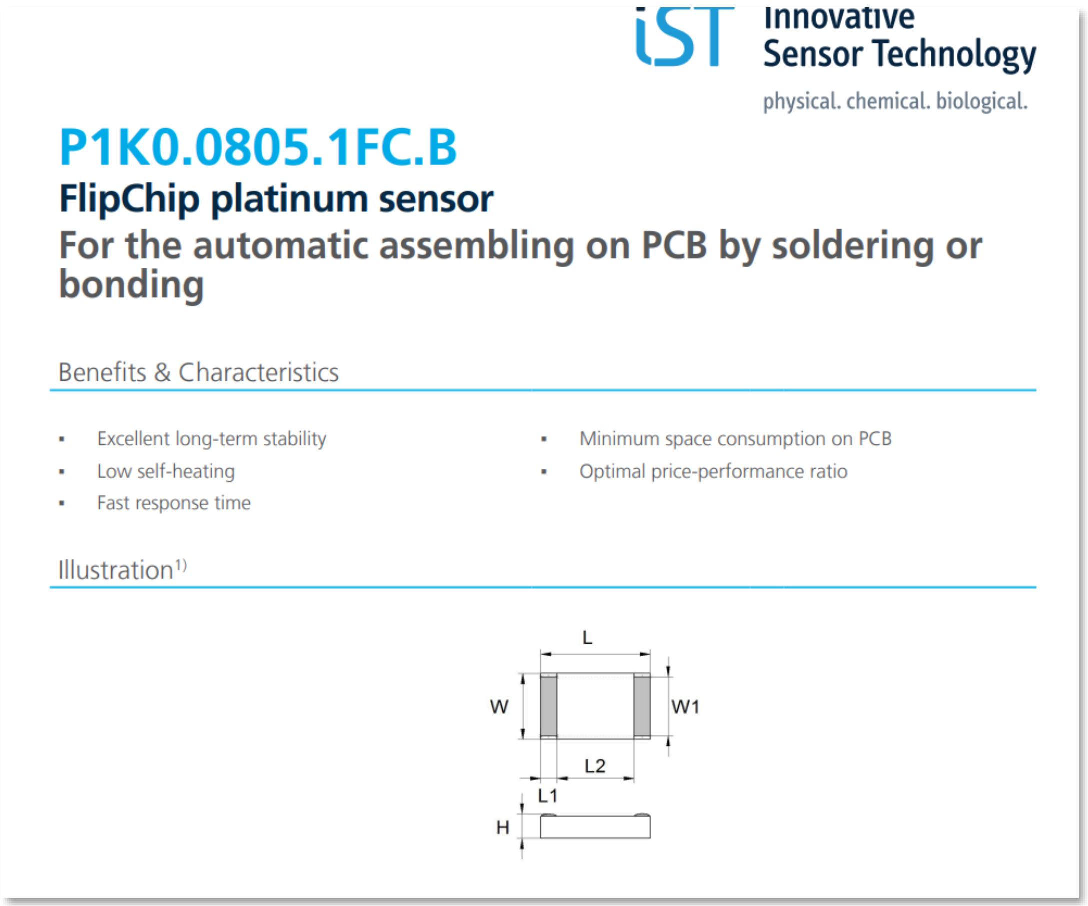
➔ use $\mathrm{V} = \mathrm{IR}(T)$

- Need at least one other resistor (or a good current source)
- May use a bridge circuit (see later)

- Issues
  - Extra components ➔ increased cost, space
  - Current for measurement will induce some heating ➔ and thus error
    - This is called *Self heating*

# RTD thermistor

- RTD: resistance temperature detectors
- Pure element (like Pt)
- Available in SMT package
- Much more expensive than NTC
  - $0.9898 @1k quantities
- Broader range esp. to high temperature
- Sensitivity < NTC but higher than regular resistor
  - TCR = 3850 ppm/°C
- Much more linear than thermistor
- Measurement circuits similar to NTC


Innovative Sensor Technology
physical. chemical. biological.

**P1K0.0805.1FC.B**

**FlipChip platinum sensor**

**For the automatic assembling on PCB by soldering or bonding**

Benefits & Characteristics

- Excellent long-term stability
- Low self-heating
- Fast response time
- Minimum space consumption on PCB
- Optimal price-performance ratio

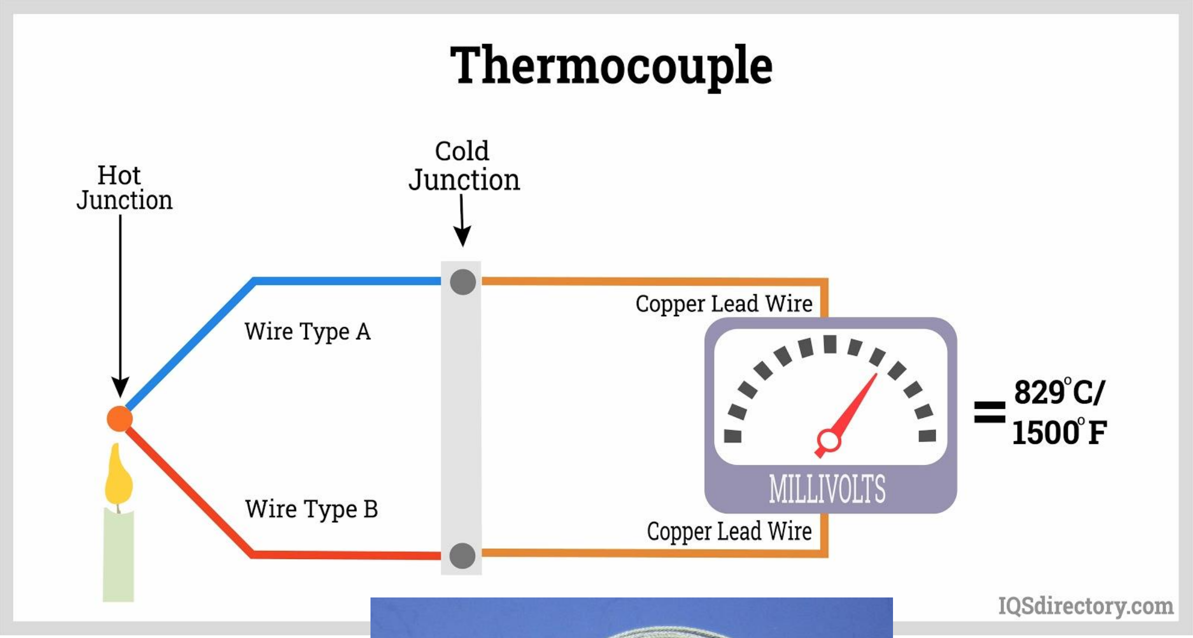
Illustration[1)]

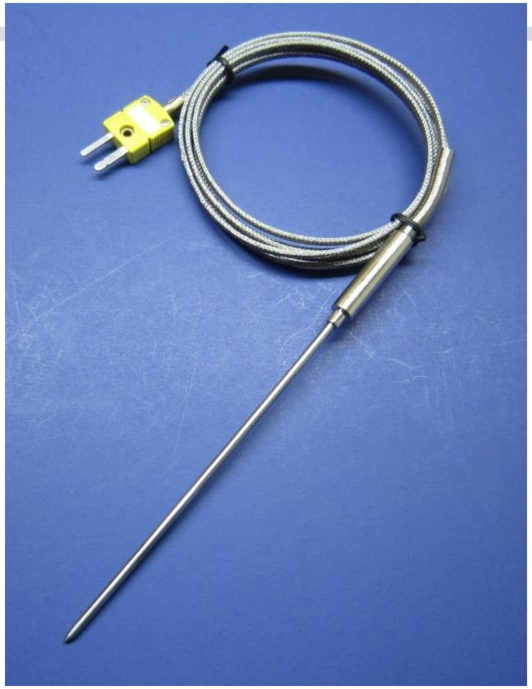
# Thermocouples

- Not a resistive temperature sensor!
- Directly converts temperature differences into voltage differences
  - Need to know temp at "cold" junction
- Mechanism involves thermoelectricity: connecting two materials with different thermoelectric coefficients
  - Thermoelectric = coupling between thermal ($\Delta T$) and electric ($\Delta V$) domains

$$-\nabla\phi = \alpha_s \nabla T$$

- This also used (in reverse) for Peltier coolers
- Can go to **really high** temperatures (2000+ K)
- Not very common in integrated systems (but we'll see one in a bit…)



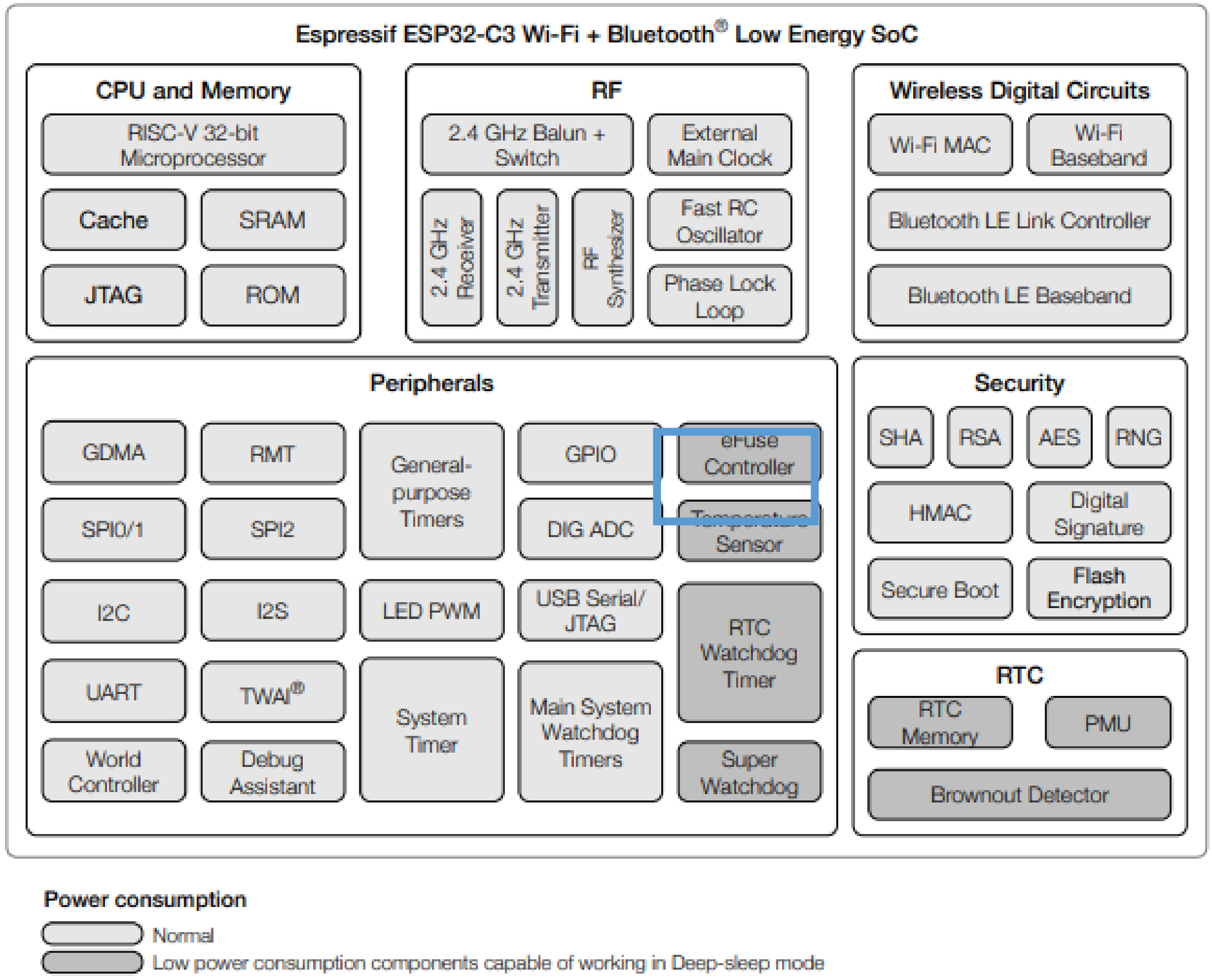
# Bandgap temperature sensors

- Use physics intrinsic to semiconductors

**pn junction (diode) equation**

$$I_D = I_0\left(e^{\frac{V_D}{\frac{kT}{q}}} - 1\right)$$

- If you already have diodes or transistors, can easily incorporate
- Good to about ~200 $°C$
- Often included “for free” in a MCU
  - Including ESP32C3
  - But only measures temperature of the MCU…
  - And will be affected by power dissipation in MCU




ESP32-C3 Functional Block Diagram


CPU: AMD Ryzen 7 1800X
TEMP
28 °C
LOAD
1 %
CLOCK SPEED
3691 MHz
FAN SPEED
1248 RPM
GPU: NVIDIA GeForce GTX 1080 Ti
TEMP
44 °C
LOAD
17 %
CLOCK SPEED
608 MHz
FAN SPEED
0 RPM
RAM
LOAD
35 %
5.68GB
STORAGE
USED
FREE
C: Drive Samsung SSD 960 PRO 512GB
476GB
253GB
Used
223GB
Free

# Bandgap temperature sensors

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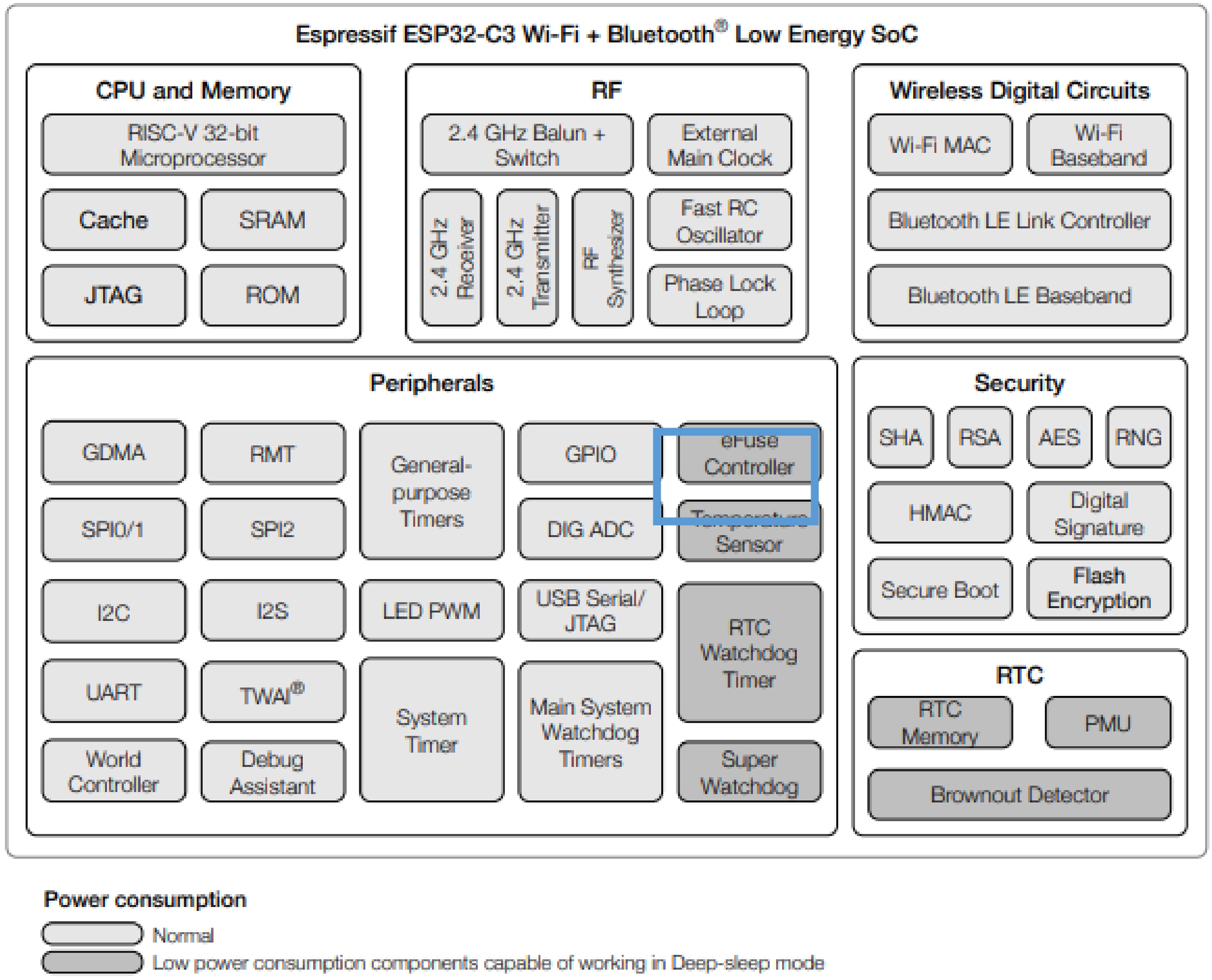



ESP32-C3 Functional Block Diagram

# Temperature sensors

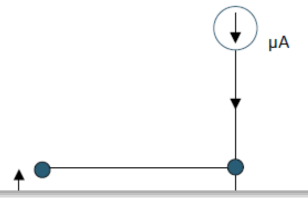
- Some comparisons, from ➔

*Temperature sensing fundamentals*

TEXAS INSTRUMENTS

**Introduction to Temperature Sensing**

In embedded systems, there is a constant need for higher performance and more features in a smaller form factor. This requires system designers to **monitor** the overall temperature to ensure safety and **protect** ...ogging further ...ement to not




**This means bandgap**

| | IC Sensor | Thermistor | RTD | Thermo couple |
|---|---|---|---|---|
| Range | –55°C to +200°C | –100°C to +500°C | –240°C to 600°C | –260°C to +2300°C |
| Accuracy | Good / Best | Calibration dependant | Best | Better |
| Footprint / Size | Smallest | Small | Moderate | Large |
| Complexity | Easy | Moderate | Complex | Complex |
| Linearity | Best | Low | Best | Better |
| Topology | Point-to-point, Multi-drop, Daisy Chain | Point-to-point | Point-to-point | Point-to-point |
| Price | Low to Moderate | Low to Moderate | Expensive | Expensive |

# Sensor specifications

In sensing, we want to choose/design an approach…

And ultimately choose a **specific** component

How do we pick? **Specs**

# Sensor specifications

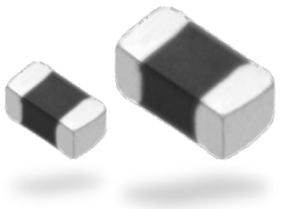
A partial list – these are common to **many** sensors (not just temperature!)

- Range
  - The range [min, max] over which the sensor is designed to operate
- Sensitivity
  - The slope (may be local) of the input-output characteristic

Panasonic INDUSTRY

Multilayer NTC Thermistors

ERTJ series



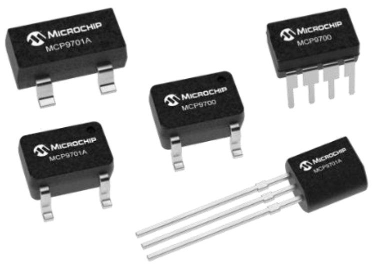
**Ratings**

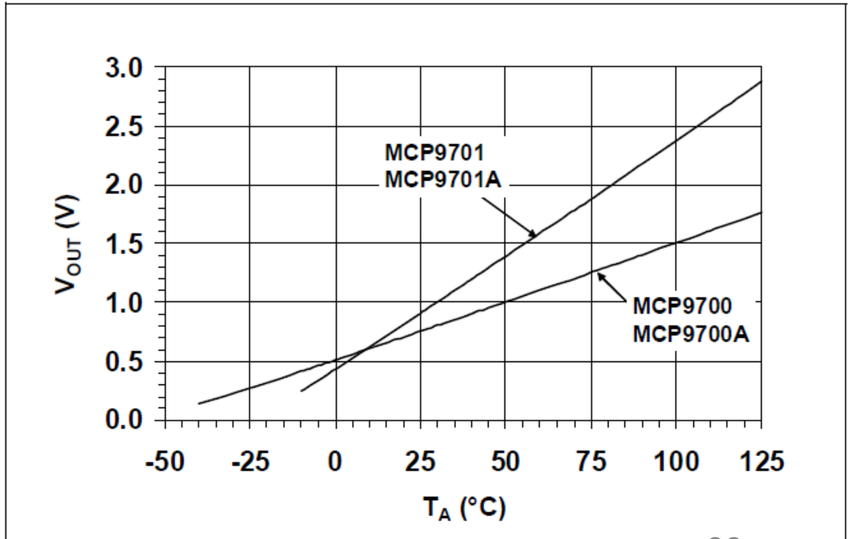
| Size code (inch size) | Z(0201) | 0(0402) | 1(0603) |
|---|---|---|---|
| Operating temperature range | –40 to 125 ℃ | | |
| Rated maximum power dissipation [*1] | 33 mW | 66 mW | 100 mW |
| Dissipation factor [*2] | Approximately 1 mW / ℃ | Approximately 2 mW / ℃ | Approximately 3 mW / ℃ |

MICROCHIP **MCP970X**

Low-Power Linear Active Thermistor ICs

***Not a thermistor!***
***This is actually a bandgap temp sensor IC***

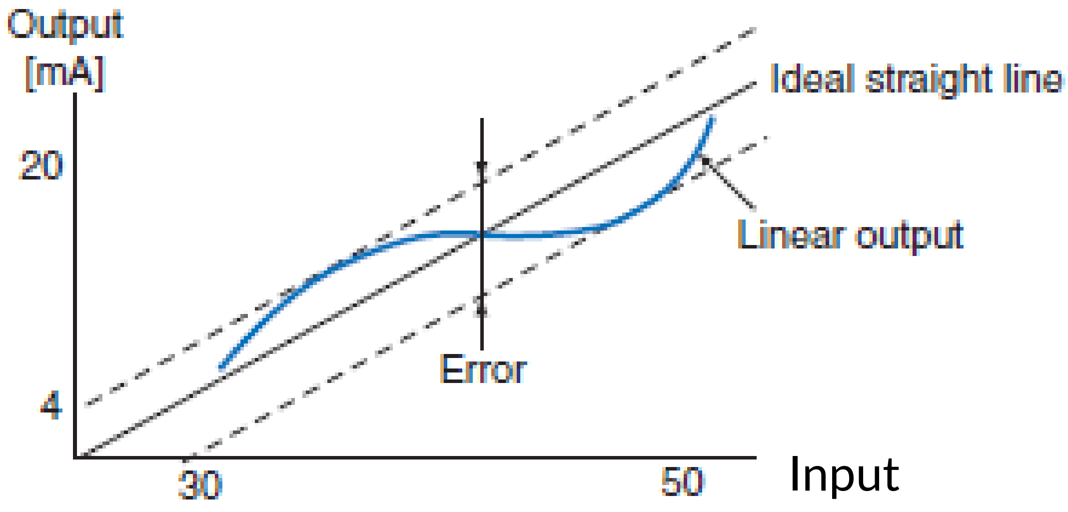


# Sensor specifications

A partial list – these are common to **many** sensors (not just temperature!)

- (non)Linearity
  - For sensors with nominally linear input-output relationship,
  - Typically the maximum deviation from the straight line



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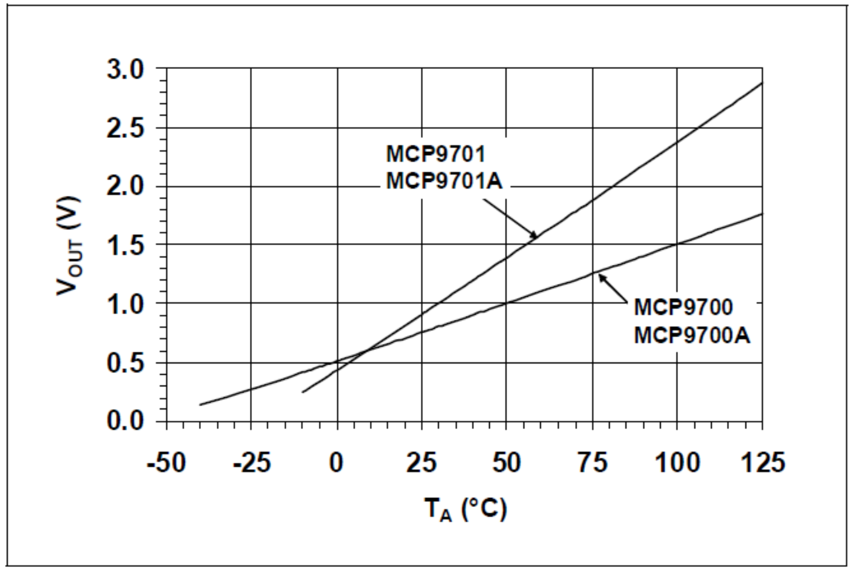
MICROCHIP **MCP970X**

**Low-Power Linear Active Thermistor ICs**




**DC ELECTRICAL CHARACTERISTICS (CONTINUED)**

**Electrical Specifications:** Unless otherwise indicated:
**MCP9700/9700A/9700B:** $V_{DD}$ = 2.3V to 5.5V, GND = Ground, $T_A$ = -40°C to +125°C and No load
**MCP9701/9701A:** $V_{DD}$ = 3.1V to 5.5V, GND = Ground, $T_A$ = -10°C to +125°C and No load

| Parameter | Sym. | Min. | Typ. | Max. | Unit | Conditions |
|---|---|---|---|---|---|---|
| Output Voltage, $T_A$ = 0°C | $V_{0°C}$ | — | 400 | — | mV | **MCP9701/9701A** |
| Temperature Coefficient | $T_C$ | — | 10.0 | — | mV/°C | **MCP9700/9700A/9700B** |
| | $T_C$ | — | 19.5 | — | mV/°C | **MCP9701/9701A** |
| Output Nonlinearity | $V_{ONL}$ | — | ±0.5 | — | °C | $T_A$ = 0°C to +70°C (Note 3) |
| Output Current | $I_{OUT}$ | — | — | 100 | µA | |
| Output Impedance | $Z_{OUT}$ | — | 20 | — | Ω | $I_{OUT}$ = 100 µA, f = 500 Hz |
| Output Load Regulation | $\Delta V_{OUT}/\Delta I_{OUT}$ | — | 2 | — | Ω | $T_A$ = 0°C to +70°C<br>$I_{OUT}$ = 100 µA |
| Turn-On Time | $t_{ON}$ | — | 800 | — | µs | |
| Typical Load Capacitance | $C_{LOAD}$ | — | — | 1000 | pF | Note 4 |
| SC-70 Thermal Response to 63% | $t_{RES}$ | — | 1.3 | — | s | 30°C (Air) to +125°C<br>(Fluid Bath) (Note 5) |
| TO-92 Thermal Response to 63% | $t_{RES}$ | — | 1.65 | — | s | |

# Sensor specifications

A partial list – these are common to **many** sensors (not just temperature!)

- Accuracy
  - Deviation from the **true** result
  - This can sometimes be improved via calibration

MICROCHIP **MCP970X**

**Low-Power Linear Active Thermistor ICs**

| Parameter | Sym. | Min. | Typ. | Max. | Unit | Conditions |
|---|---|---|---|---|---|---|
| **Sensor Accuracy (Notes 2, 3)** | | | | | | |
| $T_A$ = +25°C | $T_{ACY}$ | — | ±1 | — | °C | |
| $T_A$ = +20°C to +70°C | $T_{ACY}$ | -1.0 | ±0.5 | +1.0 | °C | MCP9700B |
| $T_A$ = -40°C to +125°C | $T_{ACY}$ | -2.0 | ±0.5 | +4.0 | °C | MCP9700B |
| $T_A$ = 0°C to +70°C | $T_{ACY}$ | -2.0 | ±1 | +2.0 | °C | MCP9700A/9701A |
| $T_A$ = -40°C to +125°C | $T_{ACY}$ | -2.0 | ±1 | +4.0 | °C | MCP9700A |
| $T_A$ = -10°C to +125°C | $T_{ACY}$ | -2.0 | ±1 | +4.0 | °C | MCP9701A |
| $T_A$ = 0°C to +70°C | $T_{ACY}$ | -4.0 | ±2 | +4.0 | °C | MCP9700/9701 |
| $T_A$ = -40°C to +125°C | $T_{ACY}$ | -4.0 | ±2 | +6.0 | °C | MCP9700 |
| $T_A$ = -10°C to +125°C | $T_{ACY}$ | -4.0 | ±2 | +6.0 | °C | MCP9701 |
| $T_A$ = -40°C to +150°C | $T_{ACY}$ | -4.0 | ±2 | +6.0 | °C | MCP9700 High Temperature (Note 1) |
| $T_A$ = -40°C to +150°C | $T_{ACY}$ | -4.0 | ±2 | +4.0 | °C | MCP9700B High Temperature (Note 1) |

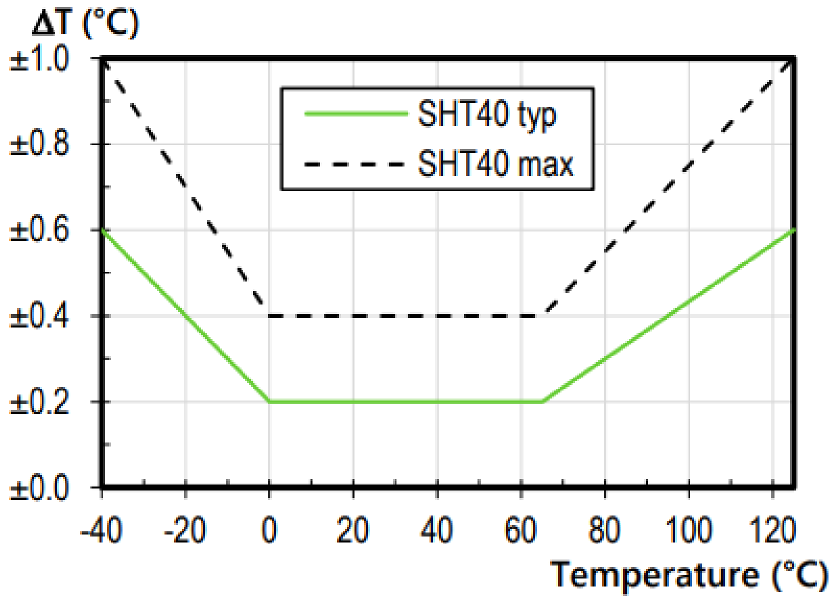



**Figure 10.** SHT40 typical and maximal temperature accuracy.

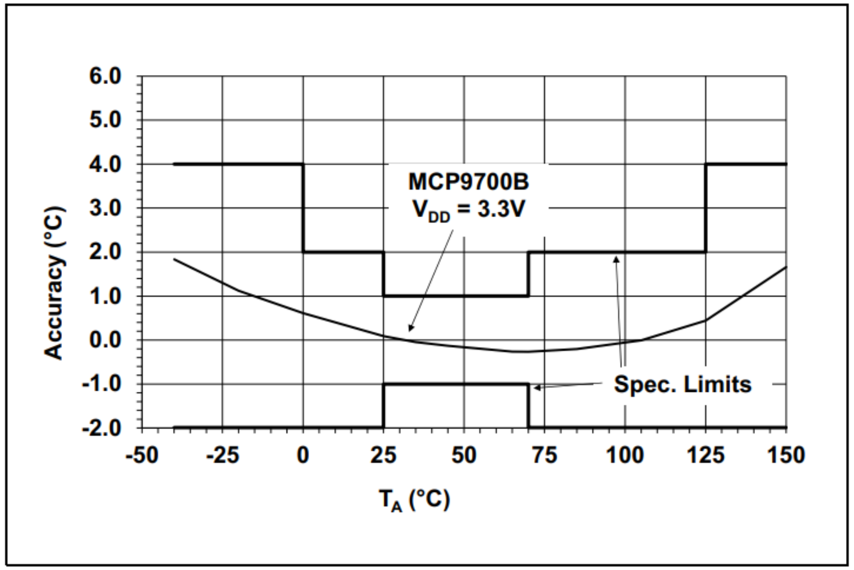



***FIGURE 2-1:*** *Accuracy vs. Ambient Temperature (MCP9700B).*

# Sensor specifications

- Response time
  - How fast will sensor output change due to sensor input change
  - For analog sensors, this may be expressed as a time constant
  - For sensors with digital output, may be the time between updates
  - May also be expressed in terms of frequency response

**DC ELECTRICAL CHARACTERISTICS (CONTINUED)**

**Electrical Specifications:** Unless otherwise indicated:
**MCP9700/9700A:** $V_{DD}$ = 2.3V to 5.5V, GND = Ground, $T_A$ = -40°C to +125°C and No load
**MCP9701/9701A:** $V_{DD}$ = 3.1V to 5.5V, GND = Ground, $T_A$ = -10°C to +125°C and No load

| Parameter | Sym. | Min. | Typ. | Max. | Unit | Conditions |
|---|---|---|---|---|---|---|
| Output Current | $I_{OUT}$ | — | — | 100 | µA | |
| Output Impedance | $Z_{OUT}$ | — | 20 | — | Ω | $I_{OUT}$ = 100 µA, f = 500 Hz |
| Output Load Regulation | $\Delta V_{OUT}/\Delta I_{OUT}$ | — | 1 | — | Ω | $T_A$ = 0°C to +70°C<br>$I_{OUT}$ = 100 µA |
| Turn-On Time | $t_{ON}$ | — | 800 | — | µs | |
| Typical Load Capacitance | $C_{LOAD}$ | — | — | 1000 | pF | Note 4 |
| SC-70 Thermal Response to 63% | $t_{RES}$ | — | 1.3 | — | s | 30°C (Air) to +125°C (Fluid Bath) (Note 5) |
| TO-92 Thermal Response to 63% | $t_{RES}$ | — | 1.65 | — | s | |

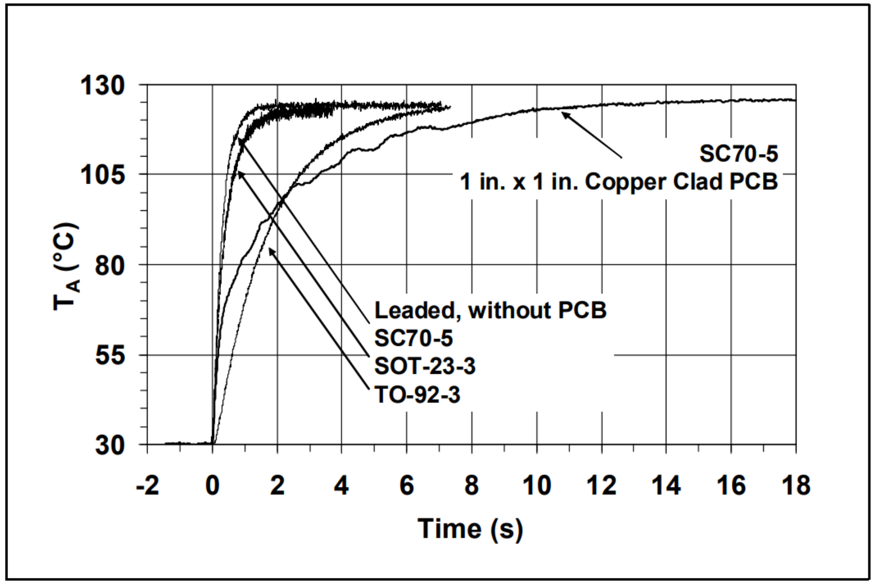



*FIGURE 2-16: Thermal Response (Air-to-Fluid Bath).*

**SHT40**

| | | | |
|---|---|---|---|
| Response time[10] | $\tau_{63\%}$ | 2 | s |

# Sensor specifications

- Stability, repeatability, long-term drift
  - If I make the same measurement 3 times, will I get the same result?
  - Will the result today be the same as it is in 1 minute, 1 day, 1 year, 10 years?
- Cost
- Size

**SHT40**

| | | | |
|---|---|---|---|
| Repeatability[3] | high | 0.04 | °C |
| | medium | 0.07 | °C |
| | low | 0.1 | °C |

[3] The stated repeatability is three times the standard deviation (3σ) of multiple consecutive measurement values at constant conditions and is a measure for the noise on the physical sensor output. Different repeatability commands are listed in **Table 8**

# Sensor specifications

- Current/power consumption
  - This is critical for battery-operated systems!
- Supply voltage
  - Is sensor voltage same as other components, or do you need to create additional supply voltages?

**SHT40**

| Parameter | Symbol | Conditions | Min | Typ | Max | Unit | Comments |
|---|---|---|---|---|---|---|---|
| Supply voltage | $V_{DD}$ | | 1.08 | 3.3 | 3.6 | V | - |
| Power-up/down | $V_{POR}$ | Static power supply | 0.6 | - | 1.08 | V | - |
| Slew rate of the supply voltage | $V_{DD,\ slew}$ | | - | - | 20 | V/ms | Voltage changes on the supply between $V_{DD,\ min}$ and $V_{DD,\ max}$. Faster slow rates may lead to a reset |
| Supply current (heater **off**) | $I_{DD}$ | Idle state | -<br>- | 0.08<br>- | 1.0<br>3.4 | μA | At 25 °C<br>At 125 °C |
| | | Power up | - | 50 | - | μA | - |
| | | Measurement | - | 320 | 500 | μA | Current while sensor is measuring |
| | | Avg., high repeatability<br>Avg., med. repeatability<br>Avg., low repeatability | -<br>-<br>- | 2.2<br>1.2<br>0.4 | -<br>-<br>- | μA | Avg. current consumption (continuous operation with 1 meas. per second) |
| Supply current (heater **on**) | $I_{DD}$ | Nomin. heater "200 mW" | - | 60 | 100 | mA | see section 4.9 |
| | | Nomin. heater "110 mW" | - | 33 | 55 | mA | |
| | | Nomin. heater "20 mW" | - | 6 | 10 | mA | |

MICROCHIP **MCP970X**

**Low-Power Linear Active Thermistor ICs**

## DC ELECTRICAL CHARACTERISTICS

**Electrical Specifications:** Unless otherwise indicated:
**MCP9700/9700A/9700B:** $V_{DD}$ = 2.3V to 5.5V, GND = Ground, $T_A$ = -40°C to +125°C and No load
**MCP9701/9701A:** $V_{DD}$ = 3.1V to 5.5V, GND = Ground, $T_A$ = -10°C to +125°C and No load

| Parameter | Sym. | Min. | Typ. | Max. | Unit | Conditions |
|---|---|---|---|---|---|---|
| **Power Supply** | | | | | | |
| Operating Voltage Range | $V_{DD}$<br>$V_{DD}$ | 2.3<br>3.1 | —<br>— | 5.5<br>5.5 | V<br>V | **MCP9700/9700A/9700B**<br>**MCP9701/9701A** |
| Operating Current | $I_{DD}$ | — | 6 | 12 | μA | |
| | $I_{DD}$ | — | — | 15 | μA | $T_A$ = +150°C (**Note 1**) |
| Line Regulation | $\Delta°C/\Delta V_{DD}$ | — | 0.1 | — | °C/V | |

# Packaging

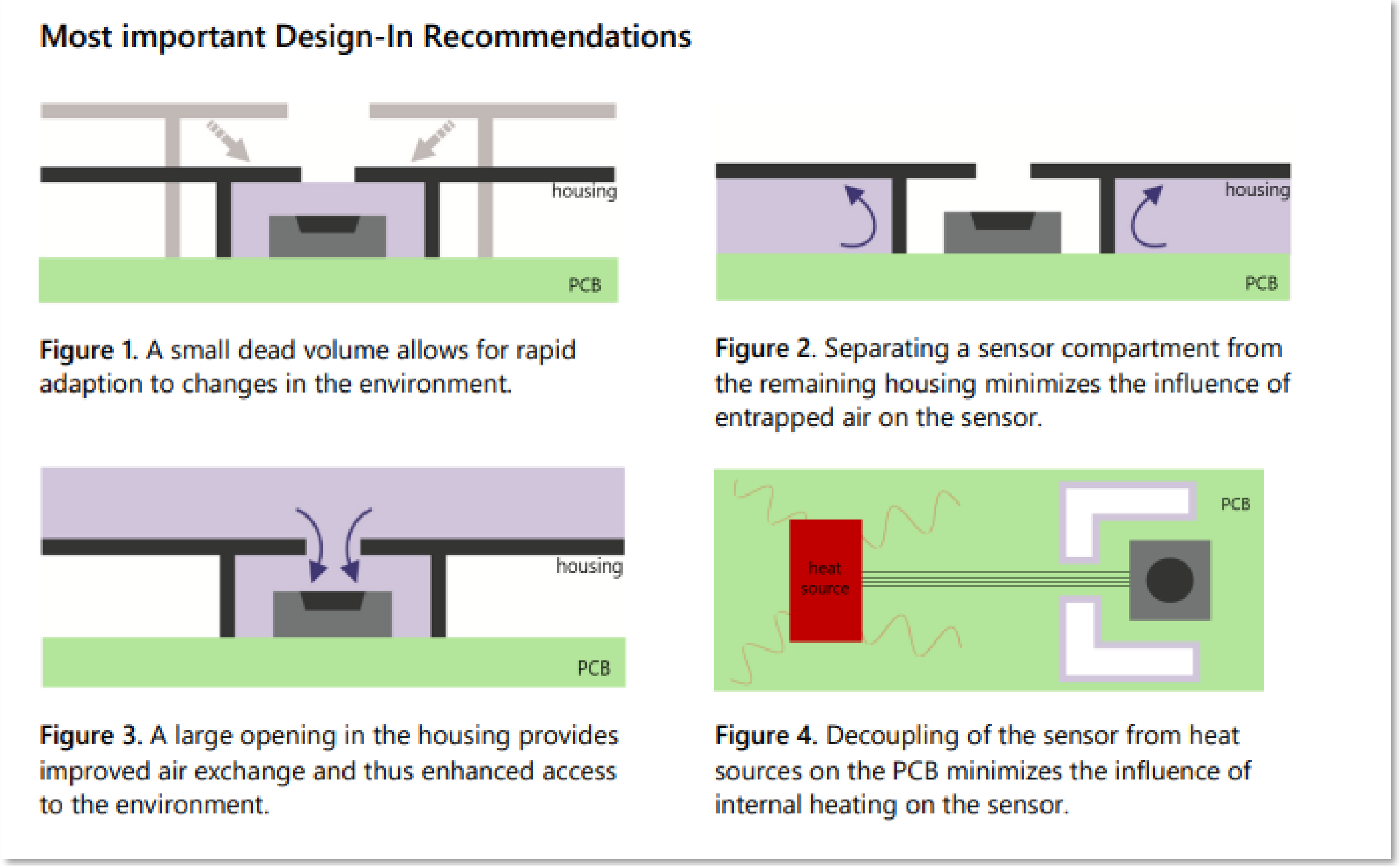
Sensors must interact with the quantity being measured

- Sometimes this is easy
  - Inertial sensors (acceleration, rotation) are easiest because those forces transmit through objects
- But usually this is not easy…

  and sometimes it is **really hard**
- Examples
  - A temperature sensor embedded in MCU can't measure temperature somewhere else
  - Humidity sensors have to interact with outside air
  - A rain sensor must sense…water!
  - A light sensor must have optical access at the relevant wavelengths

# Packaging – example for Sensirion RHT sensors

- 21-page design guide for packaging temperature (and humidity sensors)
  - This will necessarily require domain knowledge
  - Thermal design, mechanical design, etc.



**Most important Design-In Recommendations**



**Figure 1.** A small dead volume allows for rapid adaption to changes in the environment.



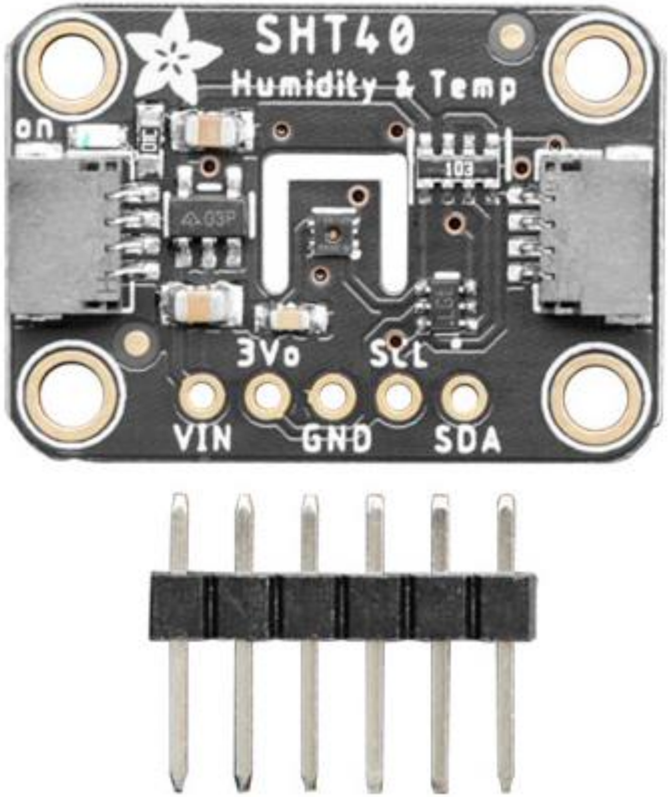
**Figure 2.** Separating a sensor compartment from the remaining housing minimizes the influence of entrapped air on the sensor.



**Figure 3.** A large opening in the housing provides improved air exchange and thus enhanced access to the environment.



**Figure 4.** Decoupling of the sensor from heat sources on the PCB minimizes the influence of internal heating on the sensor.



# Packaging – Acconeer radar

- 30-page design guide for packaging

## 2.3 Choosing a 1.8 V power regulator for A111/A121

When the A111/A121 radar sensors transfer from the "SLEEP" state to the "MEASURE" state, there is an abrupt change in current consumption from ~3 mA to ~75 mA on the 1.8 V power domain. It must be ensured that the power regulator used to supply the A111/A121 has a load transient response that handles this change in current without the output voltage dropping below the minimum operating supply voltage of A111/A121. For details regarding the power consumption of A111 and A121, refer to the datasheet of the respective product [2] [3].

## 3.7 Radomes

A radome is a dielectric layer that is transparent to the radar signal while protecting the radar from mechanical impact and weather, see Figure 11. Often the product encapsulation can be made as a radome without introducing additional costs. We will here see that by tuning the radome thickness and distance, the radome can be made transparent to the radar.

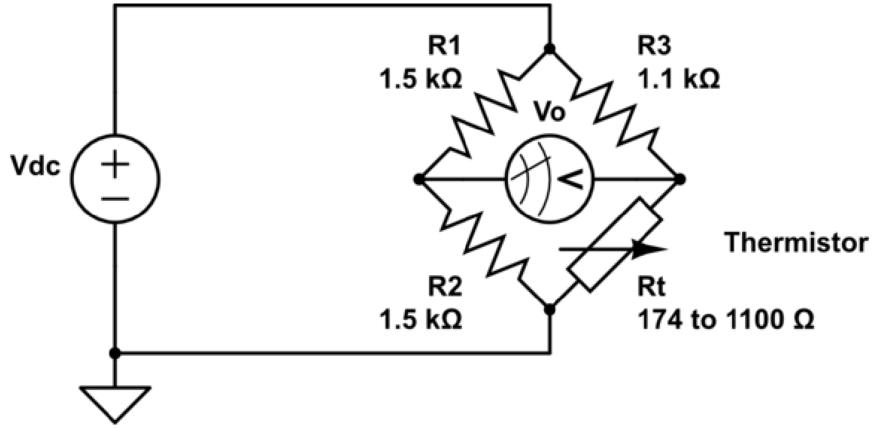
### 3.7.1 Radome thickness

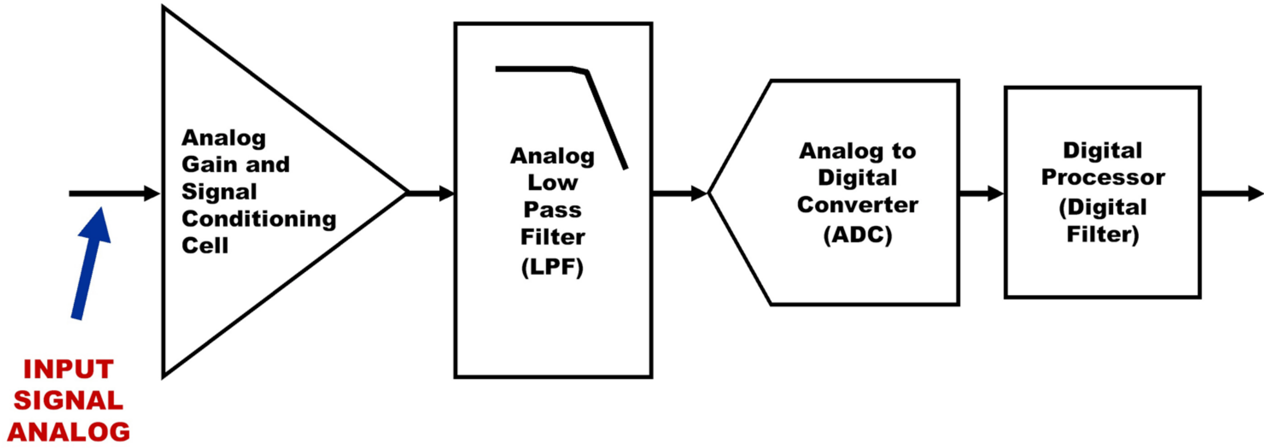
# Signal conditioning and conversion

- The designer has to consider how to connect the sensor to the rest of the system
- Do you want analog or digital data?
- Occasionally, you want an analog signal
  - Ex: for analog temperature compensation
  - Ex: sometimes cheaper

# Signal conditioning and conversion

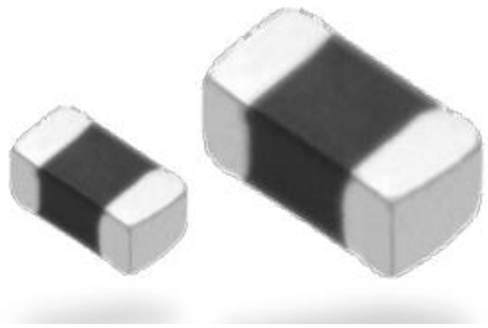
- If analog signal isn't already a voltage (aka RTD, thermistor), usually convert to voltage
  - Often via bridge circuit
- Might need to filter to reduce noise
  - RC, Sallen-Key, etc.
  - As always, tradeoff between amount of hardware vs. amount of software
- Best to make signal take full range of ADC
  - May require gain [or signal attenuation]
  - Many MCUs have on-board ADCs, or can use dedicated ADC
    - Need to consider number of bits, etc. [we won't get into this]



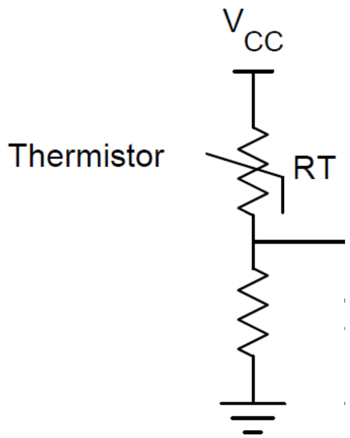
# Example: compare two approaches

- NTC (Thermistor) vs. Bandgap-referenced digital output
- Assume we are fine with measurement on a PCB
  - So SMT packages are used for both
- NTC
  - Panasonic ERT-J series
  - Range -40 to 125 °C
  - Nominally 10k resistance
  - Package 0201 [0.6 x 0.3 x 0.3 mm]
  - $0.0356 @ 1k

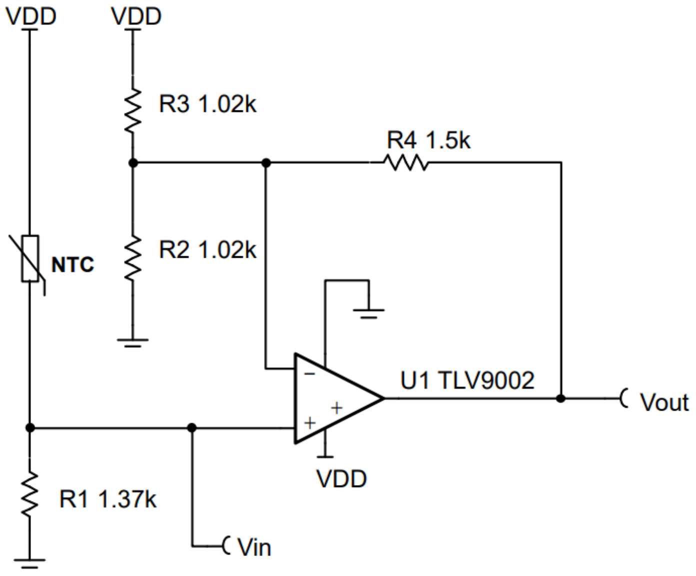


- Bandgap
  - UMW LM75BDP
  - Range -55 to 125 °C
  - I2C comms
  - Package 8-pin TSSOP [3 x 5 x 1.1 mm]
  - $0.345 @ 1k

# Compare two approaches




- NTC
  - Measure via voltage divider
    - One more resistor [1%], $0.00246
    - Good for single-supply (common these days)
  - What if we need to amplify?
    - To adjust output to span ADC for given input
    - Now we need non-inv op-amp
    - 1 op-amp + 3 resistors
    - Cheap TLV9002 op-amp
      - $0.282 @ 1k
      - 8-TSSOP [3 x 4.4 x 1.2 mm]
        - Smaller packages avail, but more $$



# Compare two approaches

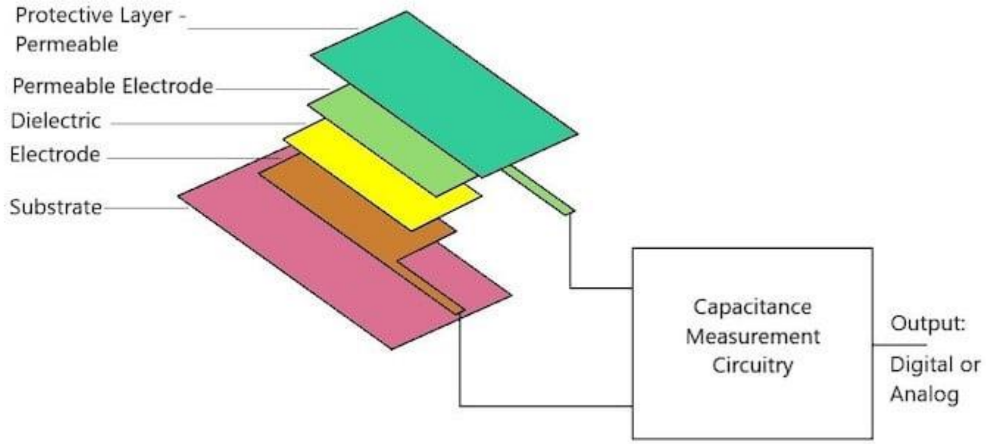
- NTC
  - Cost
    - NTC $0.0356 @ 1k
    - 4 resistors $0.00984 @ 1k
    - 1 IC $0.282 @ 1k
    - Assembly $0.0017 x 18 joints
    - **Total: $0.341**
  - Size
    - 8-TSSOP [3 x 4.4 x 1.2 mm]
    - +passives, traces,
    - So probably around similar size
- Bandgap
  - Cost
    - $0.345 @ 1k
    - Assembly $0.0017 x 8 joints
    - **Total: $0.359**
  - Size
    - Package 8-pin TSSOP [3 x 5 x 1.1 mm]

# Compare two approaches

- So how to choose?
  - May be on specs
    - Maybe having a linear output, or accuracy is really important
  - Or other issues
    - Maybe don’t need to amplify, and cost is driver, and so thermistor makes sense
    - Maybe don’t want to spend extra for MCU with ADC
    - Maybe don’t want to use two MCU pins for I2C
      - Only use one pin for ADC
    - Maybe don’t want to spend engineering time to design/test analog circuit

# Humidity

- Capacitive humidity sensor (like in SHT40)
- Parallel plate capacitor: $C = \frac{\epsilon A}{g}$
- Create capacitor with dielectric ($\epsilon$) that absorbs water (*hygroscopic*)
  - $\epsilon_{water} \approx 80 \gg \epsilon_{dielectric}$
    ➔ $C$ ↑ as humidity ↑
- And then we need a circuit that measures capacitance
  - We saw earlier how to turn C into voltage
  - Can also turn C ➔ freq → time
- There are also *resistive* humidity sensors (and probably other mechanisms), but capacitive is most common



# Humidity

- Capacitive humidity sensor (like in SHT40)
- Parallel plate capacitor: $C = $
- Create capacitor with dielect absorbs water (*hygroscopic*)
  - $\epsilon_{water} \approx 80 \gg \epsilon_{dielectric}$
    ➔ $C$ ↑ as humidity ↑
- And then we need a circuit t capacitance
  - We saw earlier how to turn C
  - Can also turn C ➔ freq → tim
- There are also *resistive* humi (and probably other mechani capacitive is most common

| Parameter | Conditions | Value | Units |
|---|---|---|---|
| SHT40 *RH* accuracy[1] | typ. | ±1.8 | %RH |
| | max. | See Figure 2 | - |
| SHT41 *RH* accuracy[1] | typ. | ±1.8 | %RH |
| | max. | See Figure 3 | - |
| SHT43 *RH* accuracy[1] | typ. | ±1.8 | %RH |
| | max. | See Figure 4 | |
| SHT45 *RH* accuracy[1] | typ. | ±1.0 | %RH |
| | max. | See Figure 5 | - |
| | long-term production[2] | ±0.5 | %RH |
| Repeatability[3, 4] | high | 0.08 | %RH |
| | medium | 0.15 | %RH |
| | low | 0.25 | %RH |
| Resolution[5] | - | 0.01 | %RH |
| Hysteresis | At 25 °C | ±0.8 | %RH |
| Specified range[6] | extended[7] | 0 to 100 | %RH |
| Response time[8] | $\tau_{63\%}$ | 4 | s |
| Long-term drift[9] | typ. | <0.2 | %RH/y |

**Table 1.** General relative humidity sensor specifications.

# Humidity

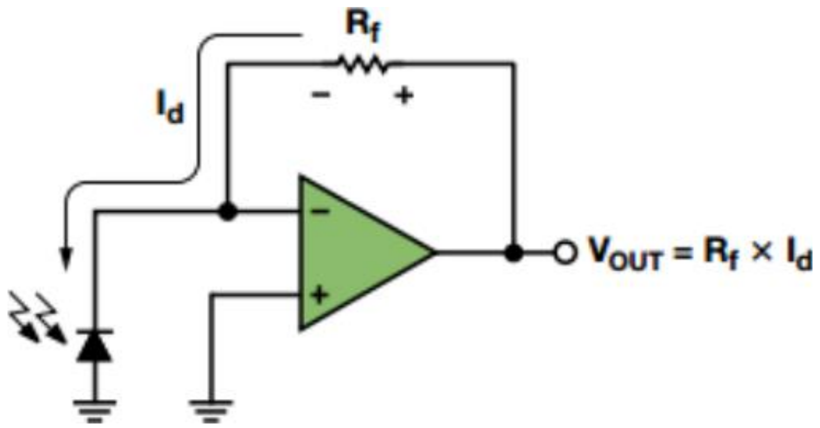
- SHT40 has a heater on it
- Can use it to “bake off” water on/in sensor
- For example, if
  - It got rained on and there is water in opening
  - Or you want to “reset” measurement

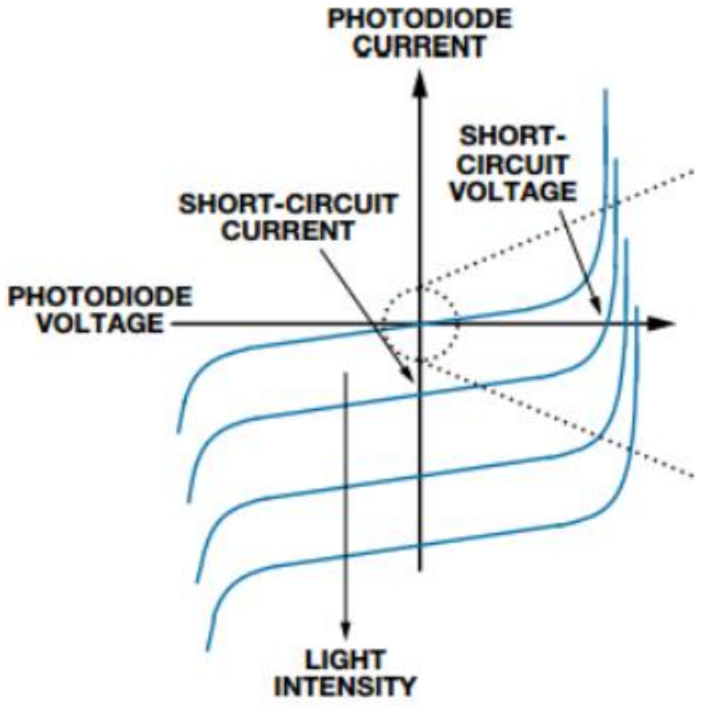
# Ambient light sensing

- Uses
  - Common use: display dimming, etc.
- Definitions
  - Lumen: Total visible light emitted, adjusted for human sensitivity
    - So not infrared, UV light
  - Lux:  Lumen/m2
    - This is an intensity
    - ~150,000 lux on a sunny day
    - ~0 lux in the dark

# Light sensing

- Transduction mechanism
  - Photoresistor
    - Light ➔ electron-hole pairs in a semiconductor ➔ increase conductivity (change in resistance) ➔ voltage
  - Photodiode
    - Light ➔ electron-hole pairs in a semiconductor ➔ current ➔ voltage
    - Generally faster and more sensitive than photoresistor




https://www.analog.com/en/resources/technical-articles/optimizing-precision-photodiode-sensor-circuit-design.html

# Light sensing

- VEML7700
  - Photodiode-based
  - Seems to have two photodiodes
    - With two different spectral responses (probably different filters), “white” and “ambient light sensor”
  - Need to set gain and integration time for various lux levels

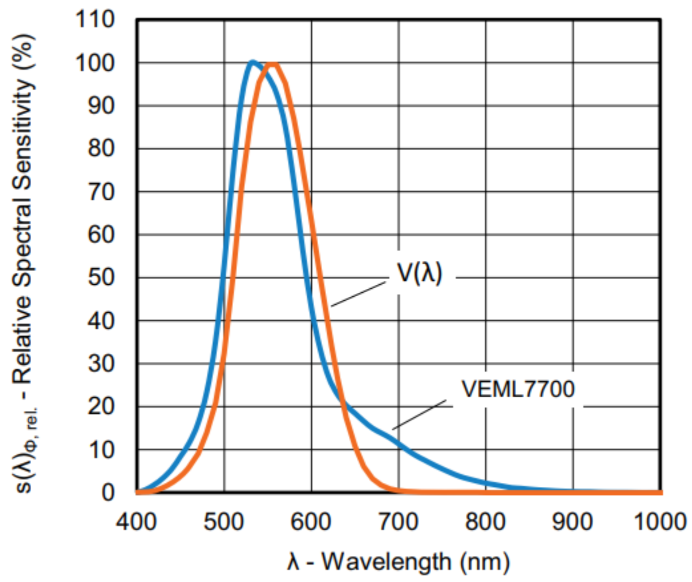


Fig. 5 - Spectral Response

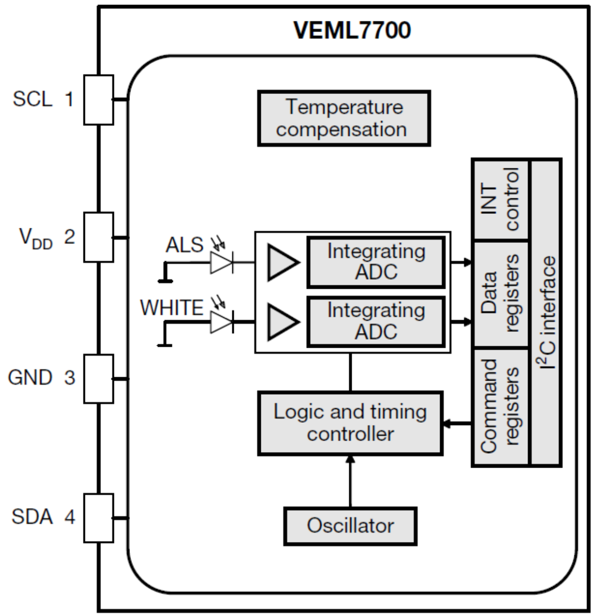
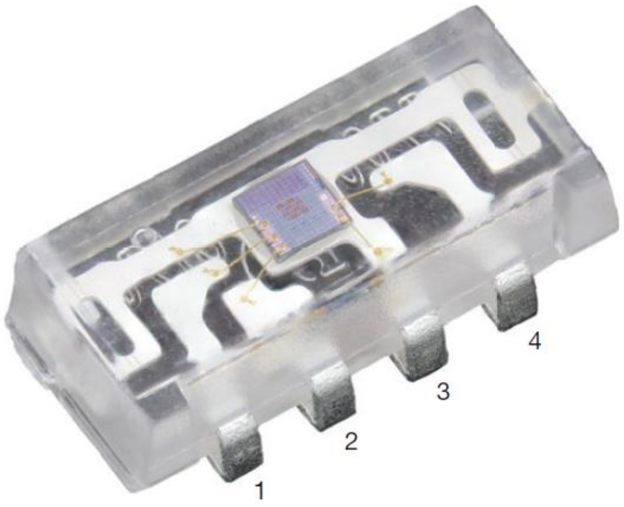


Fig. 1 - Block Diagram



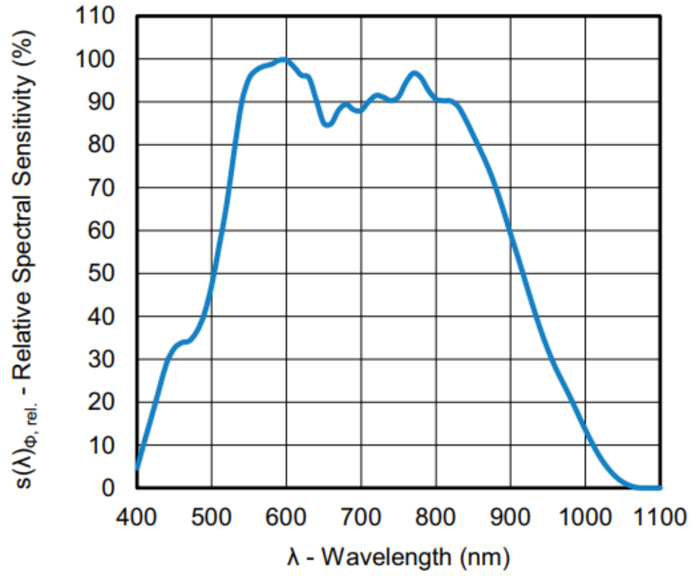
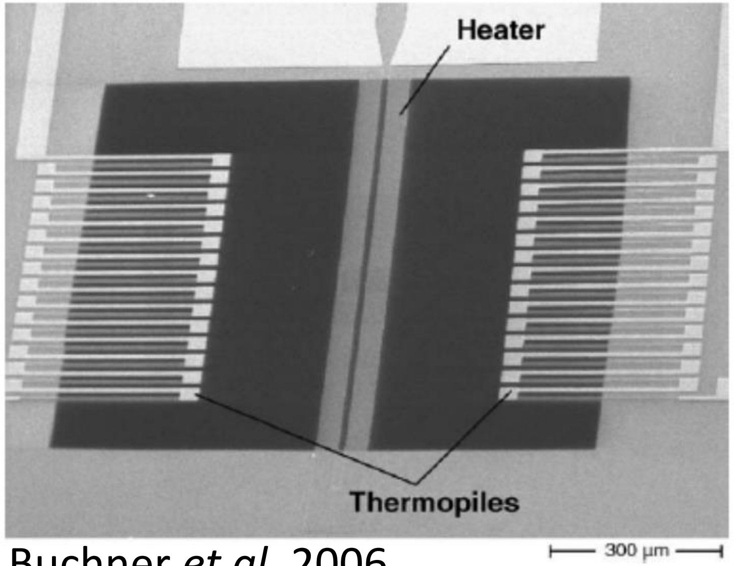



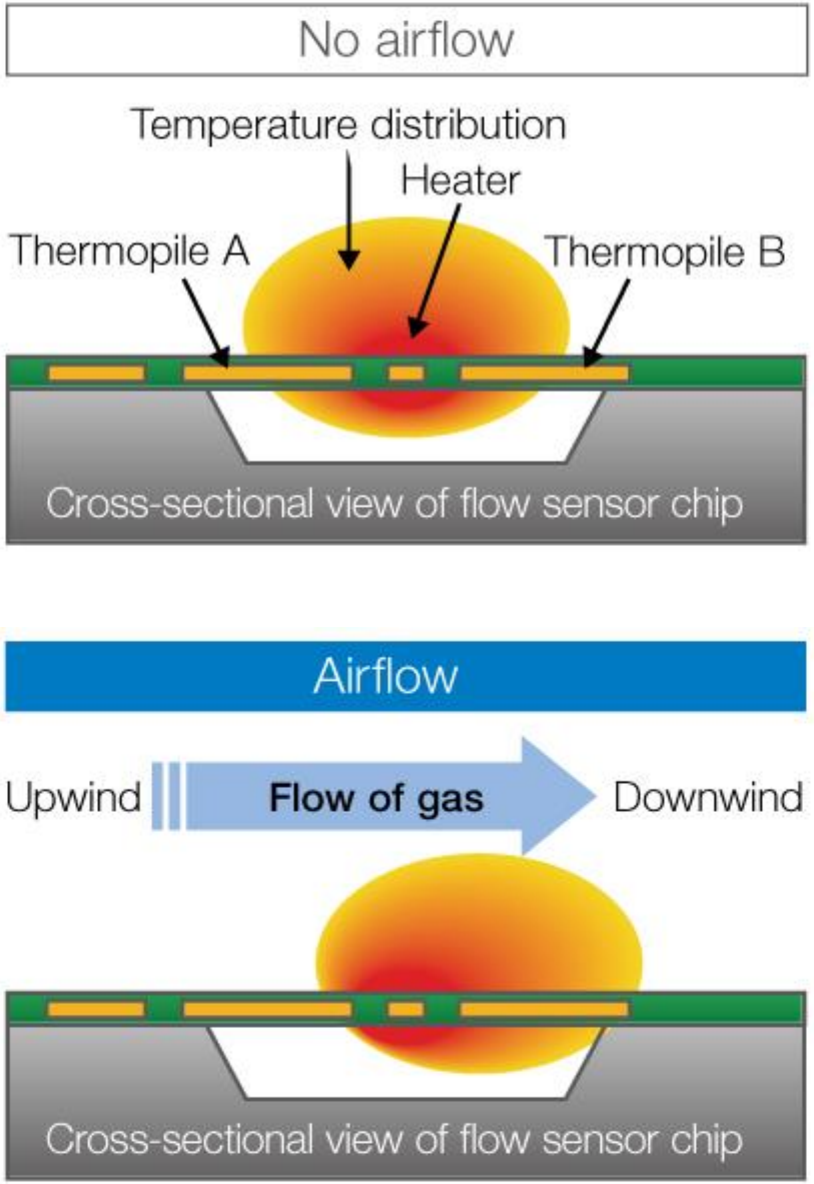
Fig. 6 - White Channel Sensitivity Spectrum

# Air velocity sensing

- Most common approach
  - Measure change in convective heat transfer
- Heater + 2 temp sensors
  - Use MEMS fabrication to thermally isolate the heater
  - Lowers power consumption

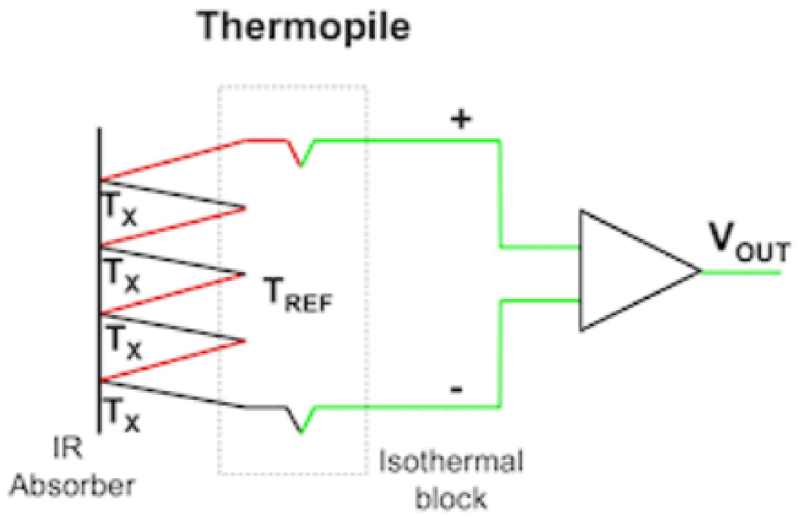



Buchner *et al.* 2006



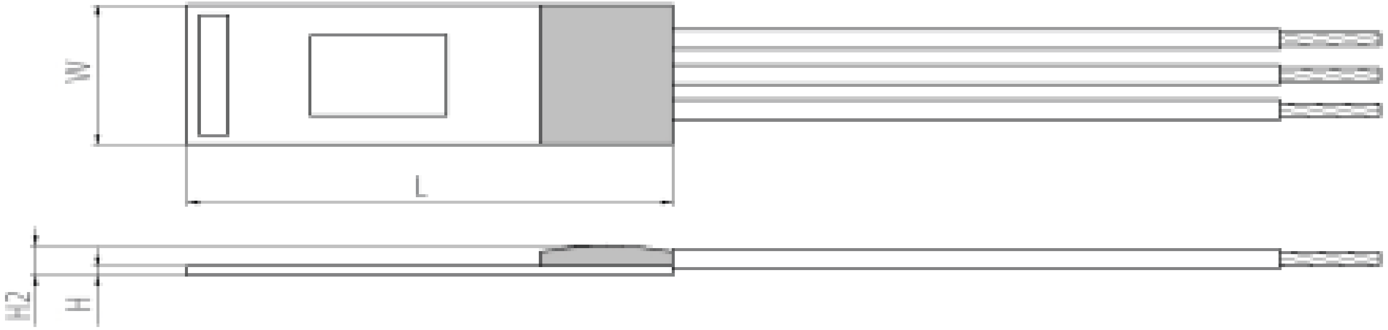
# Air velocity sensing

- Thermopile
  - Series of many thermocouples
  - Each one generates a small voltage
  - Overall get larger voltage
- Renesas FS3000
  - Thermopile flow sensor
  - 3.3V @ 10 mA
  - Only one direction of flow sensing
  - $14.47@100




# Air velocity sensing

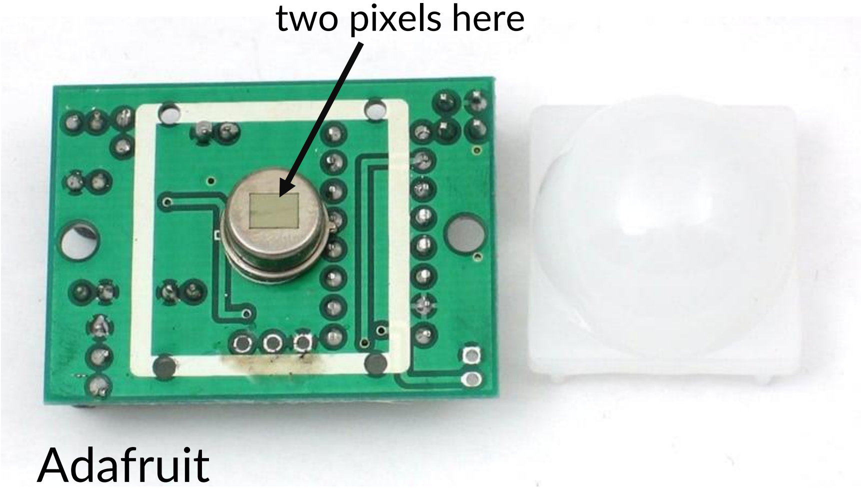
- Thermal mass sensor
  - Heat up a resistor
  - Convection cools it off
- FS7.0.1L.195
  - Heater + temp sensor
  - $9.95 @ 50
  - 200 mW max power
  - Need to calibrate R vs. wind speed
  - Should work in most any direction



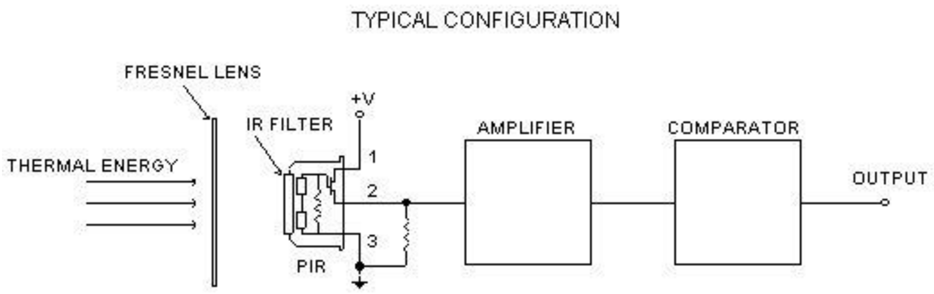

# Passive infrared (PIR) sensor

- The ones in office occupancy sensors, outdoor motion-activated lights, etc.
- Really, these are *motion* sensors
- Two pixels, each sensitive to ~9.4 um infrared radiation
    - Pyroelectric sensor: certain crystalline materials convert temperature changes into voltage changes
- Uses specialized IC to convert input voltage into output pulse (upon motion)
- Lens on top has array of Fresnel lens that bring adjacent incoming solid angles to alternating pixels → system can be sensitive to small motions

two pixels here



Adafruit




Glolab

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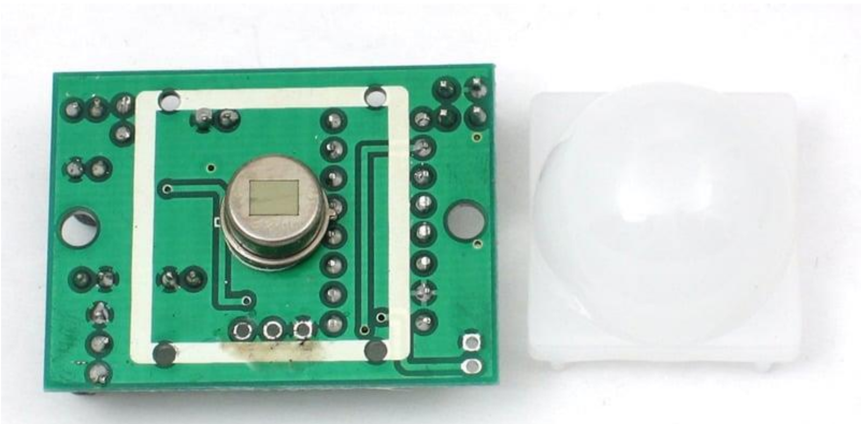
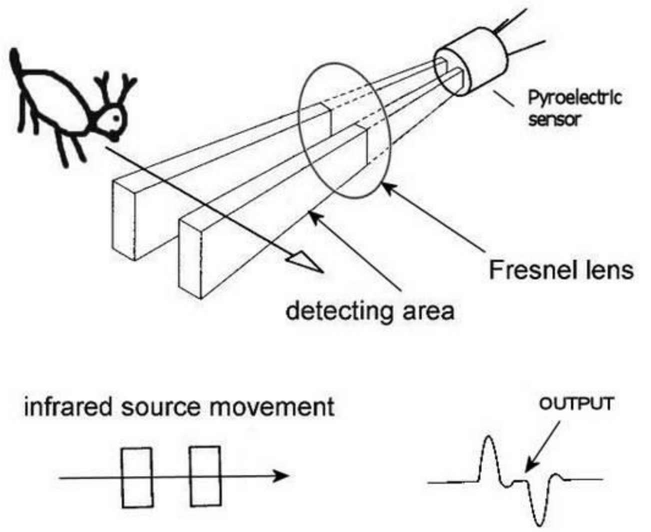


Adafruit




*Glolab*

# Passive infrared (PIR) sensor

- Cost: ~$3 @ 1
  - Presumably cheaper in bulk from China
- Size: 20-30 mm on a side
- Power/voltage: 3 mA active, ~100 μA idle @ 3-6V
- Connectivity: 1 pin into GPIO
- Privacy: excellent



*all these values need to be double-checked*

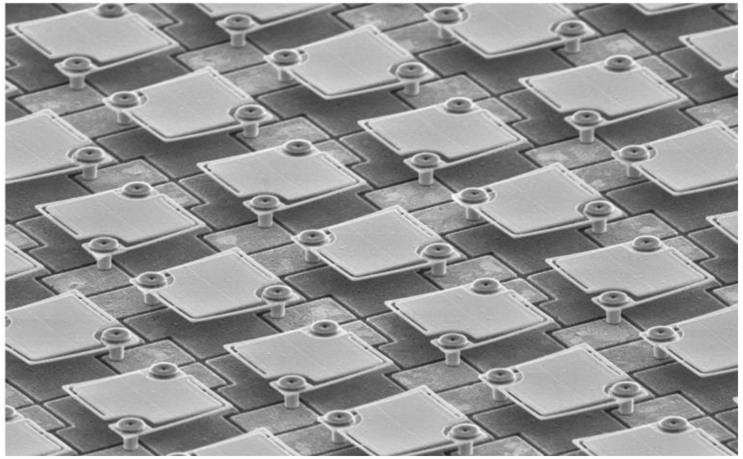
# Thermal camera

- Instead of two pixels, what if we had many pixels of thermal information
- Original used bolometers: microscale (~5-10 $\mu$m on a side) thermistors that are thermally isolated from the substrate to allow small amounts of thermal radiation to cause measurable changes in R
- System includes lens, readout electronics, etc.

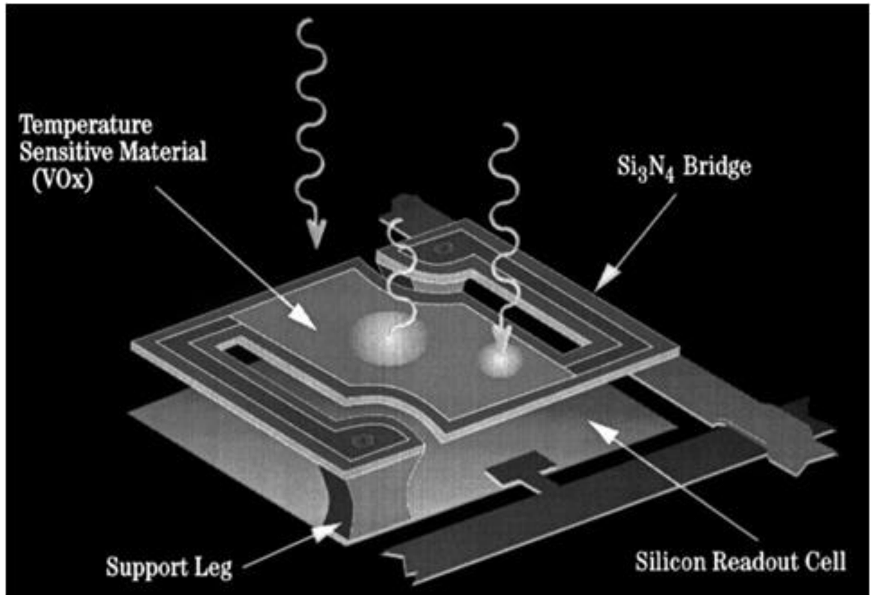
Teledyne FLiR

FLIR module

*Note that many thermal images you see are upscaled…this sensor module only has 80x60 pixels*



Array (not FLIR)

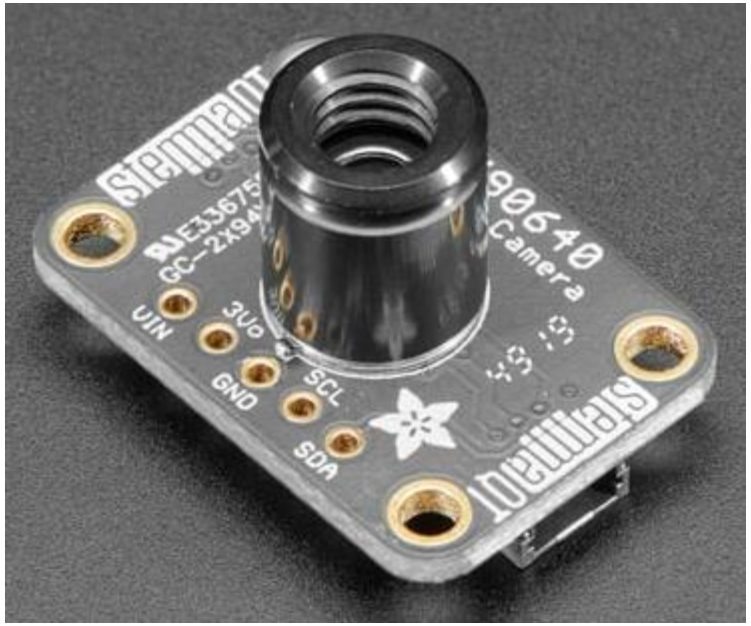



Unit cell (probably FLIR)

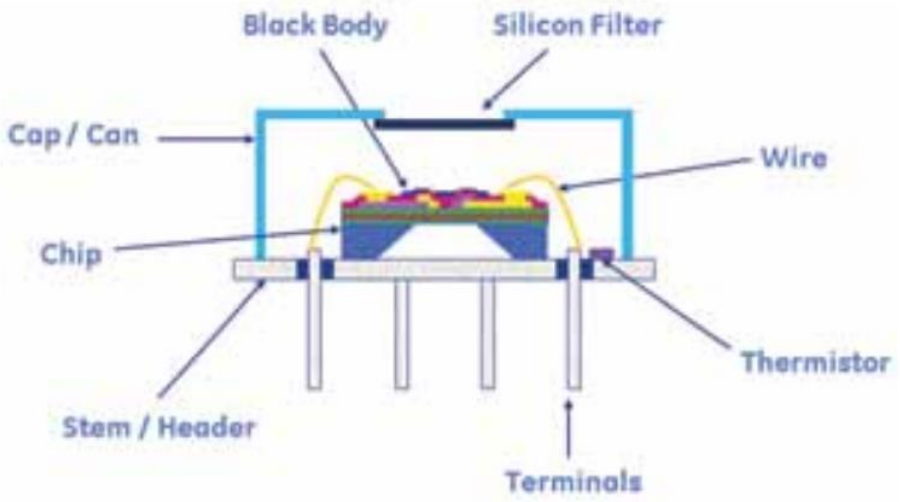
# Thermal camera

- Thermopile array
  - Lower cost than microbolometer arrays
  - Need thermal isolation (like bolometer) so that small incident radiation results in reasonable $\Delta T$ ➔ reasonable $\Delta V$

Melexis MLX90640



Adafruit, based on Melexis MLX90640



# Thermal camera

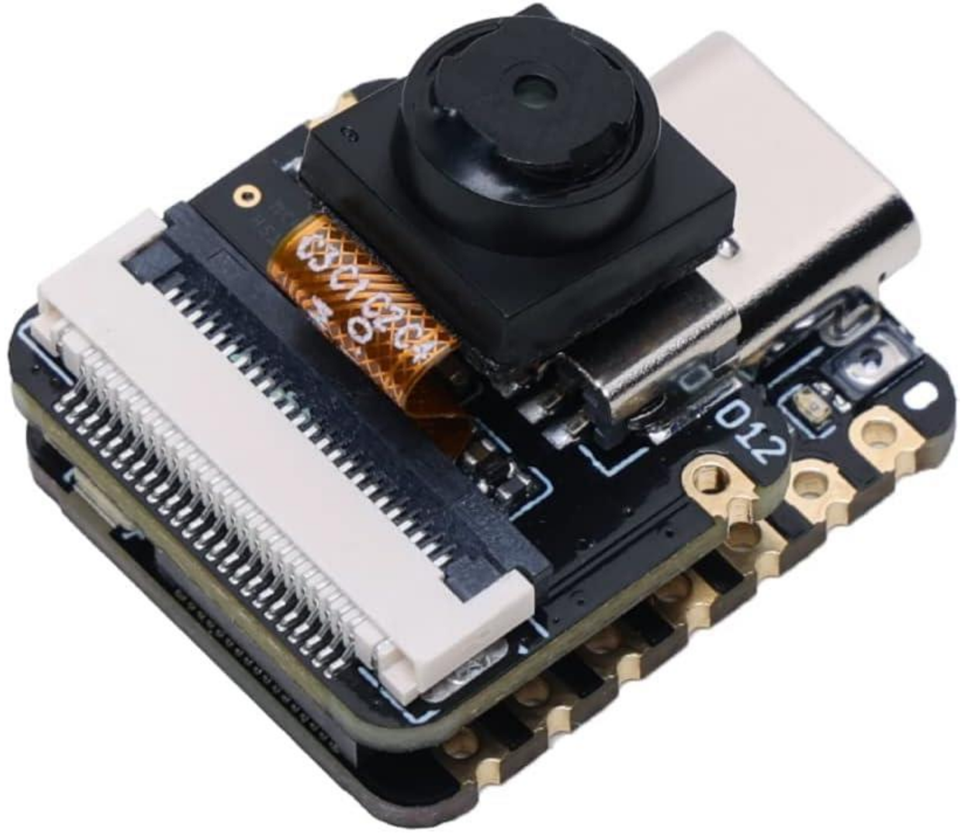
- Some comparisons

| | Thermopile | Bolometer |
|---|---|---|
| Cost | $51.28 @ 100 bare IC<br>$59.96 @ 100 Adafruit breakout | $121.58 @ 1 bare module |
| Pixels | 32 x 24 | 80 x 60 |
| Size | ~6 x 10 x 10 mm | ~10 x 10 x 10 mm |
| Power | 20 mA typical @ 3.3 V | 150 mW active, 5 mW standby<br>2.8-3.1V supply |
| Connection | I2C | I2C |
| Package | 32-pin package, fits into commercial socket | 4-pin thru-hole package |
| Privacy | Excellent | Excellent |

*all these values need to be double-checked*

# Visible-light camera

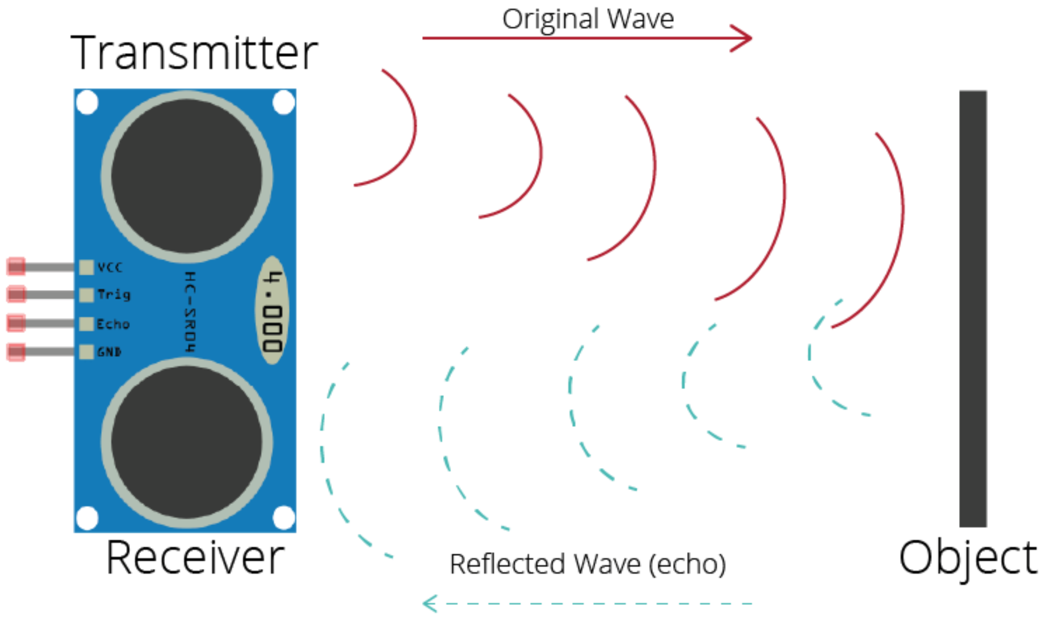
- Lots of options here
  - Easy to get 1MP+ AND ESP32S3 for $5-10
- Probably worth getting a module instead of a bare sensor
  - Avoids dealing with fine-pitch connector/cable
- Comms
  - SPI, etc.
- Power
  - ~30-100 mA depending on frame rate, etc.
  - 20 $\mu$A in standby
  - 3.3V [camera sensor uses lower voltage, so there's on-board LDO]
- Size
  - 36 x 23 x 18 mm
- Privacy
  - Problematic – need to do local processing




OV2640 sensor + ESP32-S3

# Ultrasonic sensors

- Sender + receiver of ultrasound
  - Sends US pulses, measures time to return
- 40 kHz US common
- Power
  - Widely varying numbers, but typically a few mA to 10s mA @ 3.3-5V
  - Simples have no sleep/idle, but can turn off
  - 1 pin input, 1 pin output
- Cost
  - ~$2-3/ea @ 1 up to
  - $50/ea @ 1
- Distance
  - <4 m to 10m





**Cheapo US sensors**

# Ultrasonic sensors

- Sender + receiver of ultrasound
  - Sends US pulses, measures time to return
- 40 kHz US common
- Power
  - Widely varying numbers, but typically a few mA to 10s mA @ 3.3-5V
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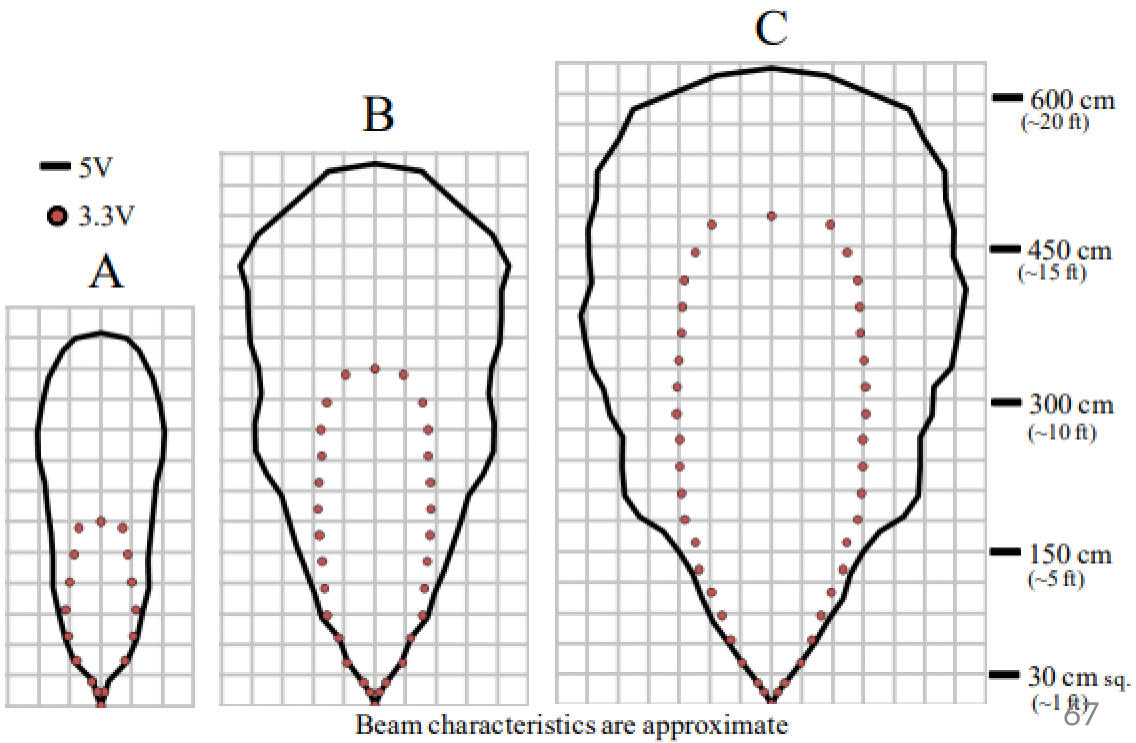
- Cost
  - ~$2-3/ea @ 1 up to
  - $50/ea @ 1
- Distance
  - <4 m to 10m

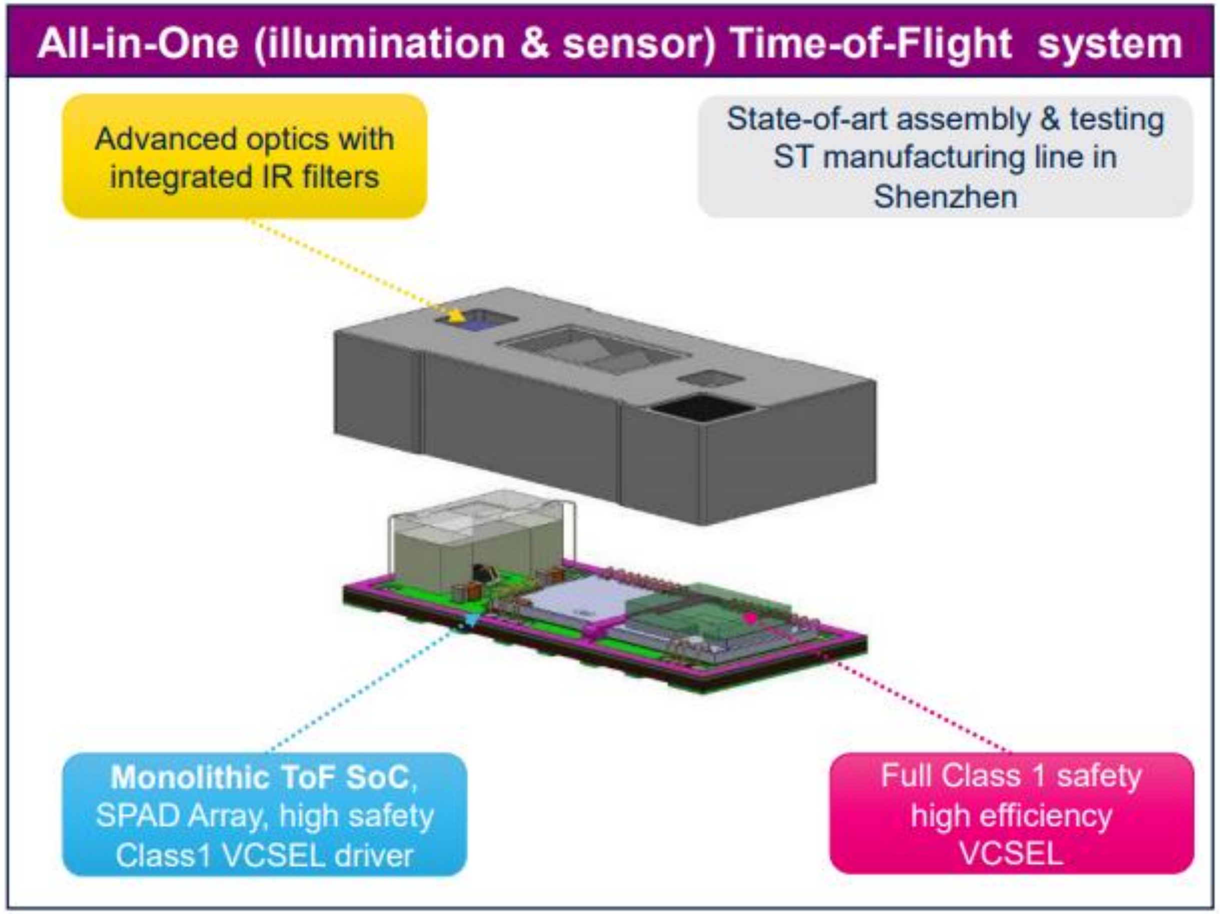
**$50 MB1260**

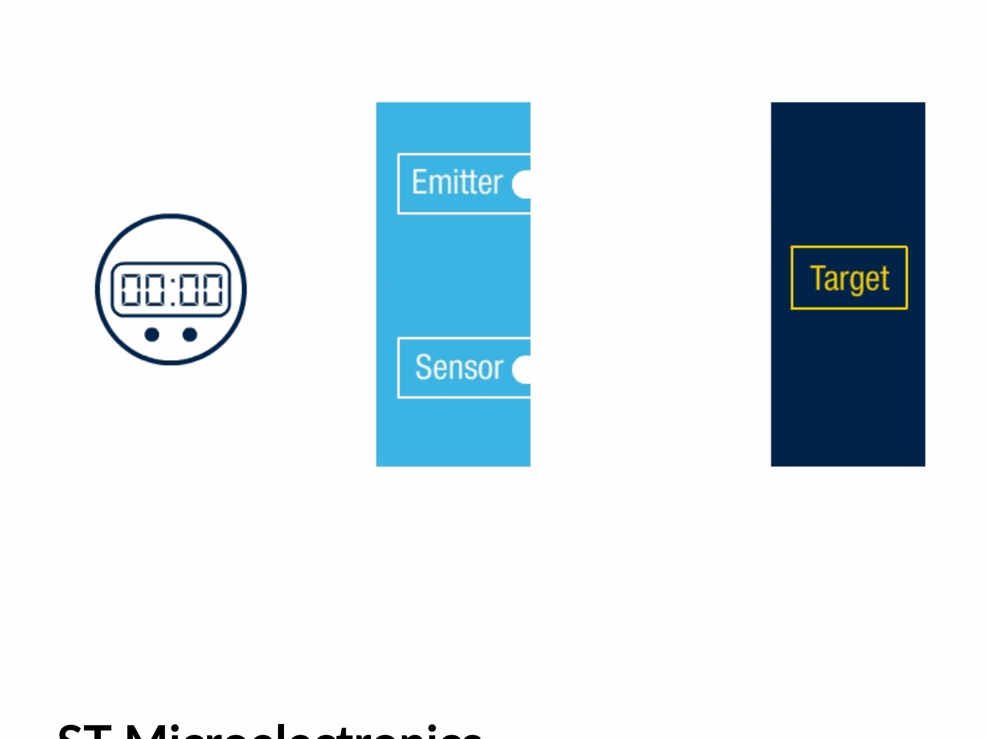


# ToF LIDAR sensors

- Optical version of US distance sensor
  - Measures time of flight of light
- Can get single-pixel versions, multi-pixel (multi-zone), ToF/LIDAR cameras


VL53L8CX
5th generation FlightSense™




ST Microelectronics

# ToF LIDAR sensors

- Optical version of US distance sensor
  - Measures time of flight of light
- VL53L8CX
  - 8x8 SPAD array
  - 940 nm IR VCSEL laser
  - 65 degree FOV
  - 3.3V
  - 215 mW power during continuous ranging
  - I2C, SPI
  - $5.62@100
  - Works great indoors, issues outside

VL53L8CX
5th generation FlightSense™

Table 21. **Maximum ranging capabilities when ranging continuously at 30 Hz**

| Target reflectance level. Full FoV (reflectance %) | Zone | Dark | Ambient light (5 kLux) |
|---|---|---|---|
| White target (88%) | Inner | Typical 4000 mm<br>Minimum 4000 mm | Typical 2850 mm<br>Minimum 2850 mm |
| | Corner | Typical 4000 mm<br>Minimum 4000 mm | Typical 2850 mm<br>Minimum 2700 mm |
| Light gray target (54%) | Inner | Typical 4000 mm<br>Minimum 4000 mm | Typical 2600 mm<br>Minimum 2550 mm |
| | Corner | Typical 4000 mm<br>Minimum 4000 mm | Typical 2500 mm<br>Minimum 2400 mm |
| Gray target (17%) | Inner | Typical 4000 mm<br>Minimum 4000 mm | Typical 1650 mm<br>Minimum 1600 mm |
| | Corner | Typical 3950 mm<br>Minimum 3900 mm | Typical 1550 mm<br>Minimum 1500 mm |

# RF/mmWave

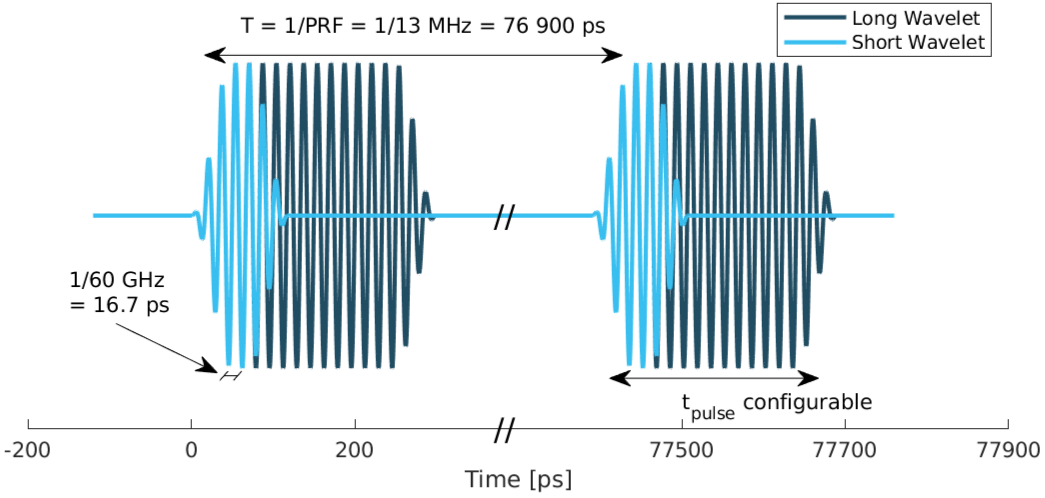
- mmWave/RF version of US distance sensor
- Use antenna arrays to send out narrow beams of RF energy and record time of flight back
- Cost
  - $10-40 @ 100
- XM125
  - A module containing the A121 radar sensor
    - Includes MCU, stuff to make life easier
- A121
  - 60 GHz pulsed coherent radar
  - Human presence detection range: 7 m


TI IWR6843


Acconeer XM125/A121

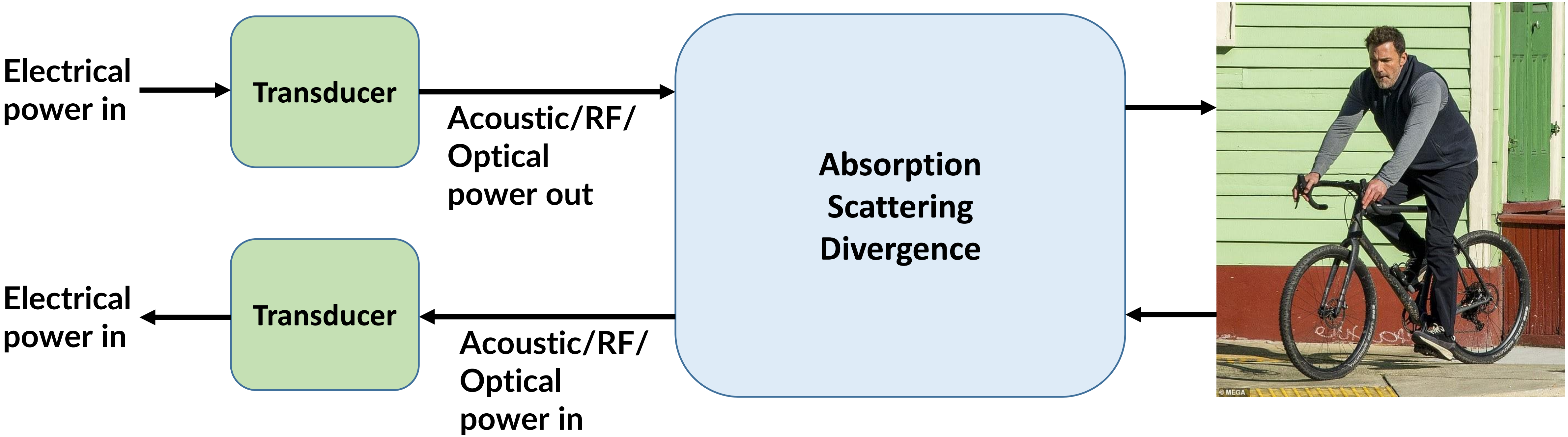
# RF/mmWave

- A121
  - 60 GHz pulsed coherent radar
  - 1.8 V and 3.3 V (if you want to talk to 3V3 MCU)
  - ~mA to ~10s mA depending on measurement mode
  - Includes antenna
- Pulsed coherent radar
  - Send pulses and use ToF for ranging
  - But use very good oscillator and transmitter so that the phase of the signals is controlled (*aka* ***coherent)***
  - Allows
    - Better SNR as you integrate returned pulses
    - Phase allows detection of very small movements



# US, RF, LIDAR

- They are all doing basically the same thing




- Differences will arise due to differences in
  - Transduction efficiency
  - Absorption/scattering & beam divergence
  - Reflection/absorption cross section of target