



Lecture 12

March 31, 2026

# TODAY

- Sensors, general and specific
- UPCOMING
  - No more labs
  - No more psets **except** for various surveys
  - No more lectures **except** presentations on Thu Apr 23 and Tue May 12

*Our focus is the project*

# Ordering digikey parts

Product Index > Integrated Circuits (ICs) > Power Management (PMIC) > Battery Chargers >

Dark Mode

Texas Instruments BQ25185DLHR



Image shown is a representation only. Exact specifications should be obtained from the product data sheet.

## BQ25185DLHR

**DigiKey Part Number**  
296-BQ25185DLHRTR-ND - Tape & Reel (TR)  
296-BQ25185DLHRCT-ND - Cut Tape (CT) ← **Vendor part number**  
296-BQ25185DLHRDKR-ND - Digi-Reel®

**Manufacturer** [Texas Instruments](#)

**Manufacturer Product Number** BQ25185DLHR ← **Mfg part number**

**Description** 1-CELL, 1-A STAND-ALONE LINEAR B

**Manufacturer Standard Lead Time** 12 Weeks

**Customer Reference**

**Detailed Description** Charger IC Multi-Chemistry 10-WSON (2.2x2)

**In-Stock: 2,861**

[Check for Additional Incoming Stock](#)

QUANTITY

**Add to Cart**

All prices are in USD

**Cut Tape (CT) & Digi-Reel®**

QUANTITY	UNIT PRICE	EXT PRICE
-	\$2.03000	\$2.03
	\$1.50000 ←	\$15.00
25	\$1.36640	\$34.16
100	\$1.22010	\$122.01
250	\$1.15032	\$287.58
500	\$1.10822	\$554.11
1,000	\$1.07357	\$1,073.57

\* All Digi-Reel orders will add a \$7.00 reeling fee.

**All\* sensors are electrical**

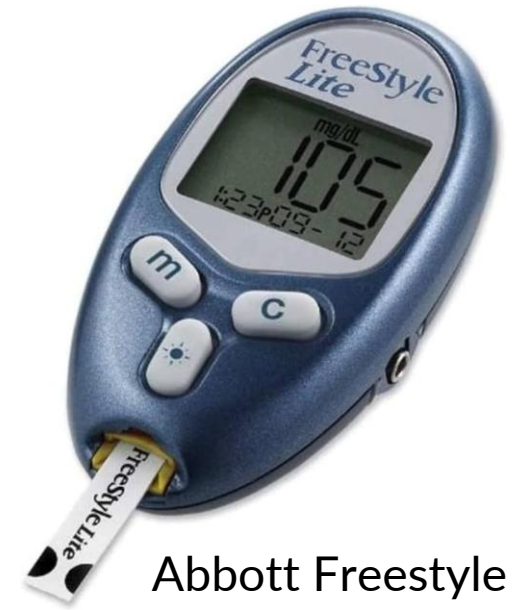
# Why sensors

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



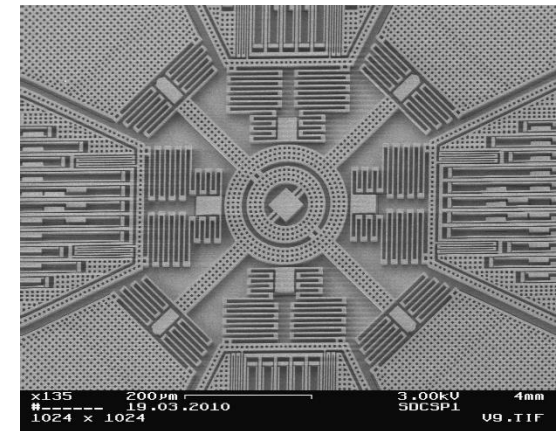
Abbott Freestyle



Ultrasonic distance sensor

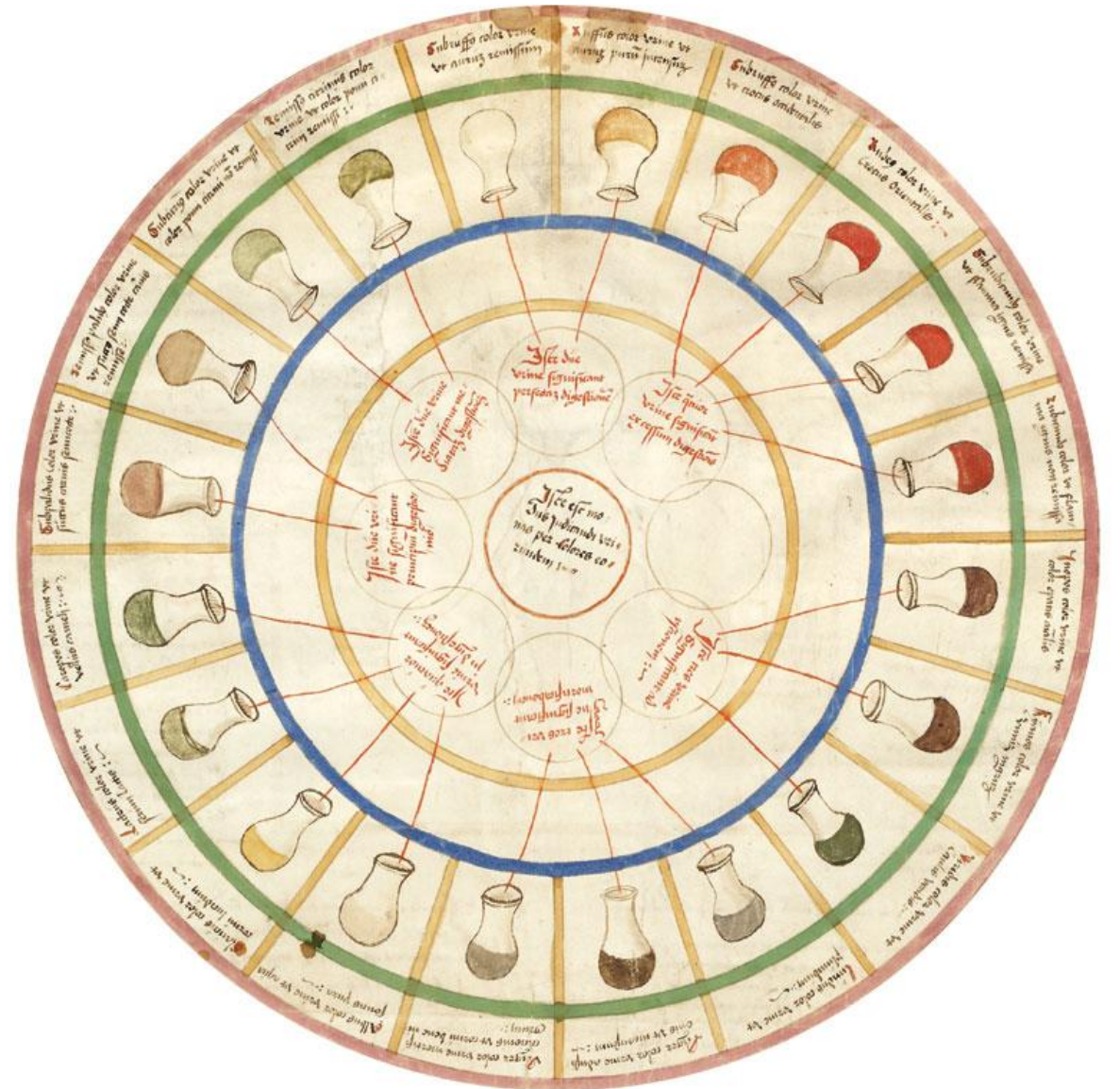


Plantower PMS particulate sensor



Invensense MPU6050

# Example: glucose sensing



**Rufus ut aurum purum intensum**

*(Ruddy as pure intense gold)*

**Subrubicundus color ut crocus occidentalis**

*(Slightly red as occidental saffron)*

**Rubeus ut crocus orientalis**

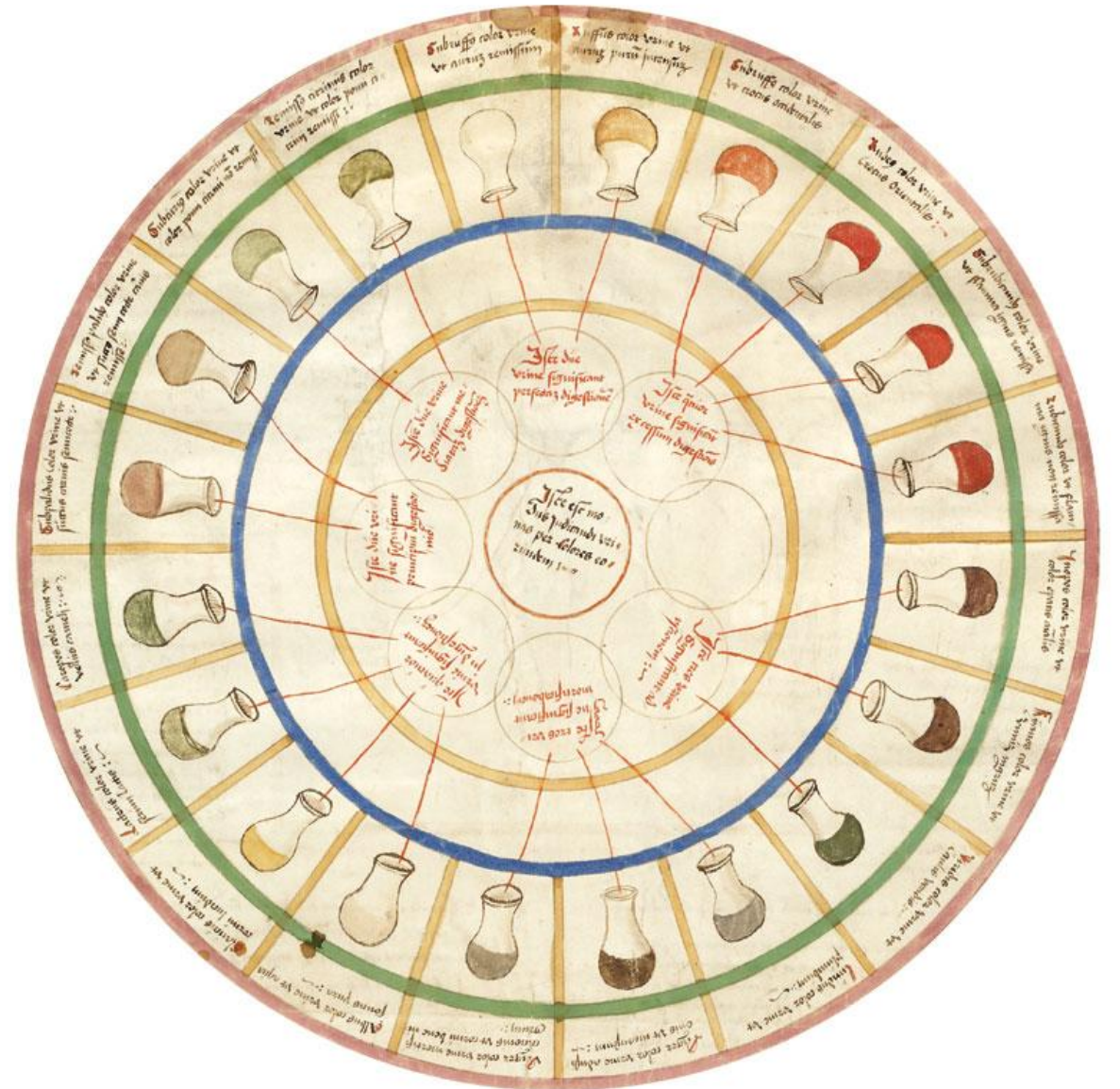
*(Red as oriental saffron)*

**Subrubicundus ut flamma ignis remissa**

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



# Example: glucose sensing



**Rufus ut aurum purum intensum**

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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

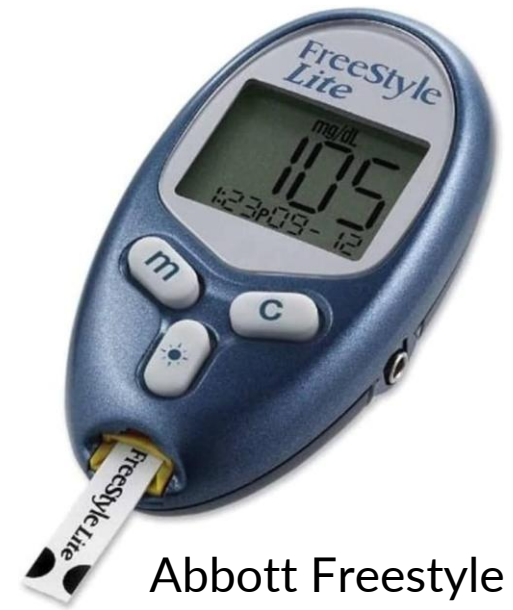
- **First protein ever synthesized (1963)**

- **One of the first proteins whose 3D structure was determined (1971)**

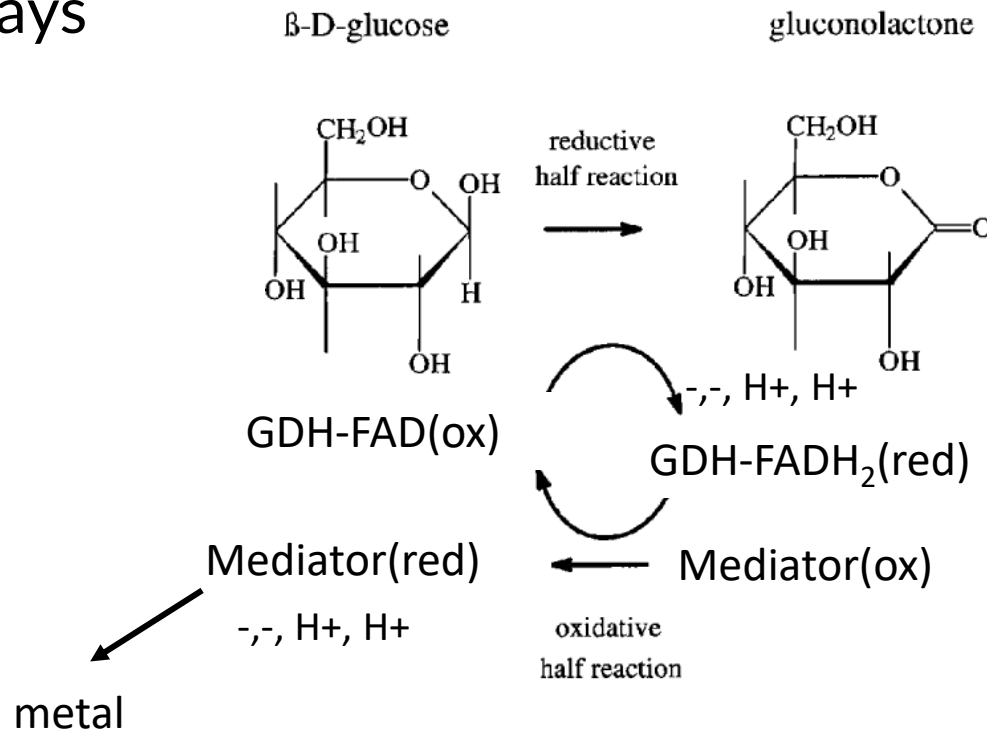
- **First protein synthesized by recombinant DNA technology (1979)**

# 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



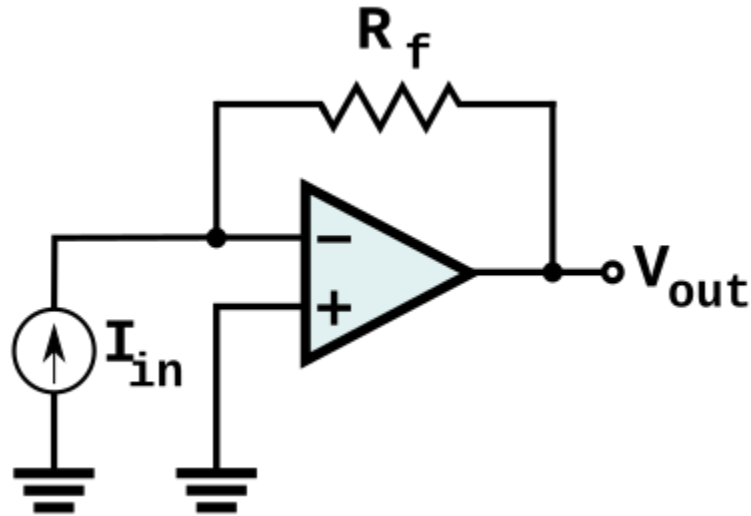
# Example: glucose sensing

- Glucose test strips have the chemistry to do the reaction
- For continuous glucose monitors (CGM), 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: glucose sensing

## LMP91000 Sensor AFE System: Configurable AFE Potentiostat for Low-Power Chemical-Sensing Applications

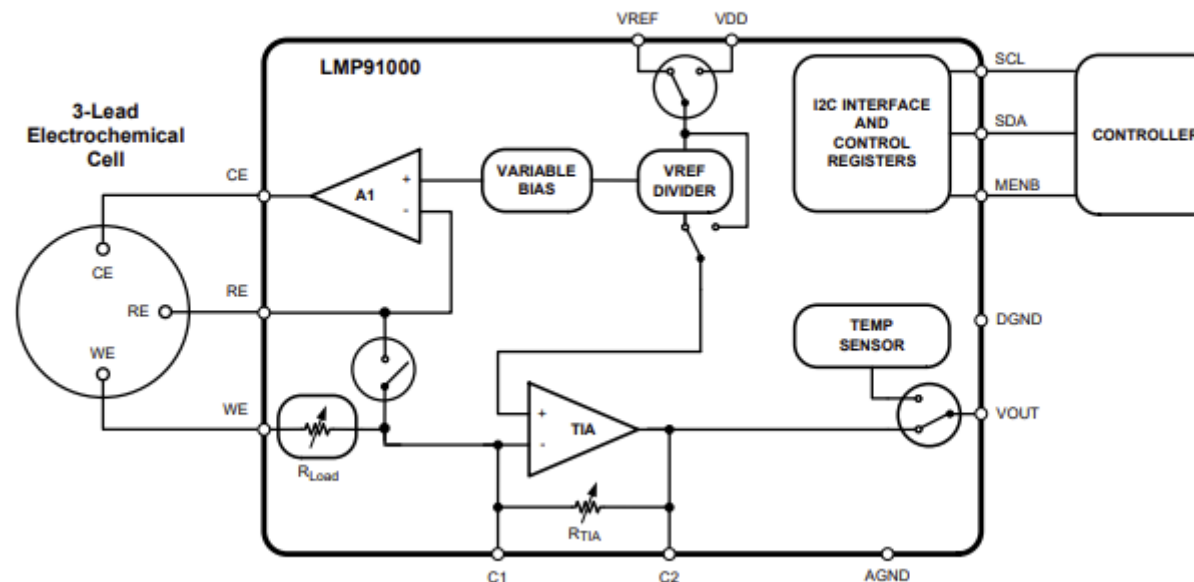
### 1 Features

- Typical Values,  $T_A = 25^\circ\text{C}$
- Supply Voltage 2.7 V to 5.25 V
- Supply Current (Average Over Time)  $<10\ \mu\text{A}$
- Cell Conditioning Current Up to 10 mA

### 3 Description

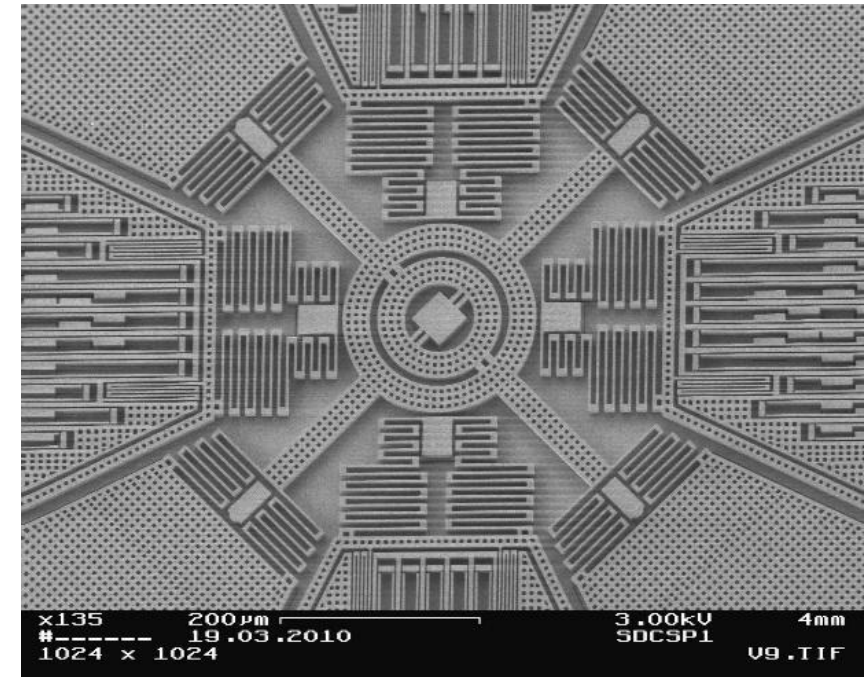
The LMP91000 is a programmable analog front-end (AFE) for use in micro-power electrochemical sensing applications. It provides a complete signal path solution between a sensor and a microcontroller that generates an output voltage proportional to the cell

### Simplified Application Schematic



# Example: inertial sensing

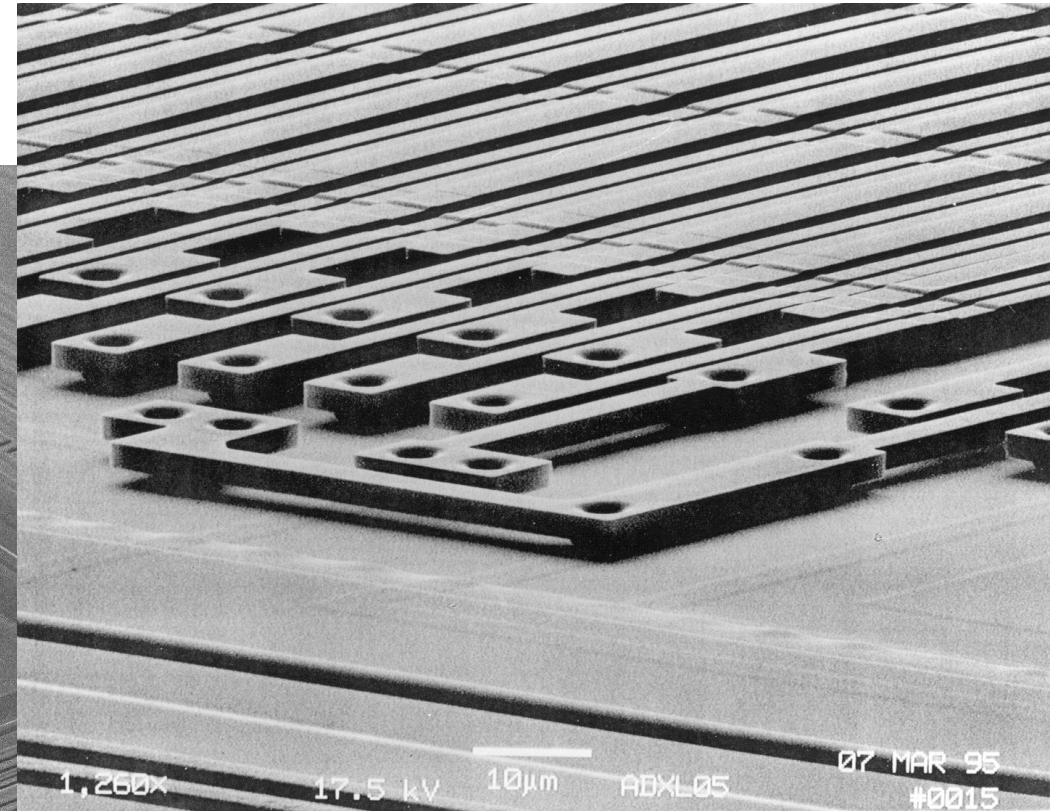
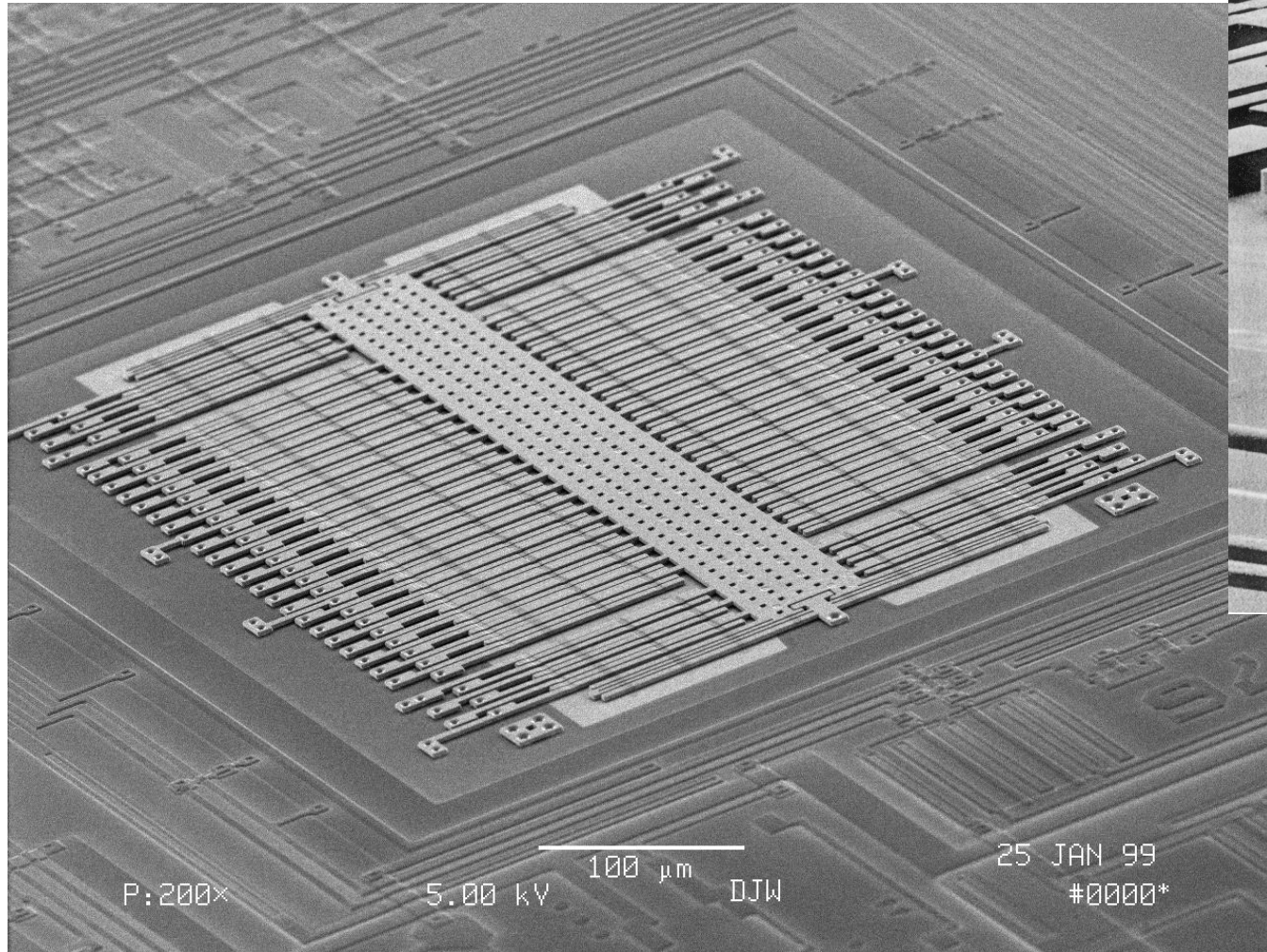
- Genesis: In 1980s, an ADI engineer heard about forming mechanical sensors in silicon
- Market pull was airbag accelerometers (50 g)
  - Current product was \$50
  - Auto manufacturers wanted \$5 price point
- Team was formed in 1986, first product in 1993
  - Fabrication process was under development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



Invensense MPU6050

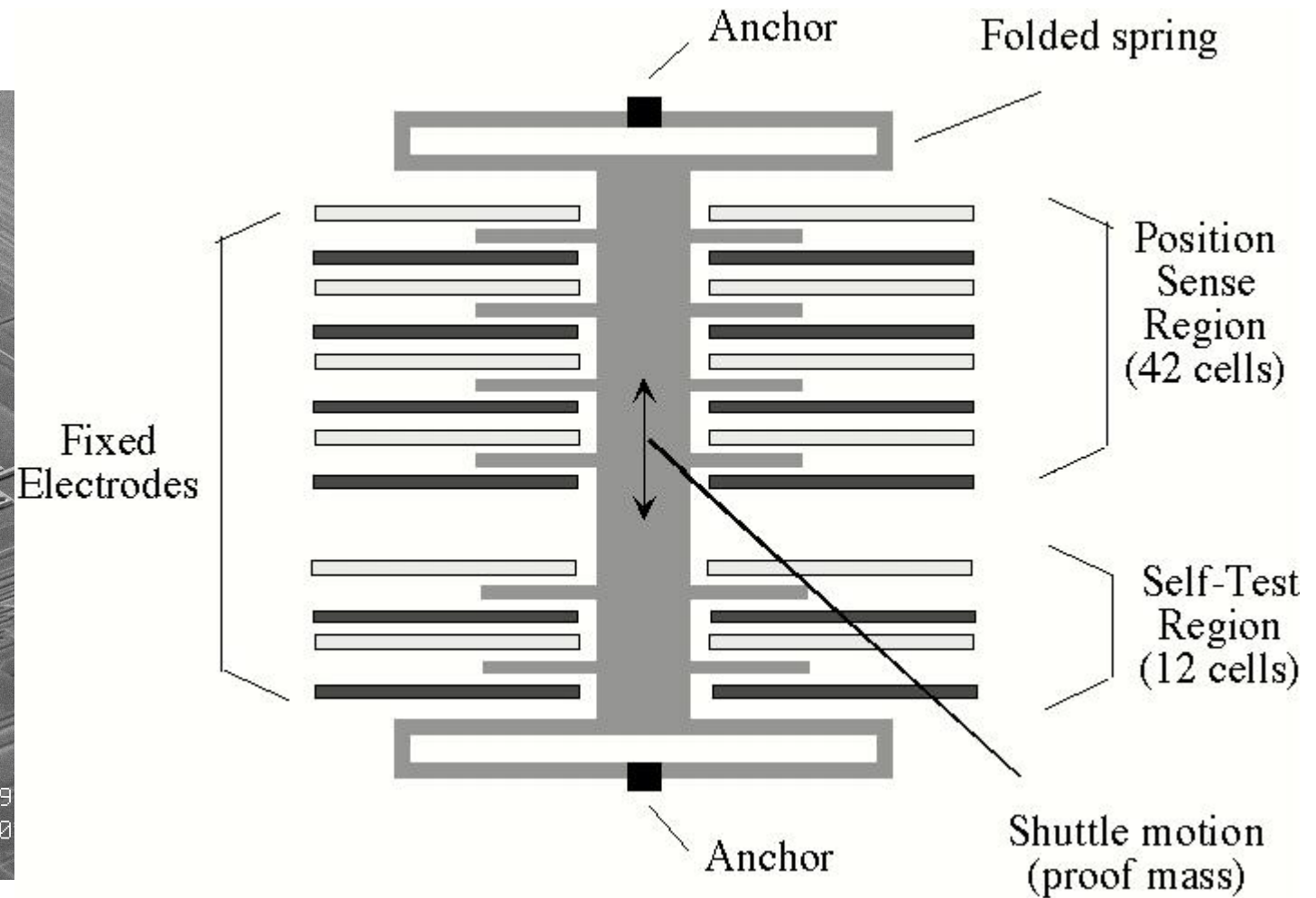
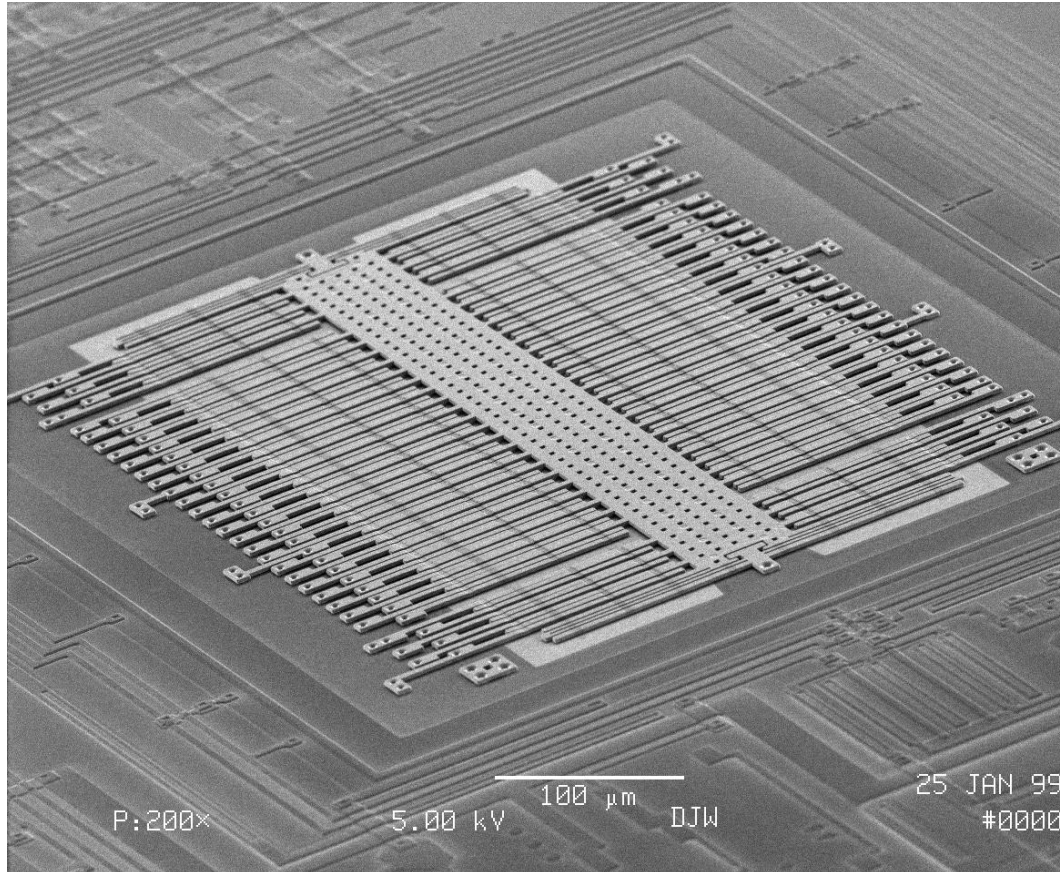
# Example: inertial sensing

- Original ADXL50



# Example: inertial sensing

- Original ADXL50



Acceleration → motion of proof mass → change in gap

# Example: inertial sensing

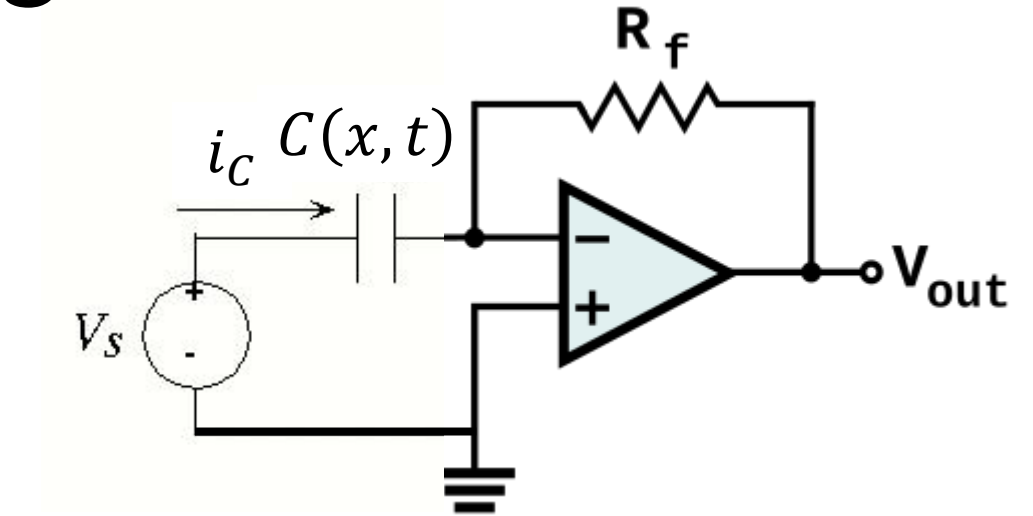
- Original ADXL50

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  $V_s$   $i_C = \frac{dQ}{dt} = C(x, t) \frac{dV_s}{dt} + V_s \left. \frac{\partial C}{\partial x} \right|_{V_s} \frac{dx}{dt}$

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



Acceleration  $\rightarrow$  motion of proof mass  
 $\rightarrow$  change in gap  $\rightarrow$  change in C  $\rightarrow$   
 change in current  $\rightarrow$  change in voltage

Just a constant

**Circuits can model the world**

# 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



# 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

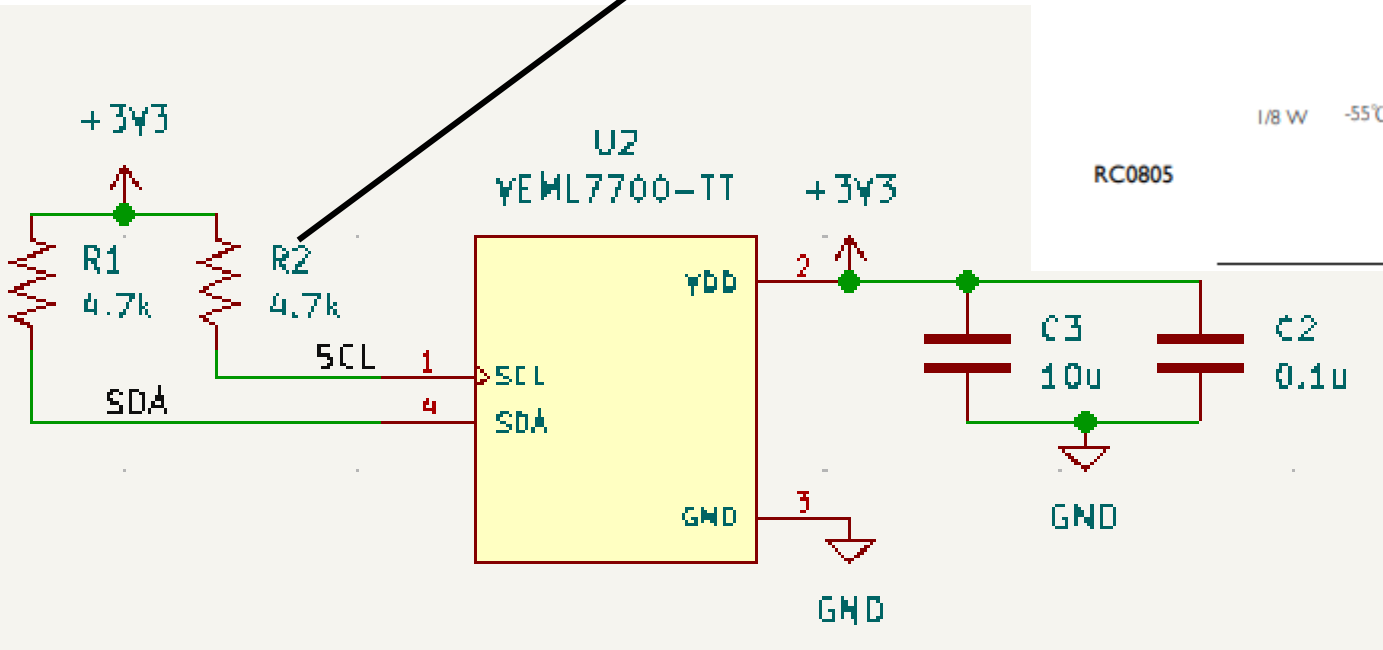
# Temperature sensing

## Temperature-varying resistors

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

Datasheet

$$R = R(T)$$



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

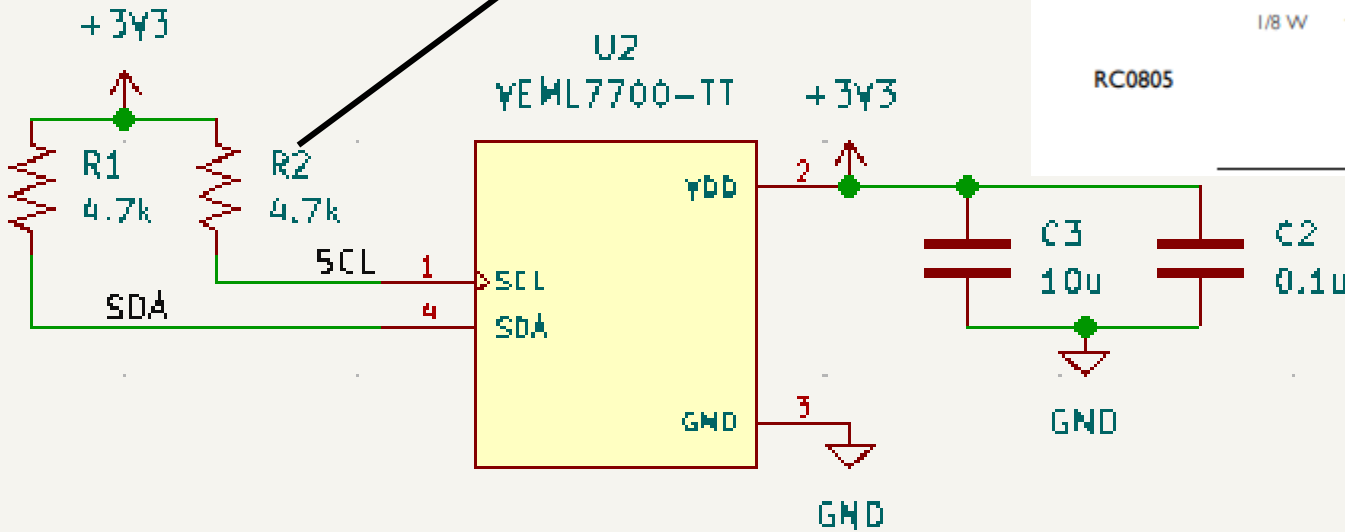
VEML7700 sensor board

# Temperature sensing

## Temperature-varying resistors

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

$$R = R(T)$$



VEML7700 sensor board

CHARACTERISTICS	POWER	OPERATING TEMPERATURE RANGE	MAXIMUM WORKING VOLTAGE	MAXIMUM OVERLOAD VOLTAGE	DISSIPATION WITHSTANDING	TEMPERATURE COEFFICIENT	TEMPERATURE COEFFICIENT	JUMPER CRITERIA
	1/8 W	-55°C to 155°C	150V	300V		$1\Omega \leq R \leq 10\Omega$ $\pm 200\text{ppm}^\circ\text{C}$	$1\Omega \leq R \leq 10\Omega$ $\pm 200\text{ppm}^\circ\text{C}$	Rated Current 2.0A
						$10\Omega < R \leq 10\text{M}\Omega$ $\pm 100\text{ppm}^\circ\text{C}$	$10\Omega < R \leq 10\text{M}\Omega$ $\pm 100\text{ppm}^\circ\text{C}$	Maximum Current 5.0A
						$10\text{M}\Omega < R \leq 22\text{M}\Omega$ $\pm 200\text{ppm}^\circ\text{C}$	$10\text{M}\Omega < R \leq 22\text{M}\Omega$ $\pm 200\text{ppm}^\circ\text{C}$	
						$24\text{M}\Omega < R \leq 100\text{M}\Omega$ $\pm 300\text{ppm}^\circ\text{C}$	$24\text{M}\Omega < R \leq 100\text{M}\Omega$ $\pm 300\text{ppm}^\circ\text{C}$	

# Temperature sensing

## Temperature-varying resistors

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

$$R = R(T)$$

Temperature  
Coefficient of  
Resistance (TCR)

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

$T_1$  is typically 25 °C

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

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

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

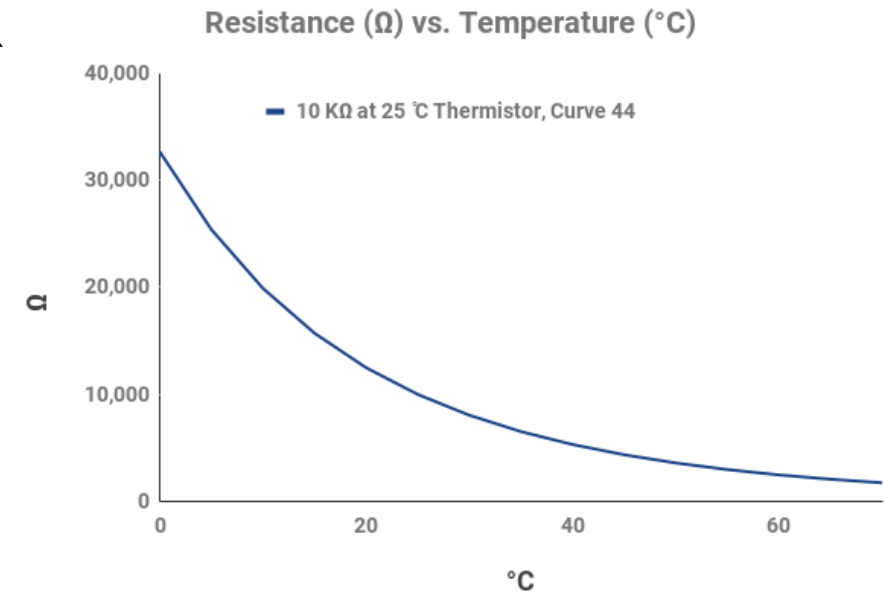
$$R(T_2) = 4.7k(1.0075) = 4.73k$$

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  $R \rightarrow T$  requires some math
  - 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  $V = IR(T)$

- 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
  - $TCR = 3850 \text{ ppm}/^{\circ}\text{C}$
- Much more linear than thermistor
- Measurement circuits similar to NTC

## P1K0.0805.1FC.B

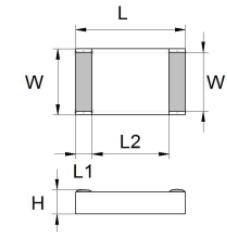
### FlipChip platinum sensor

For the automatic assembling on PCB by soldering or bonding

#### Benefits & Characteristics

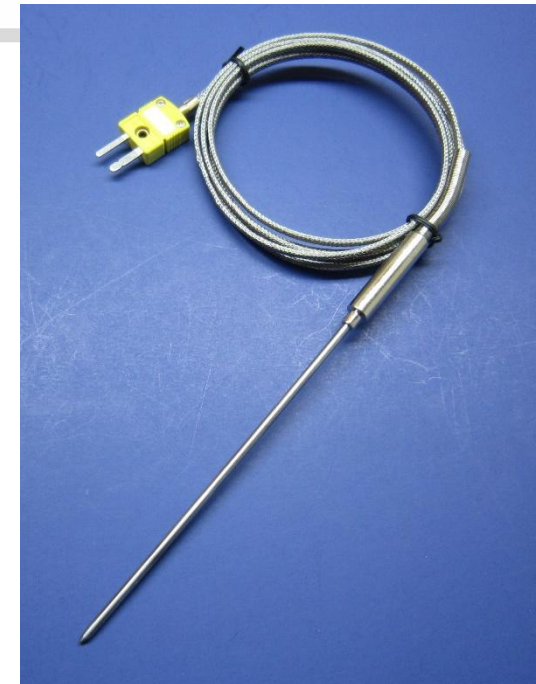
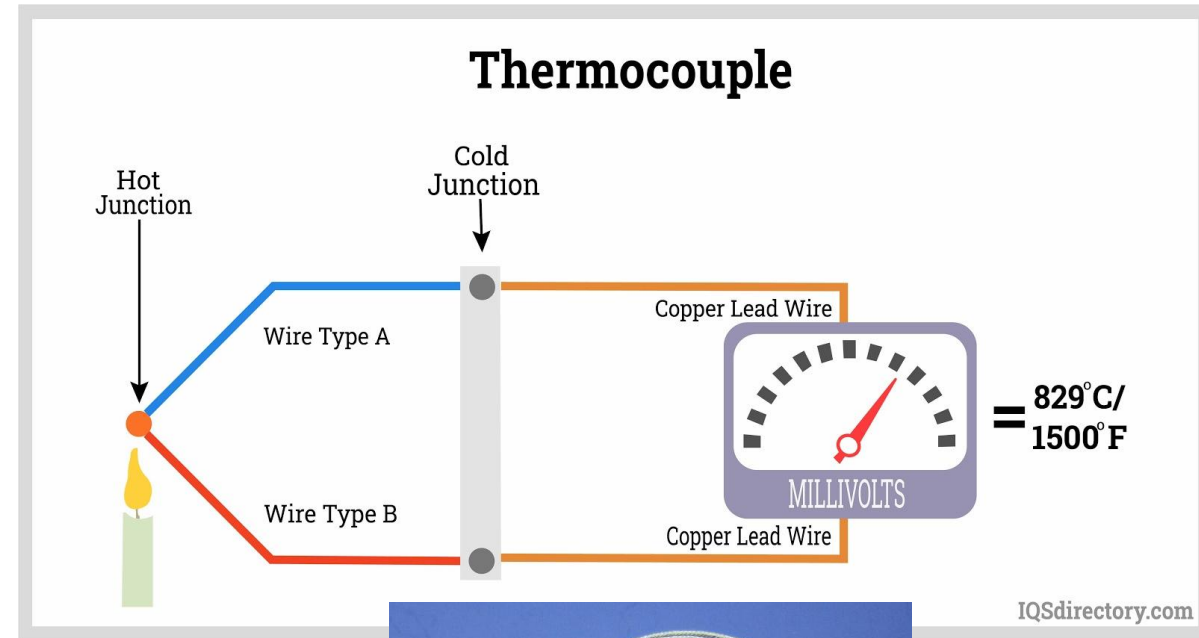
- Excellent long-term stability
- Low self-heating
- Fast response time
- Minimum space consumption on PCB
- Optimal price-performance ratio

#### Illustration<sup>1)</sup>



# 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 some in a bit...)

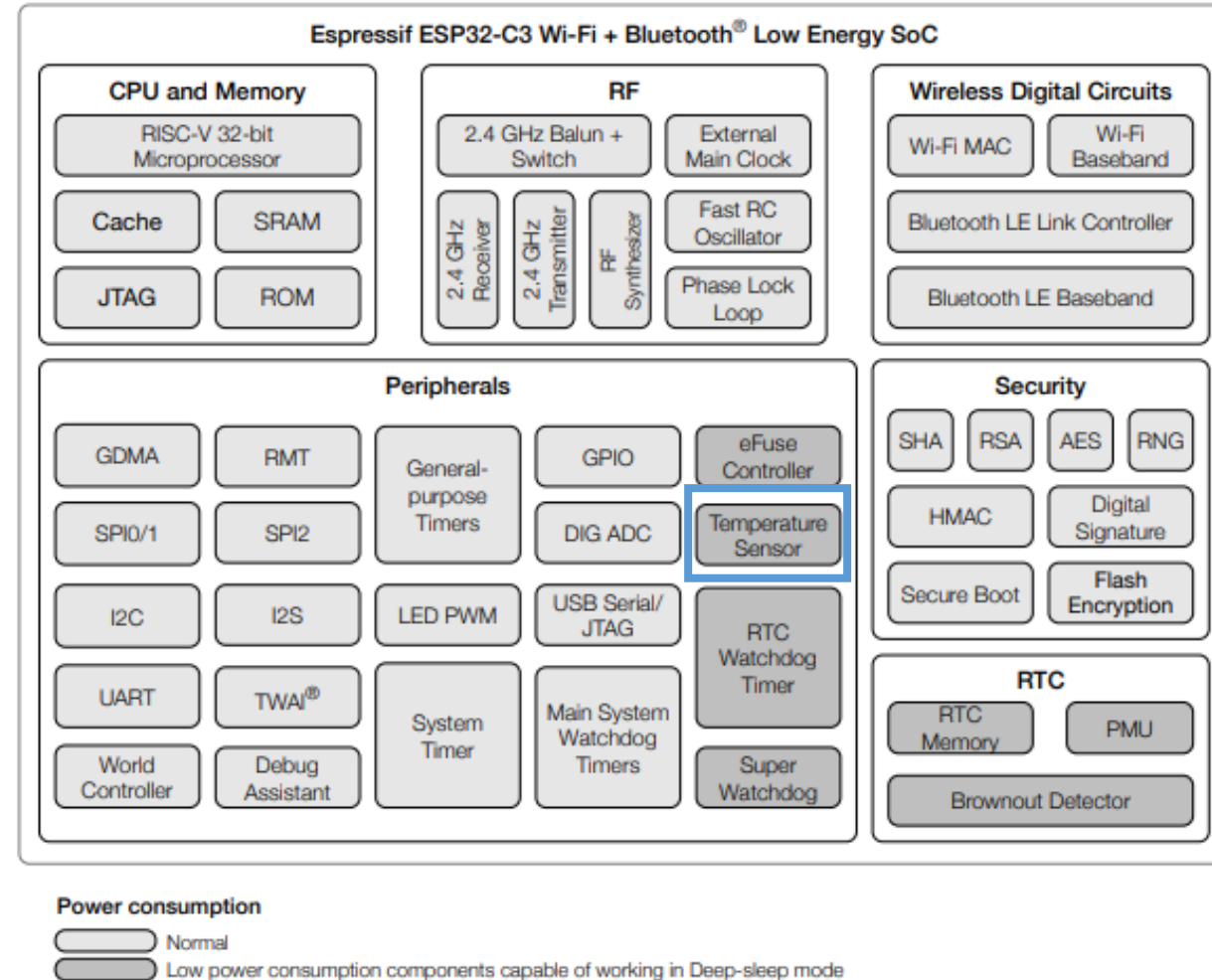


# Bandgap temperature sensors

- Use physics intrinsic to semiconductors

pn junction (diode) equation 
$$I_D = I_0 \left( e^{\frac{V_D}{qkT}} - 1 \right)$$

- If you already have diodes or transistors, can easily incorporate
- Good to about  $\sim 200^\circ\text{C}$
- 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**

Metric	Value
TEMP	28 °C
LOAD	1 %
CLOCK SPEED	3691 MHz
FAN SPEED	1248 RPM

**GPU: NVIDIA GeForce GTX 1080 Ti**

Metric	Value
TEMP	44 °C
LOAD	17 %
CLOCK SPEED	608 MHz
FAN SPEED	0 RPM

**RAM**

Metric	Value
LOAD	35 %
Usage	5.68GB

**STORAGE**

● USED ● FREE

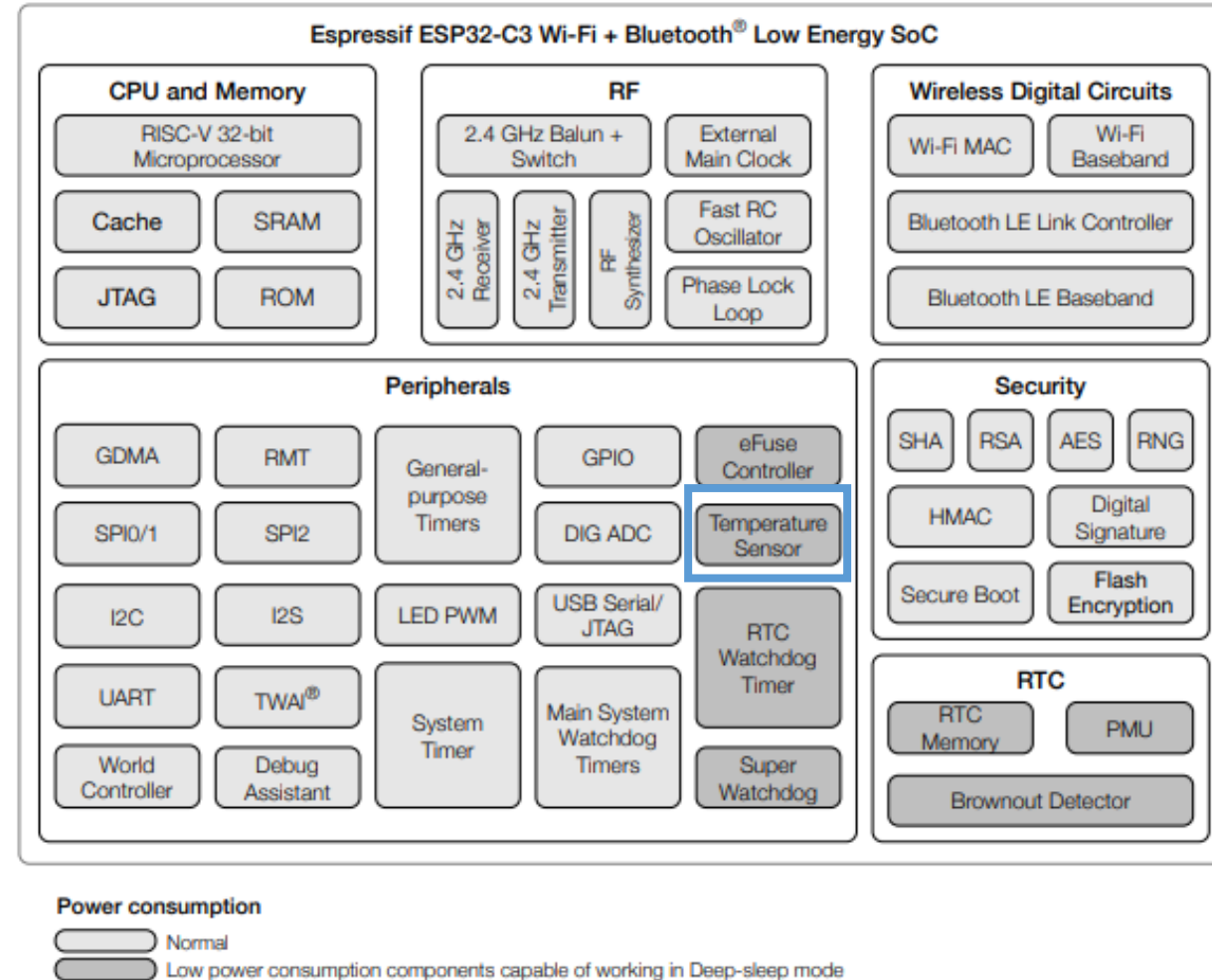
Drive	Capacity	Used	Free
C: Drive Samsung SSD 960 PRO 512GB	512GB	253GB	259GB

# Bandgap temperature sensors

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pn junction (diode) equation 
$$I_D = I_0 \left( e^{\frac{V_D}{qkT}} - 1 \right)$$

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ESP32-C3 Functional Block Diagram

# Temperature sensors

- Some comparisons, from →

## Temperature sensing fundamentals



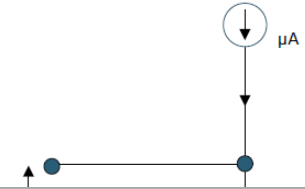
This means bandgap

	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

### 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**

logging further  
ement to not



# Sensor specifications

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

And ultimately choose a **specific** component

How do we pick? **Specs**

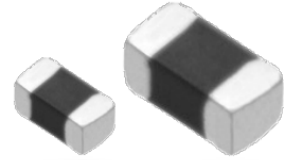
# Sensor specifications

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



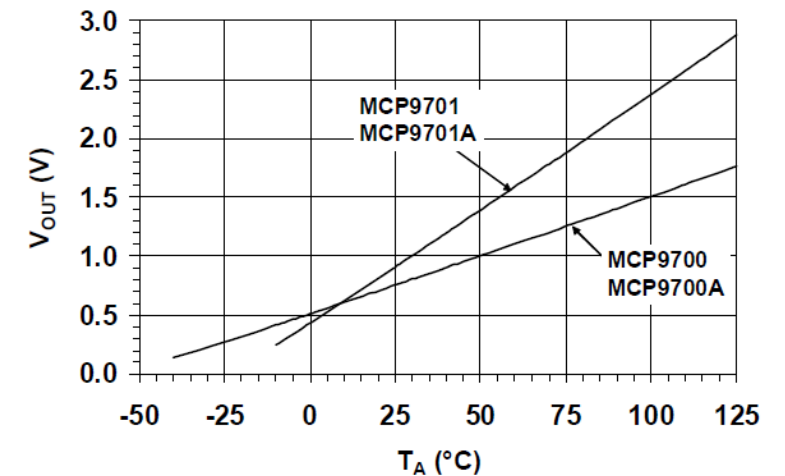
## Ratings

Size code (inch size)	Z(0201)	0(0402)	1(0603)
Operating temperature range	-40 to 125 °C		
Rated maximum power dissipation <sup>1</sup>	33 mW	66 mW	100 mW
Dissipation factor <sup>2</sup>	Approximately 1 mW / °C	Approximately 2 mW / °C	Approximately 3 mW / °C

  
**MICROCHIP**

# MCP970X

Low-Power Linear Active Thermistor ICs



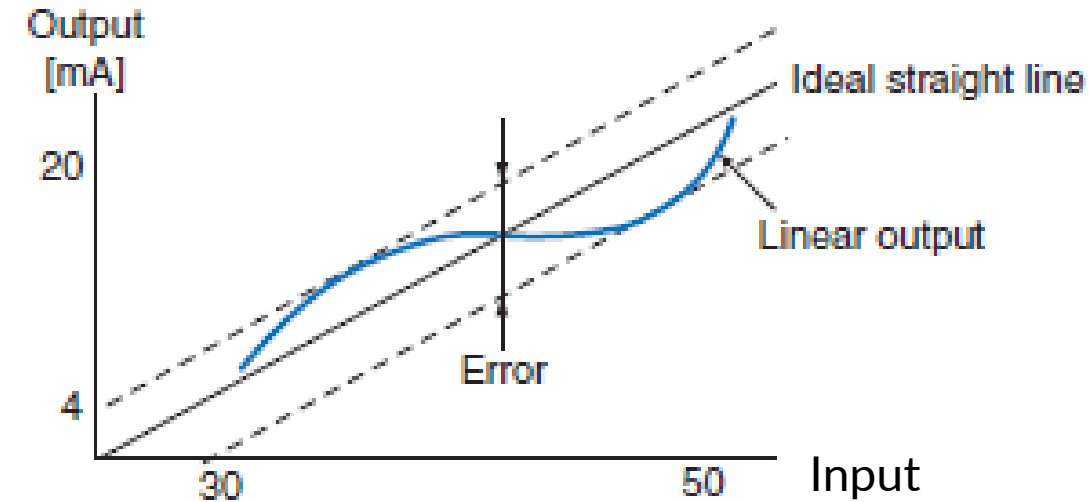
*Not a thermistor!*  
*This is actually a bandgap temp sensor IC*



# 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



# Sensor specifications

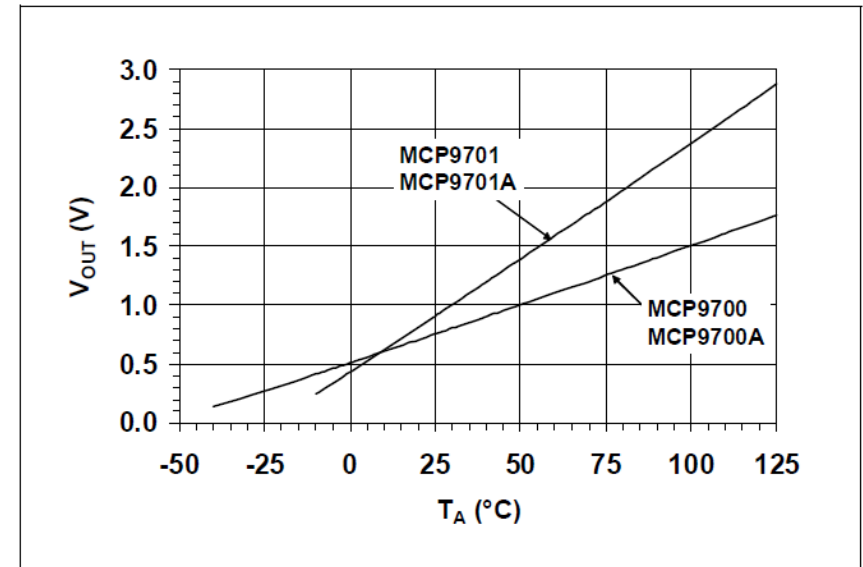
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**MCP970X**

Low-Power Linear Active Thermistor ICs



## DC ELECTRICAL CHARACTERISTICS (CONTINUED)

**Electrical Specifications:** Unless otherwise indicated:  
**MCP9700/9700A/9700B:** V<sub>DD</sub> = 2.3V to 5.5V, GND = Ground, T<sub>A</sub> = -40°C to +125°C and No load  
**MCP9701/9701A:** V<sub>DD</sub> = 3.1V to 5.5V, GND = Ground, T<sub>A</sub> = -10°C to +125°C and No load

Parameter	Sym.	Min.	Typ.	Max.	Unit	Conditions
Output Voltage, T <sub>A</sub> = 0°C	V <sub>0°C</sub>	—	400	—	mV	<b>MCP9701/9701A</b>
Temperature Coefficient	T <sub>C</sub>	—	10.0	—	mV/°C	<b>MCP9700/9700A/9700B</b>
	T <sub>C</sub>	—	19.5	—	mV/°C	<b>MCP9701/9701A</b>
Output Nonlinearity	V <sub>ONL</sub>	—	±0.5	—	°C	T <sub>A</sub> = 0°C to +70°C ( <b>Note 3</b> )
Output Current	I <sub>OUT</sub>	—	—	100	µA	
Output Impedance	Z <sub>OUT</sub>	—	20	—	Ω	I <sub>OUT</sub> = 100 µA, f = 500 Hz
Output Load Regulation	ΔV <sub>OUT</sub> /ΔI <sub>OUT</sub>	—	2	—	Ω	T <sub>A</sub> = 0°C to +70°C I <sub>OUT</sub> = 100 µA
Turn-On Time	t <sub>ON</sub>	—	800	—	µs	
Typical Load Capacitance	C <sub>LOAD</sub>	—	—	1000	pF	<b>Note 4</b>
SC-70 Thermal Response to 63%	t <sub>RES</sub>	—	1.3	—	s	30°C (Air) to +125°C
TO-92 Thermal Response to 63%	t <sub>RES</sub>	—	1.65	—	s	(Fluid Bath) ( <b>Note 5</b> )

# 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

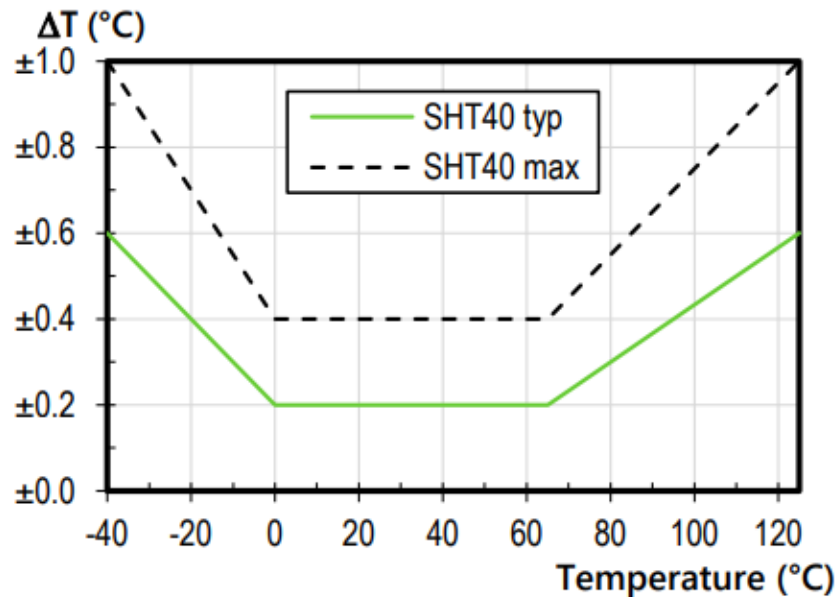


Figure 10. SHT40 typical and maximal temperature accuracy.

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

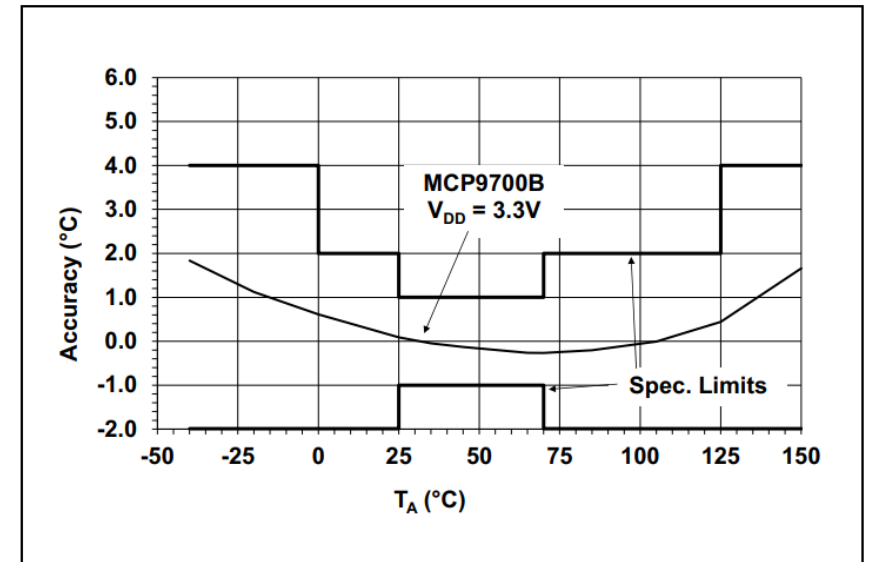
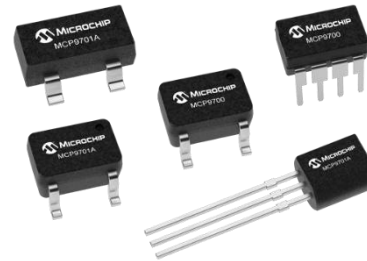


FIGURE 2-1: Accuracy vs. Ambient Temperature (MCP9700B).

# Sensor specifications

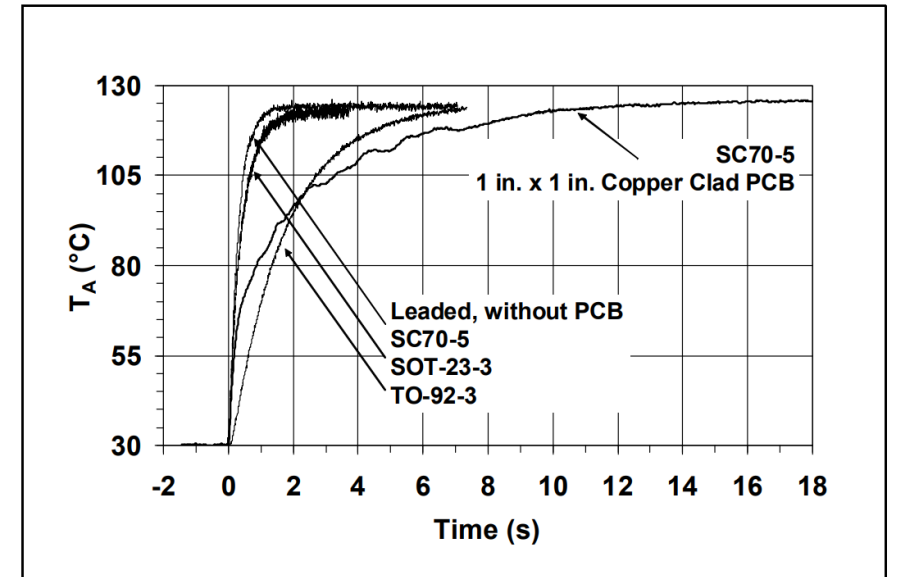
- Response time
  - How fast will sensor output change due to sensor input change
  - For analog sensors, this may be expressed as a time constant
  - For sensors with digital output, may be the time between updates
  - May also be expressed in terms of frequency response
  - **This is the response time of the sensor, not your system...**



## DC ELECTRICAL CHARACTERISTICS (CONTINUED)

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

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



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

## SHT40

Response time <sup>10</sup>	$\tau_{63\%}$	2	s	41
-----------------------------	---------------	---	---	----

# 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 <sup>3</sup>	high	0.04	°C
	medium	0.07	°C
	low	0.1	°C

<sup>3</sup> The stated repeatability is three times the standard deviation ( $3\sigma$ ) 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

SHT40

- 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?



**MCP970X**

Low-Power Linear Active Thermistor ICs

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/m s	Voltage changes on the supply between $V_{DD, min}$ and $V_{DD, max}$ . Faster slow rates may lead to a reset
Supply current (heater <b>off</b> )	$I_{DD}$	Idle state	-	0.08	1.0 3.4	$\mu$ A	At 25 °C At 125 °C
		Power up	-	50	-	$\mu$ A	-
		Measurement	-	320	500	$\mu$ A	Current while sensor is measuring
		Avg., high repeatability Avg., med. repeatability Avg., low repeatability	-	2.2 1.2 0.4	- - -	$\mu$ A	Avg. current consumption (continuous operation with 1 meas. per second)
Supply current (heater <b>on</b> )	$I_{DD}$	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	

## DC ELECTRICAL CHARACTERISTICS

Electrical Specifications: Unless otherwise indicated:						
<b>MCP9700/9700A/9700B:</b> $V_{DD}$ = 2.3V to 5.5V, GND = Ground, $T_A$ = -40°C to +125°C and No load						
<b>MCP9701/9701A:</b> $V_{DD}$ = 3.1V to 5.5V, GND = Ground, $T_A$ = -10°C to +125°C and No load						
Parameter	Sym.	Min.	Typ.	Max.	Unit	Conditions
<b>Power Supply</b>						
Operating Voltage Range	$V_{DD}$	2.3	—	5.5	V	<b>MCP9700/9700A/9700B</b>
	$V_{DD}$	3.1	—	5.5	V	<b>MCP9701/9701A</b>
Operating Current	$I_{DD}$	—	6	12	$\mu$ A	
	$I_{DD}$	—	—	15	$\mu$ A	$T_A$ = +150°C (Note 1)
Line Regulation	$\Delta^\circ\text{C}/\Delta V_{DD}$	—	0.1	—	$^\circ\text{C}/\text{V}$	

# 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 the 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.

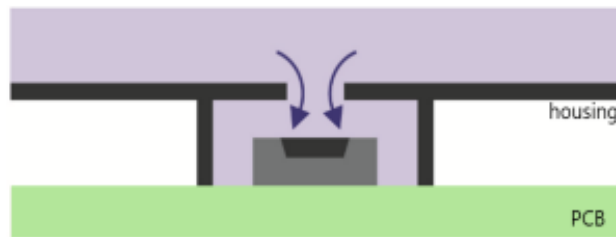


Figure 3. A large opening in the housing provides improved air exchange and thus enhanced access to the environment.

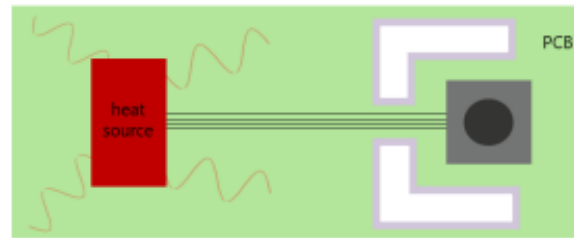
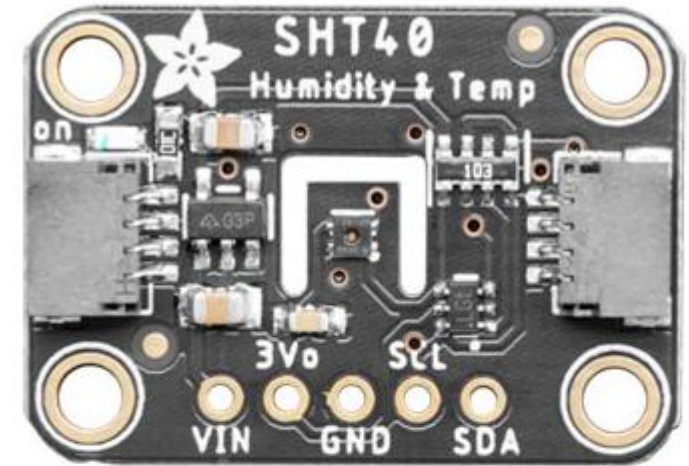


Figure 4. Decoupling of the sensor from heat sources on the PCB minimizes the influence of internal heating on the sensor.



# Packaging – Acconeer XM125 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

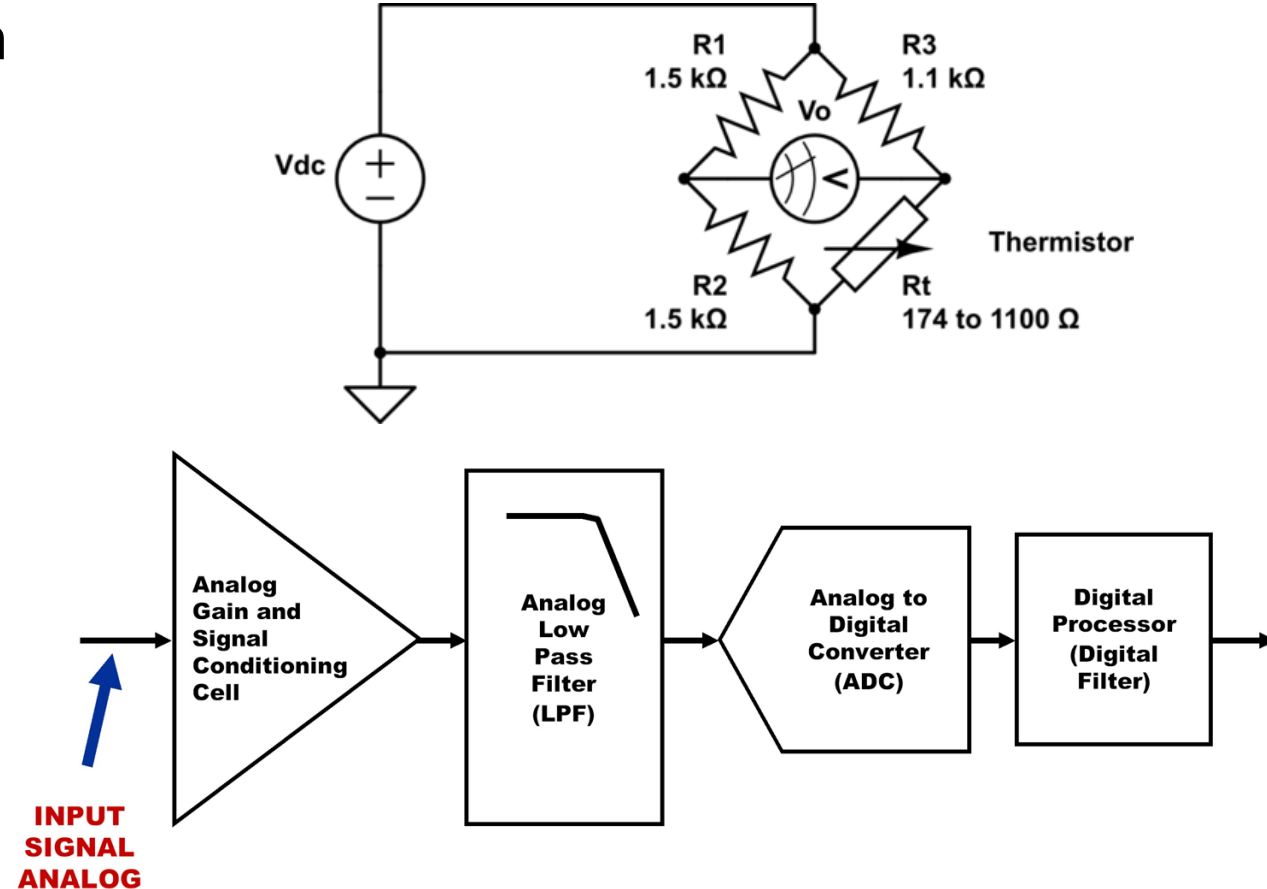
A radome is a dielectric layer that is transparent to the radar signal while protecting the radar from mechanical impact and weather, see Figure 11. Often the product encapsulation can be made as a radome without introducing additional costs. We will here see that by tuning the radome thickness and distance,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

# 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
- Usually, though, we let the manufacturer provide digital data

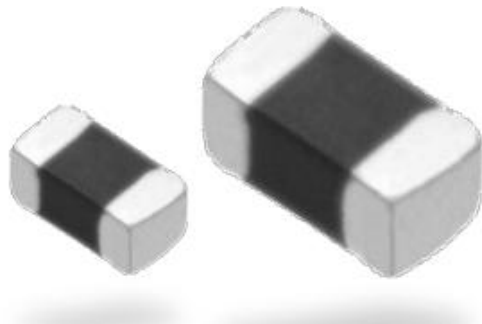
# Signal conditioning and conversion

- 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.

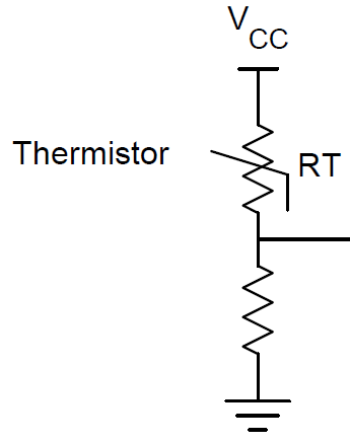


# Example: compare two approaches

- 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



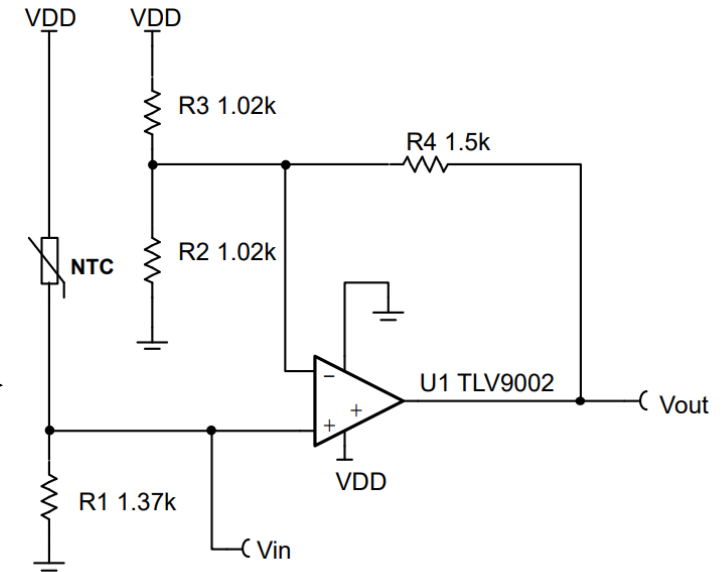
- NTC

- 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 \$\$



# Lots of guides out there



## AN-43: Bridge Circuits

### Marrying Gain and Balance

by [Jim Williams](#)

 [Download PDF](#)

Bridge circuits are among the most elemental and powerful electrical switching, oscillator and transducer circuits. Additionally, bridge techniques extend from DC to bandwidths well into the GHz range. The electrical analog of mechanical systems is also the progenitor of all electrical differential techniques.

#### Resistance Bridges

Figure 1 shows a basic resistor bridge. The circuit is usually credited to [Christie](#), who demonstrated it in 1833, almost certainly preceded his

#### Application Note

### A Basic Guide to Bridge Measurements



Bryan Lizon, Joseph Wu

Precision ADC

#### ABSTRACT

Many precision sensors are formed from a Wheatstone bridge circuit configuration. This circuit configuration enables accurate differential measurements for resistive elements. These elements can be used to measure weight, pressure, temperature, and a variety of other types of sensor parameters. Achieving the most accurate bridge measurements with precision analog-to-digital converters (ADCs) requires a detailed understanding of how these sensors work, how they are calibrated, how they connect to an ADC, and how the ADC is configured. This application note presents an overview of the bridge circuit, how bridges are used to measure different forces, how the ADC measurement is set up, and what errors can arise in the measurement. This application note starts with an overview of bridge circuit basics, how they are constructed, and what parameters are important when designing a bridge measurement system. Circuits are presented showing connections to precision ADCs.

#### Table of Contents

<b>1 Bridge Overview</b> .....	<b>3</b>
<b>2 Bridge Construction</b> .....	<b>5</b>
2.1 Active Elements in Bridge Topologies.....	5
2.2 Strain Gauge and Bridge Construction.....	9
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3.1 Ratiometric Measurements.....	12
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<b>4 Electrical Characteristics of Bridge Measurements</b> .....	<b>15</b>
4.1 Bridge Sensitivity.....	15
4.2 Bridge Resistance.....	15
4.3 Output Common-Mode Voltage.....	16

# 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]

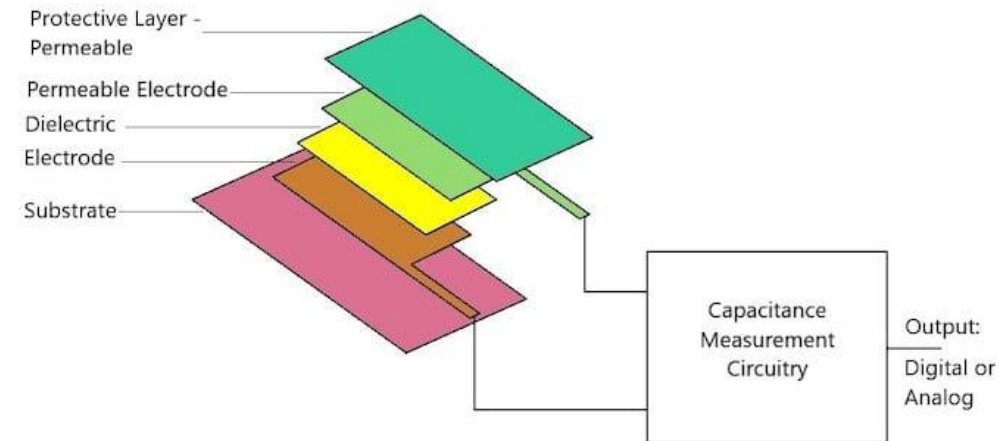
# Compare two approaches

- 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

**Thank you, materials science**

# Humidity

- Capacitive humidity sensor (like in SHT4x)
- Parallel plate capacitor:  $C = \frac{\epsilon A}{g}$
- Create capacitor with dielectric ( $\epsilon$ ) that absorbs water (*hygroscopic*)
  - $\epsilon_{water} \approx 80 \gg \epsilon_{dielectric}$   
→  $C \uparrow$  as humidity  $\uparrow$
- And then we need a circuit that measures capacitance
  - We saw earlier how to turn  $C$  into voltage
  - Can also turn  $C \rightarrow \text{freq} \rightarrow \text{time}$
- 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:  $C = \epsilon \cdot A / d$

- Create capacitor with dielect absorbs water (*hygroscopic*)

- $\epsilon_{water} \approx 80 \gg \epsilon_{dielectric}$   
 $\rightarrow C \uparrow$  as humidity  $\uparrow$

- And then we need a circuit to measure capacitance

- We saw earlier how to turn C into voltage
  - Can also turn C  $\rightarrow$  freq  $\rightarrow$  time

- There are also *resistive* humidity sensors (and probably other mechanical sensors) but capacitive is most common

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

Table 1. General relative humidity sensor specifications.

# Humidity

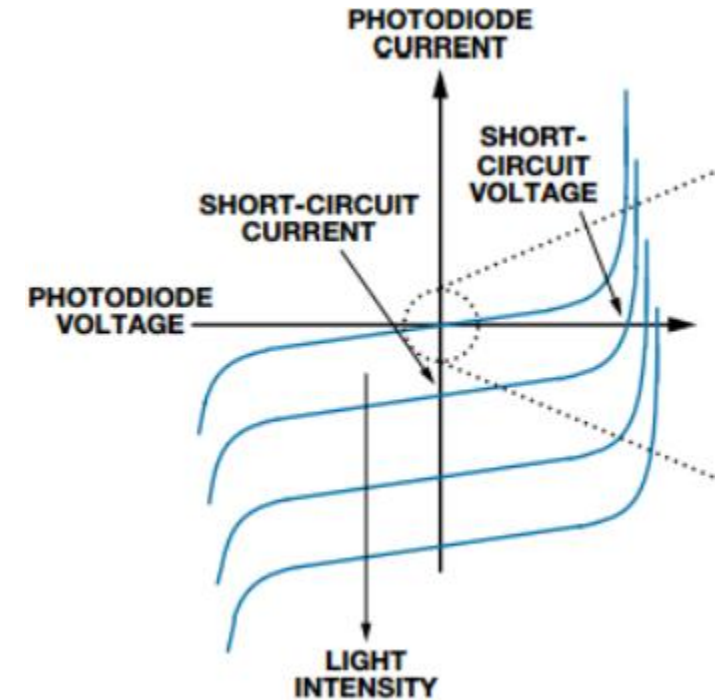
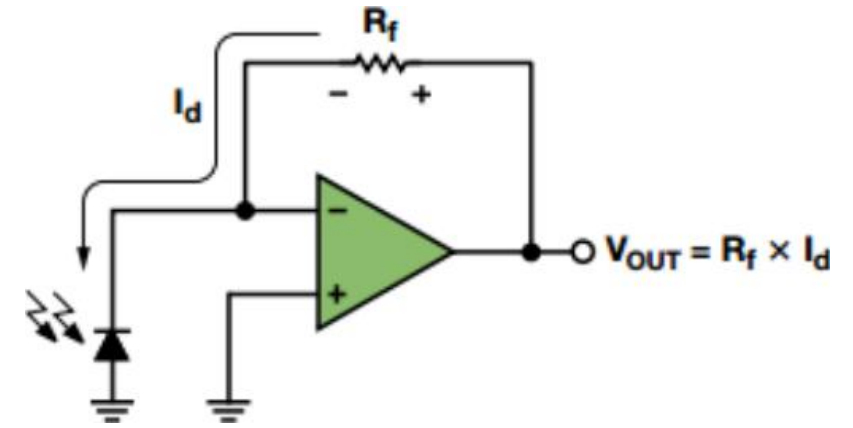
- SHT40 has a heater on it
- Can use it to “bake off” water on/in sensor
- For example, if
  - It got rained on and there is water in opening
  - Or you want to “reset” measurement

# 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/m<sup>2</sup>
    - This is an intensity
    - ~100,000+ 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
    - Basically a solar cell



# 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

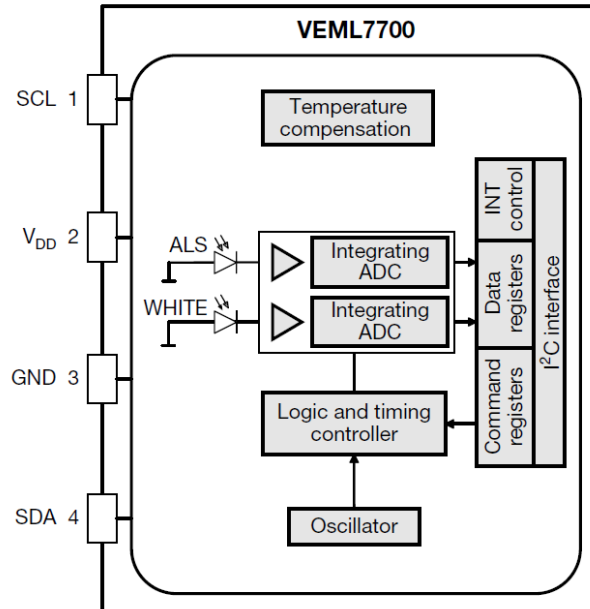


Fig. 1 - Block Diagram

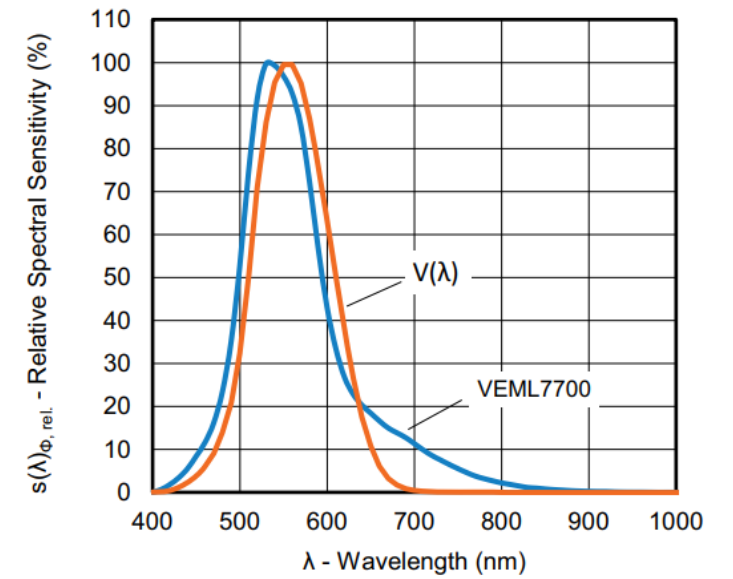
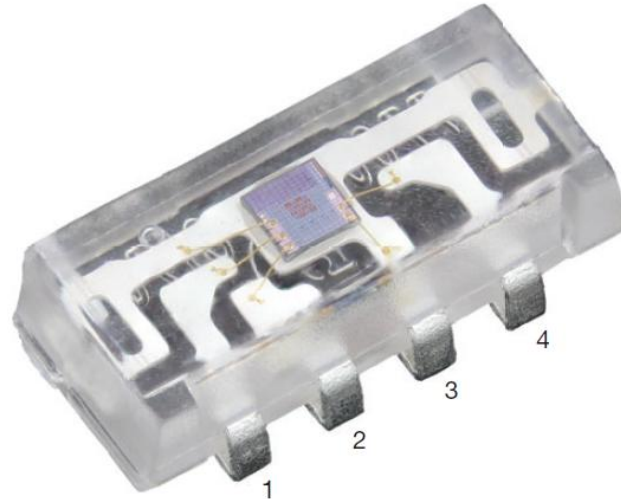


Fig. 5 - Spectral Response

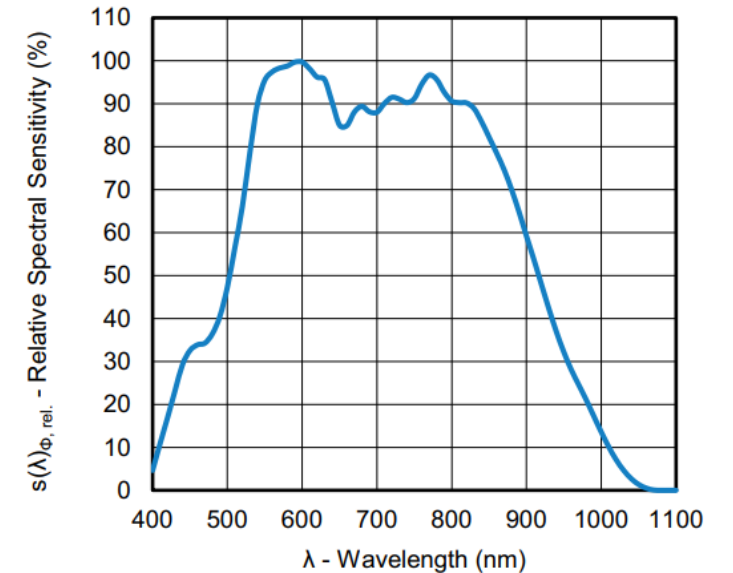
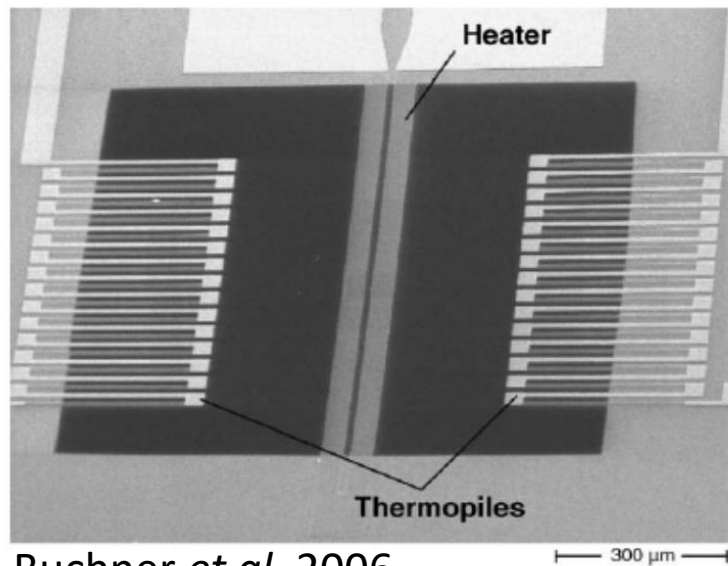


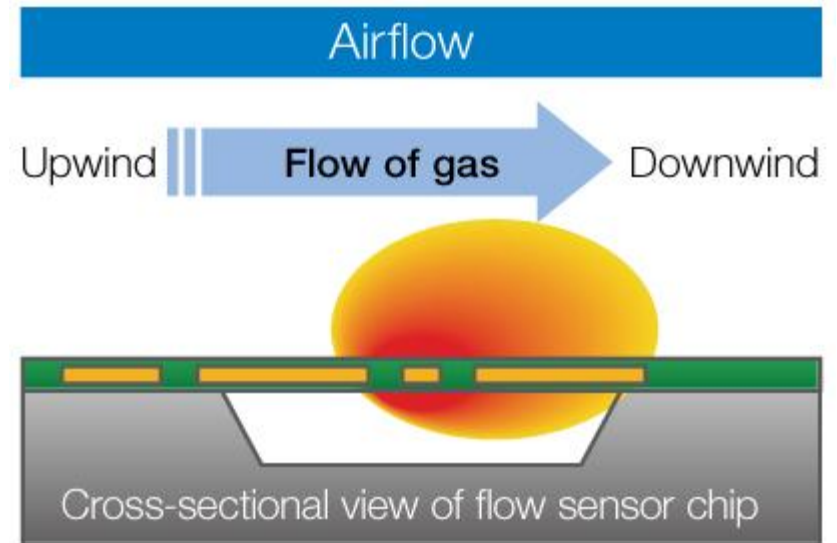
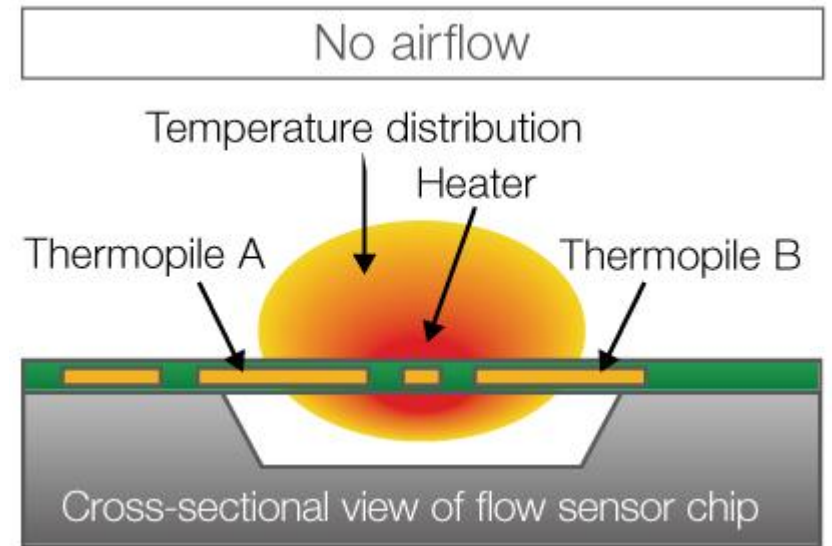
Fig. 6 - White Channel Sensitivity Spectrum

# 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

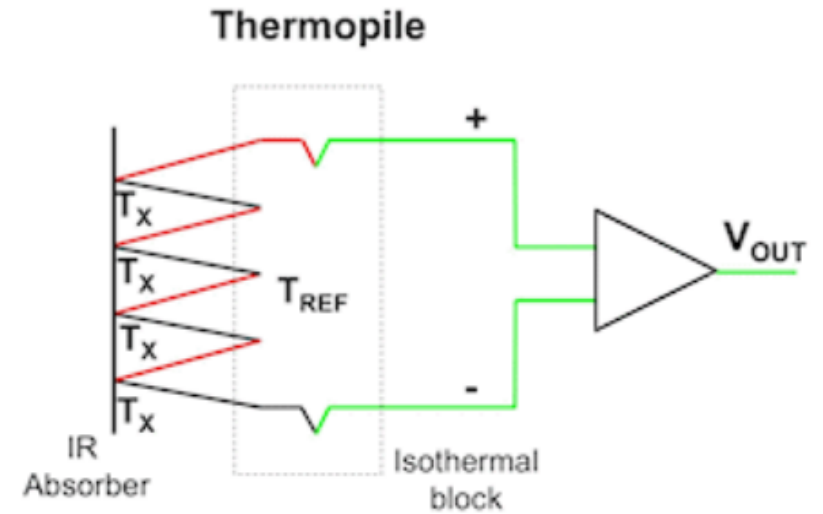


Buchner *et al.* 2006



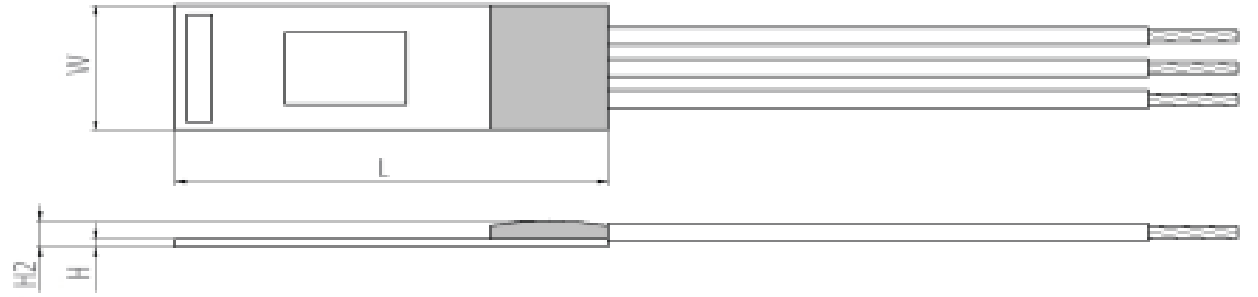
# Air velocity sensing

- 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@100



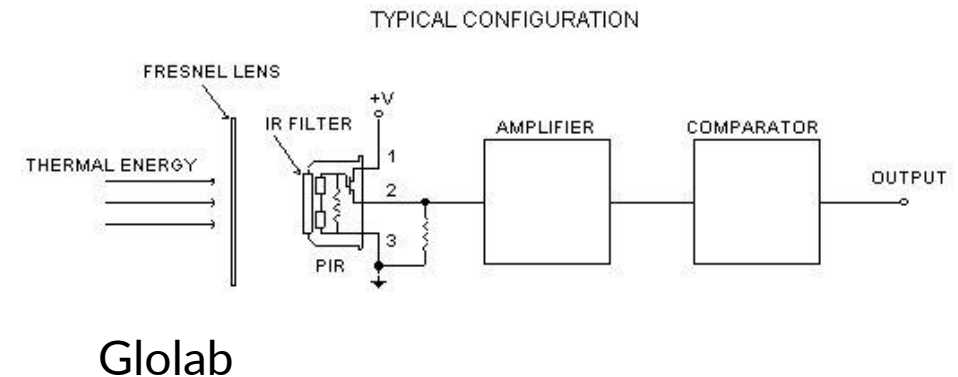
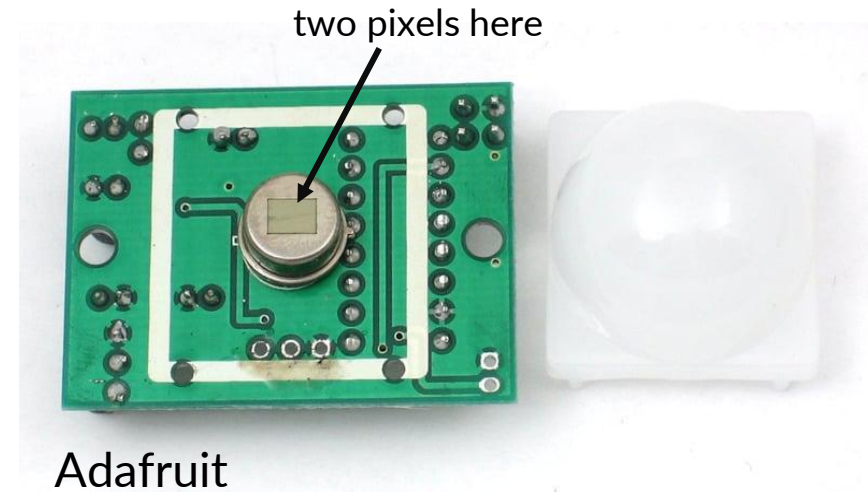
# Air velocity sensing

- Thermal mass sensor *aka* hot wire anemometer
  - 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
- Or make your own (*a la* team 8)
  - RTD on an isolated platform



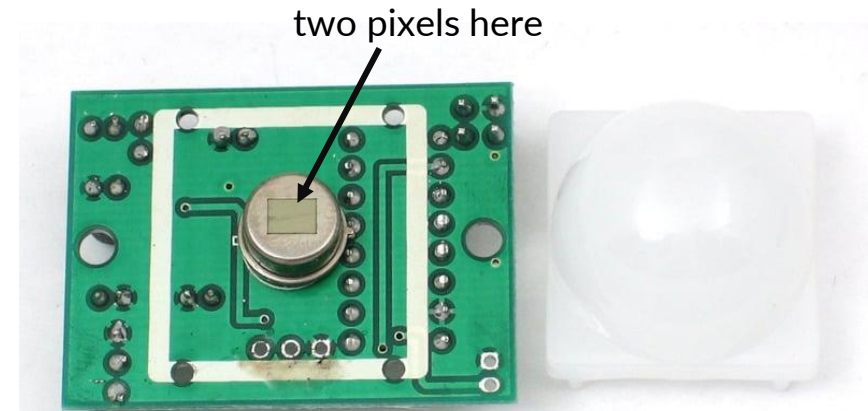
# Passive infrared (PIR) sensor

- The ones in office occupancy sensors, outdoor motion-activated lights, etc.
- Really, these are *motion* sensors
- Two pixels, each sensitive to  $\sim 8\text{-}13$   $\mu\text{m}$  infrared radiation
  - Pyroelectric sensor: certain crystalline materials convert temperature changes into voltage changes
- Uses circuit to convert input voltage into output pulse (upon motion)
- Dome on top has array of Fresnel lens that bring adjacent incoming solid angles to alternating pixels  $\rightarrow$  system can be sensitive to small motions

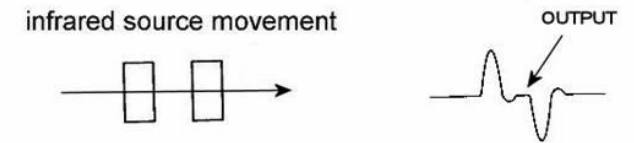
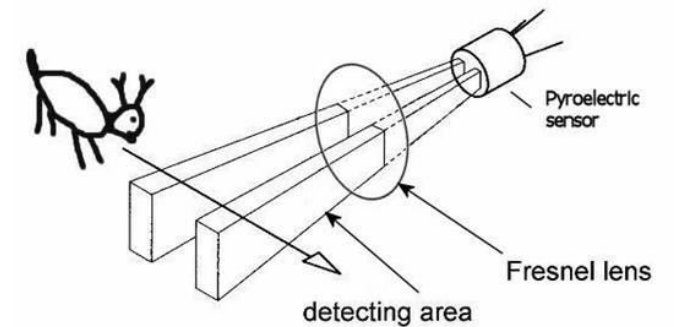


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- Really, these are *motion* sensors
- Two pixels, each sensitive to  $\sim 8\text{-}13$   $\mu\text{m}$  infrared radiation
  - Pyroelectric sensor: certain crystalline materials convert temperature changes into voltage changes
- Uses circuit to convert input voltage into output pulse (upon motion)
- Lens on top has array of Fresnel lens that bring adjacent incoming solid angles to alternating pixels  $\rightarrow$  system can be sensitive to small motions



Adafruit



Glolab

# Passive infrared (PIR) sensor

- Cost
  - Module: ~\$3 @ 1
  - Sensor (ZRE200GE): ~\$1 @ 1
- Size
  - Module: 20-30 mm on a side
  - Sensor: ~9 mm for TO-5 can
- Power/voltage
  - Module: 3 mA active, ~100  $\mu$ A idle @ 3-6V
  - Sensor: depends on use case
- Connectivity
  - Module: 1 pin into GPIO
  - Sensor: depends on circuit (2 pins for team 6)
- Privacy: excellent

# Thermal camera

- Instead of two pixels, what if we had many pixels of thermal information
- Originally used bolometers: microscale ( $\sim 5\text{-}10\ \mu\text{m}$  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.

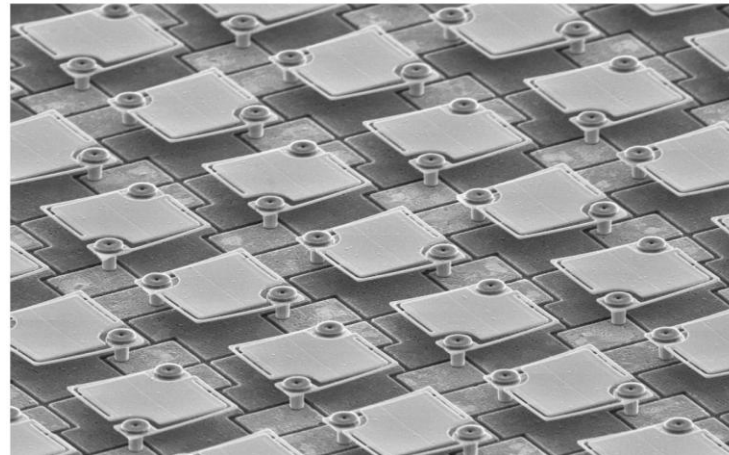


Teledyne FLiR

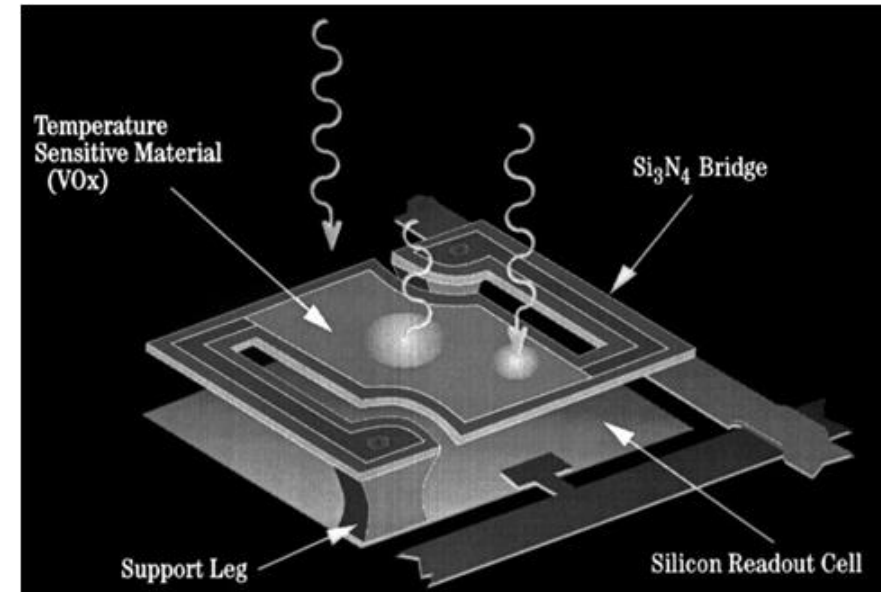


FLIR module

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



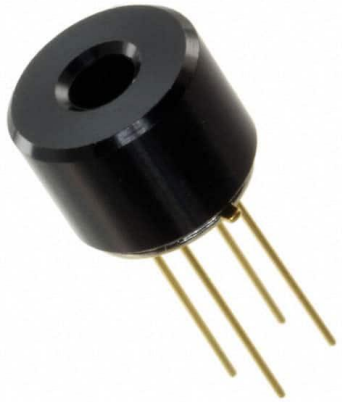
Array (not FLIR)



Unit cell (probably FLIR)

# Thermal camera

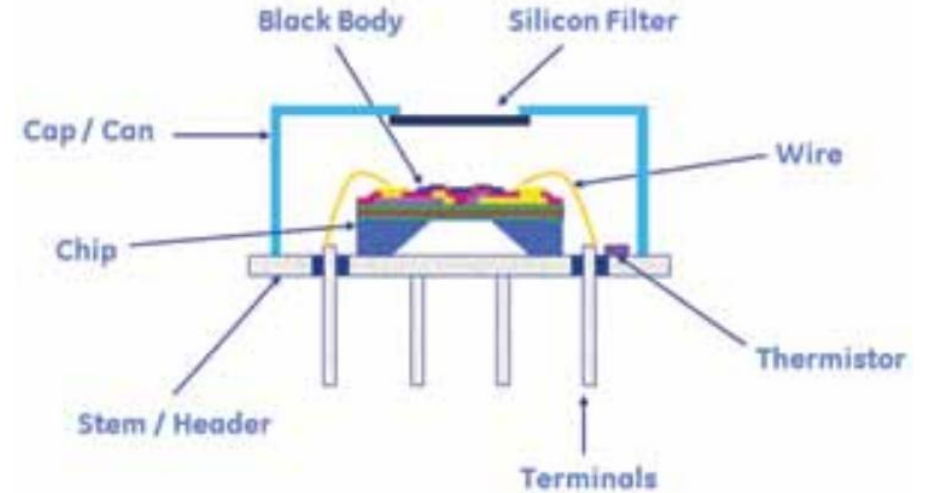
- Thermopile array
  - Lower cost than microbolometer arrays
  - Need thermal isolation (like bolometer) so that small incident radiation results in reasonable  $\Delta T \rightarrow$  reasonable  $\Delta V$



Melexis MLX90640



Adafruit, based on Melexis MLX90640



# Thermal camera

- Some comparisons

	Thermopile	Bolometer
Cost	\$51.28 @ 100 bare IC \$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 2.8-3.1V supply
Connection	I2C	I2C
Package	32-pin package, fits into commercial socket	4-pin thru-hole package
Privacy	Excellent	Excellent

# Thermal temperature sensor

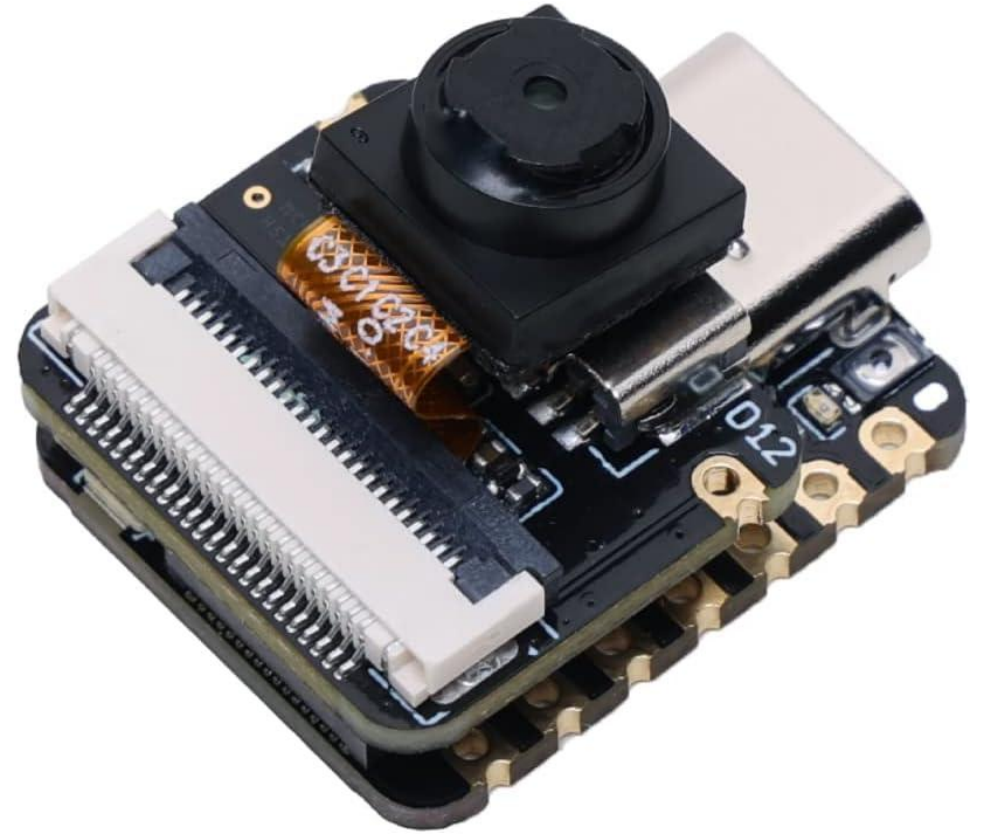
- One-pixel camera *aka* infra-red thermometer
  - Thermopile array
  - With on-board circuitry to condition signal and provide I2C output
  - Expensive: ~\$10@1



MLX90614

# Visible-light camera

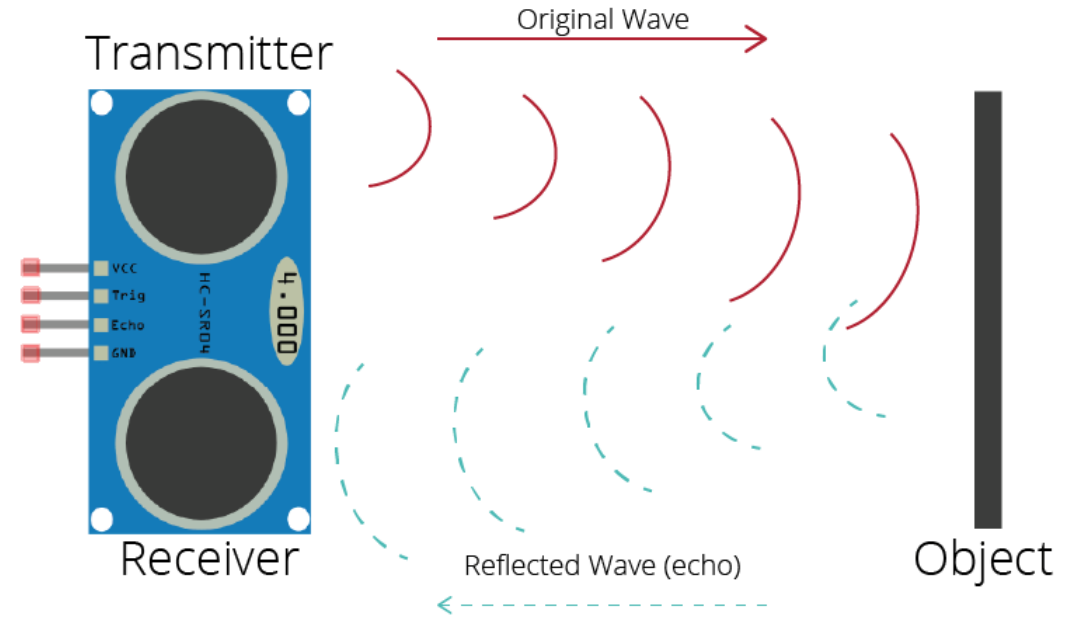
- Lots of options here
  - Easy to get 1MP+ AND ESP32S3 for \$5-10
- Probably worth getting a module instead of a bare sensor
  - Avoids dealing with fine-pitch connector/cable
- Comms
  - SPI, etc.
- Power
  - ~30-100 mA depending on frame rate, etc.
  - 20  $\mu$ A in standby
  - 3.3V [camera sensor 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



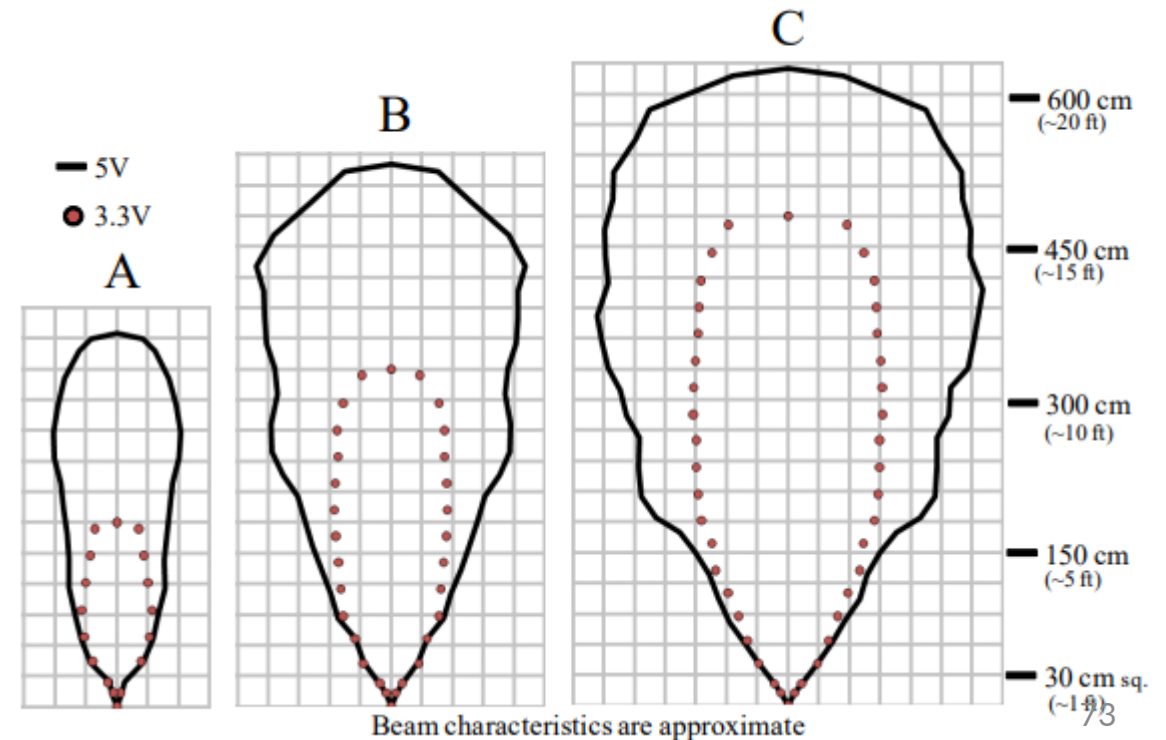
Cheapo US sensors

# 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
  - 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



**\$50 MB1260**

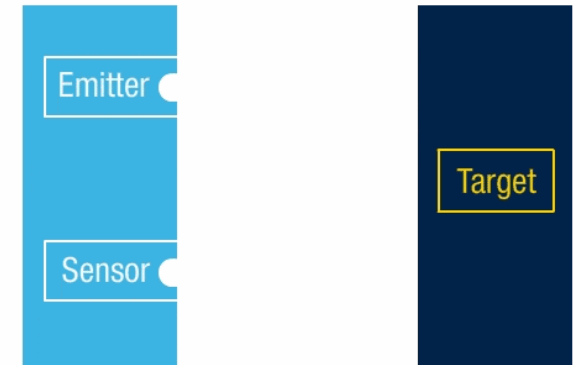
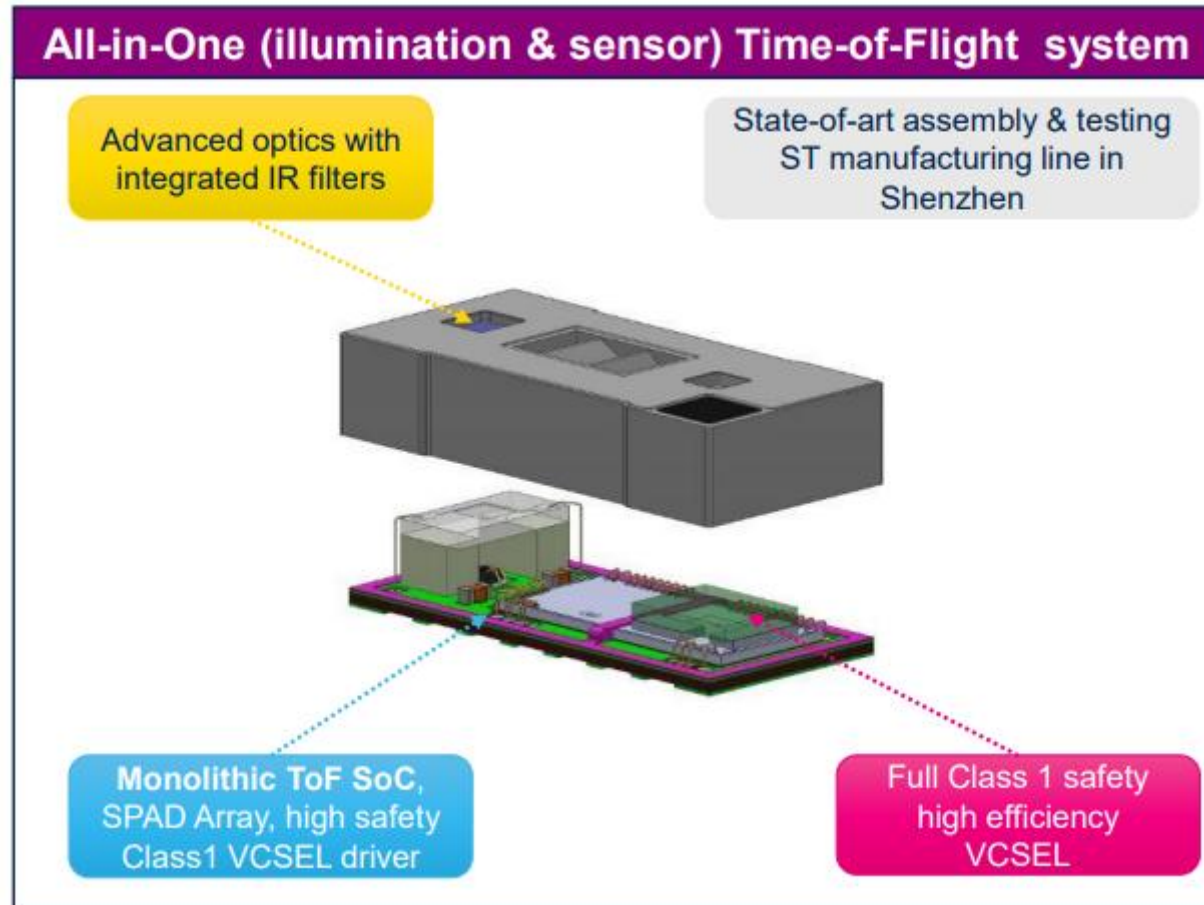


# ToF LIDAR sensors

- 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



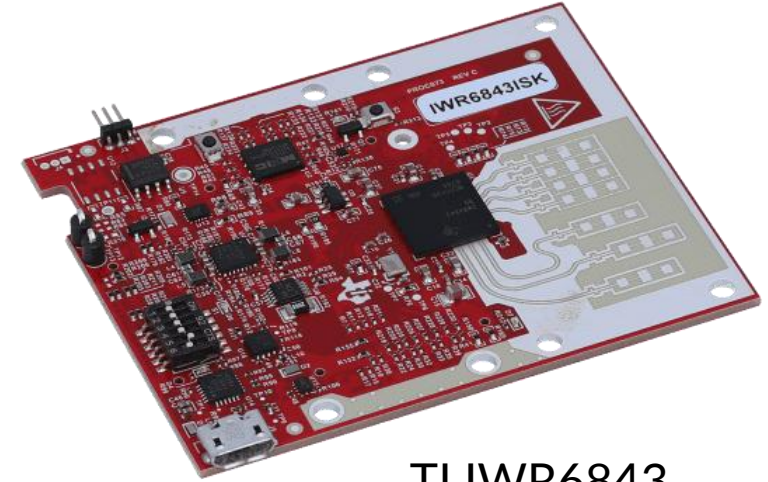
VL53L8CX  
5th generation FlightSense™

**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 Minimum 4000 mm	Typical 2850 mm Minimum 2850 mm
	Corner	Typical 4000 mm Minimum 4000 mm	Typical 2850 mm Minimum 2700 mm
Light gray target (54%)	Inner	Typical 4000 mm Minimum 4000 mm	Typical 2600 mm Minimum 2550 mm
	Corner	Typical 4000 mm Minimum 4000 mm	Typical 2500 mm Minimum 2400 mm
Gray target (17%)	Inner	Typical 4000 mm Minimum 4000 mm	Typical 1650 mm Minimum 1600 mm
	Corner	Typical 3950 mm Minimum 3900 mm	Typical 1550 mm Minimum 1500 mm

# RF/mmWave

- mmWave/RF version of US distance sensor
  - OK, much more than that...
- Use antenna arrays to send out narrow beams of RF energy and record time of flight back
- Cost
  - ~\$17@ 100
- A121
  - 60 GHz pulsed coherent radar
  - Human presence detection range: 7 m
- XM125
  - A module containing the A121 radar sensor
  - Includes MCU, pre-processing to make life easier



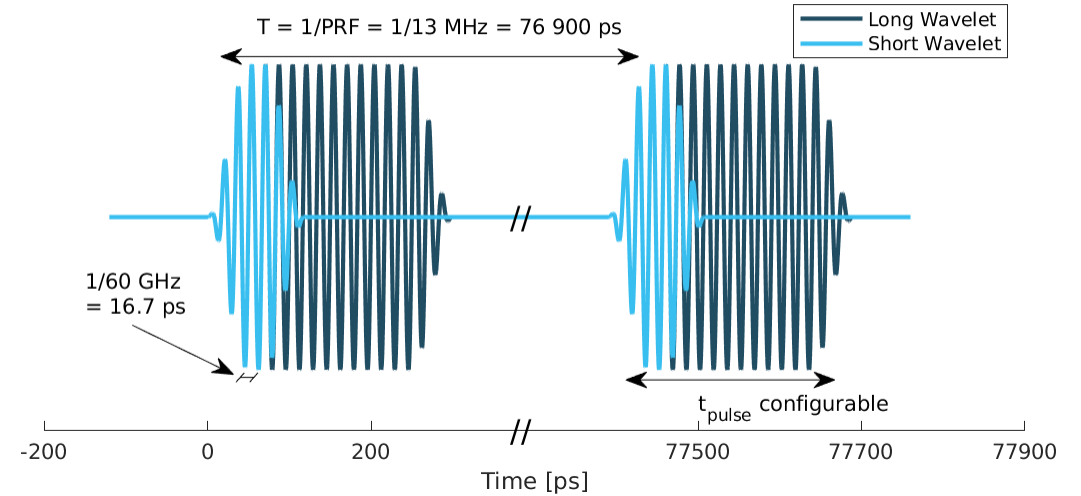
TI IWR6843



Acconeer XM125/A121

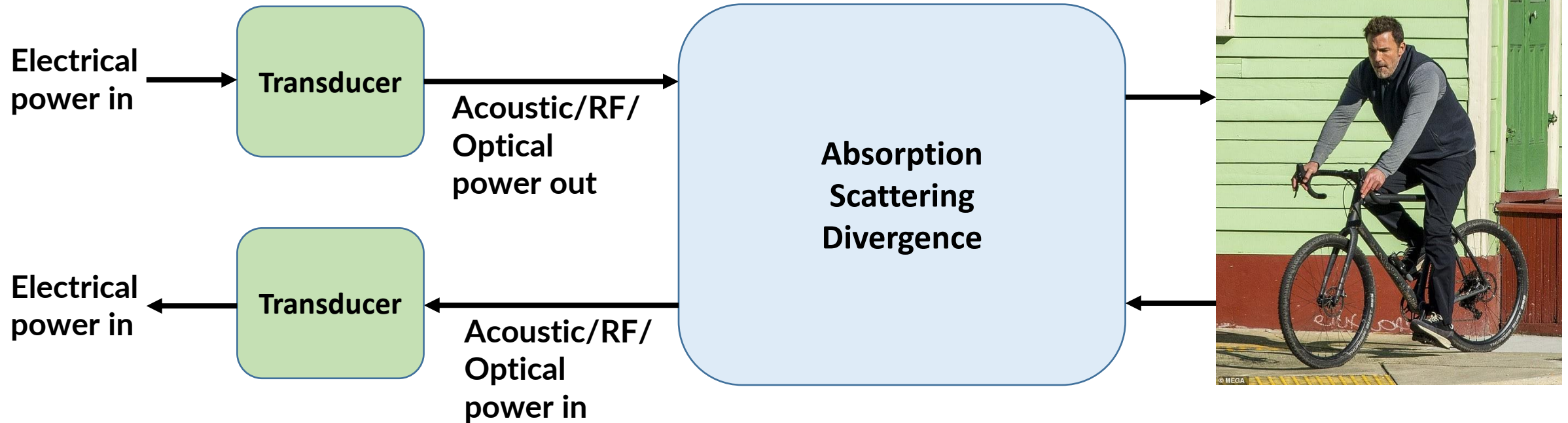
# RF/mmWave

- A121
  - 60 GHz pulsed coherent radar
  - 1.8 V and 3.3 V
  - ~mA to ~10s mA depending on measurement mode
  - Includes antenna on-board
- 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 (and thus direction...)



# 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