ENGINEERING FOR *impact*

mit 6.900

Lecture 9

March 9, 2023

TODAY

- Sensors, using temperature as an example
- MILO air quality sensors

Tuesday we’ll have a discussion about occupancy sensing

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

For HW/SW systems, we always need to convert a physical quantity into an electrical signal and ultimately (usually) into bits

- Most commonly voltage or time
- Less often in to current (charge), magnetic flux (less commonly) or photons, etc.

Sensirion SGP41

Ultrasonic distance sensor

Plantower PMS series [1003, 3003, etc.]

FLIR module

Today’s focus: temperature sensing

The “hello world” of sensing

- Very common and very important for many applications…

  …including MILO, Valerie

- 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 air quality…and occupancy..

- To select among approaches, it helps to understand how they work
  - To understand technical tradeoffs (not so much about cost)

Temperature sensing

Several common ways to measure temperature

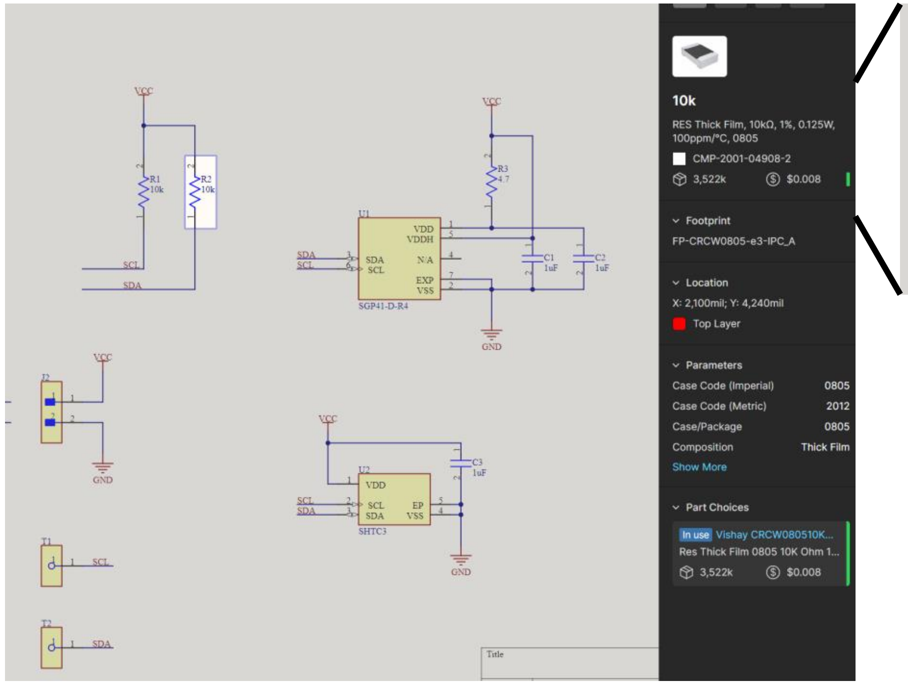
- Most common: via resistance
- Less common: turning temperature directly into voltage
- Coolest: via bandgap

Temperature sensing

Temperature-varying resistors

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

$$R = R(T)$$



10k

RES Thick Film, 10kΩ, 1%, 0.125W, 100ppm/°C, 0805

☐ CMP-2001-04908-2

3,522k $0.008

Footprint

FP-CRCW0805-e3-IPC_A

Location

X: 2,100mil; Y: 4,240mil

🟥 Top Layer

Parameters

Case Code (Imperial)	0805
Case Code (Metric)	2012
Case/Package	0805
Composition	Thick Film

Show More

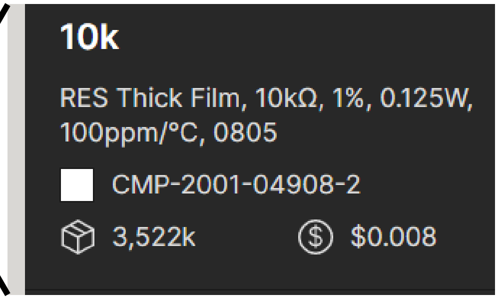
Part Choices

In use Vishay CRCW080510K...

Res Thick Film 0805 10K Ohm 1...

3,522k $0.008

Staff sensor board



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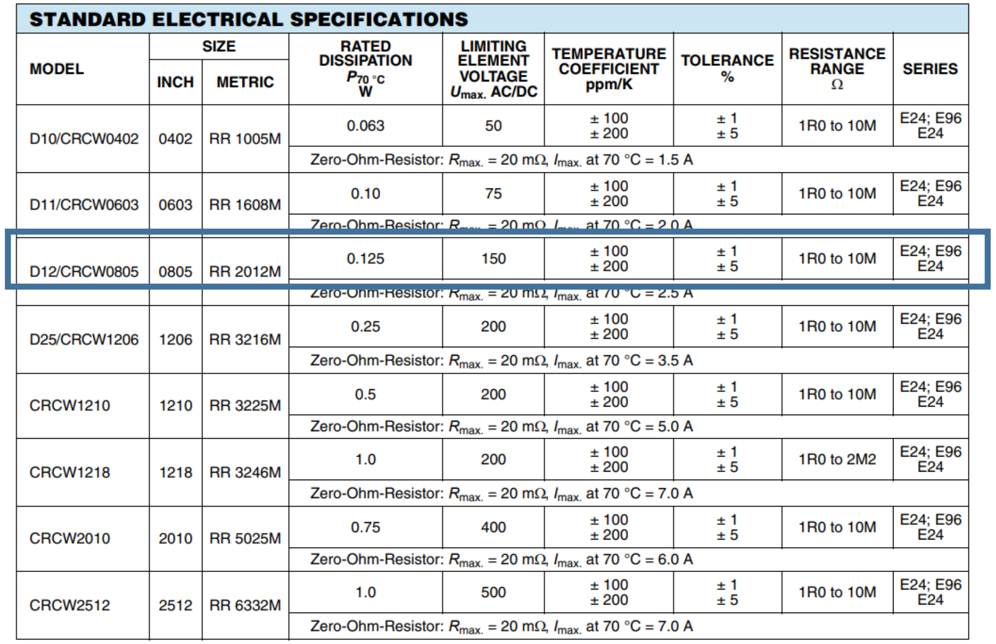
3,522k $0.008

Datasheet



STANDARD ELECTRICAL SPECIFICATIONS

MODEL	SIZE		RATED DISSIPATION $P_{70\,°C}$ W	LIMITING ELEMENT VOLTAGE $U_{max.}$ AC/DC	TEMPERATURE COEFFICIENT ppm/K	TOLERANCE %	RESISTANCE RANGE Ω	SERIES
	INCH	METRIC						
D10/CRCW0402	0402	RR 1005M	0.063	50	± 100 ± 200	± 1 ± 5	1R0 to 10M	E24; E96 E24
			Zero-Ohm-Resistor: $R_{max.}$ = 20 mΩ, $I_{max.}$ at 70 °C = 1.5 A					
D11/CRCW0603	0603	RR 1608M	0.10	75	± 100 ± 200	± 1 ± 5	1R0 to 10M	E24; E96 E24
			Zero-Ohm-Resistor: $R_{max.}$ = 20 mΩ, $I_{max.}$ at 70 °C = 2.0 A					
D12/CRCW0805	0805	RR 2012M	0.125	150	± 100 ± 200	± 1 ± 5	1R0 to 10M	E24; E96 E24
			Zero-Ohm-Resistor: $R_{max.}$ = 20 mΩ, $I_{max.}$ at 70 °C = 2.5 A					
D25/CRCW1206	1206	RR 3216M	0.25	200	± 100 ± 200	± 1 ± 5	1R0 to 10M	E24; E96 E24
			Zero-Ohm-Resistor: $R_{max.}$ = 20 mΩ, $I_{max.}$ at 70 °C = 3.5 A					
CRCW1210	1210	RR 3225M	0.5	200	± 100 ± 200	± 1 ± 5	1R0 to 10M	E24; E96 E24
			Zero-Ohm-Resistor: $R_{max.}$ = 20 mΩ, $I_{max.}$ at 70 °C = 5.0 A					
CRCW1218	1218	RR 3246M	1.0	200	± 100 ± 200	± 1 ± 5	1R0 to 2M2	E24; E96 E24
			Zero-Ohm-Resistor: $R_{max.}$ = 20 mΩ, $I_{max.}$ at 70 °C = 7.0 A					
CRCW2010	2010	RR 5025M	0.75	400	± 100 ± 200	± 1 ± 5	1R0 to 10M	E24; E96 E24
			Zero-Ohm-Resistor: $R_{max.}$ = 20 mΩ, $I_{max.}$ at 70 °C = 6.0 A					
CRCW2512	2512	RR 6332M	1.0	500	± 100 ± 200	± 1 ± 5	1R0 to 10M	E24; E96 E24
			Zero-Ohm-Resistor: $R_{max.}$ = 20 mΩ, $I_{max.}$ at 70 °C = 7.0 A					

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 10k resistor from sensor board, at $T_2 = 100$ °C:

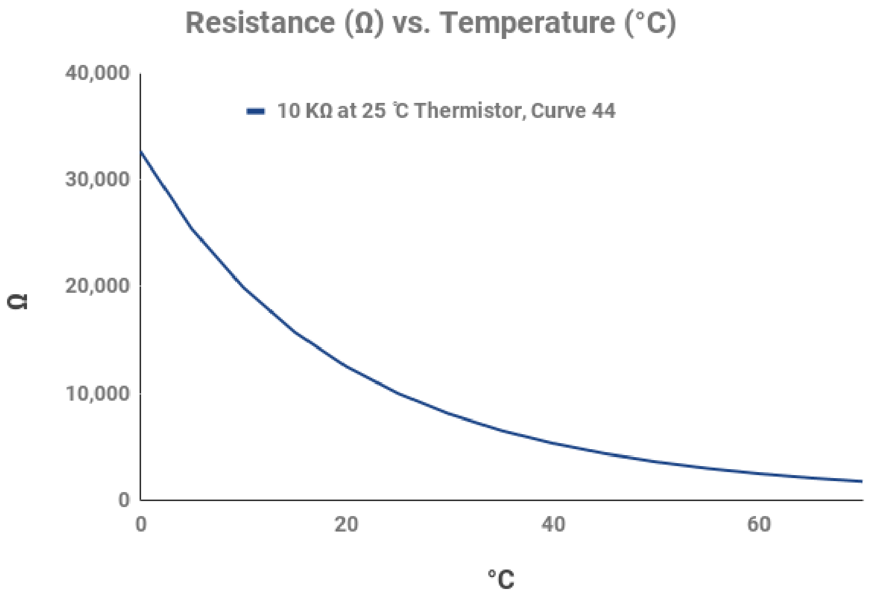
$$R(T_2) = 10k\big(1 + 100e^{-6} \cdot (75°C)\big)$$

$$R(T_2) = 10k(1.0075) = 10.075\text{k}$$

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

$$\beta = \frac{ln(\frac{R1}{R2})}{(\frac{1}{T1} - \frac{1}{T2})}$$

  - Though sometimes the absolute temperature doesn't matter, just trying to keep a system near a reference temperature

NTC thermistor

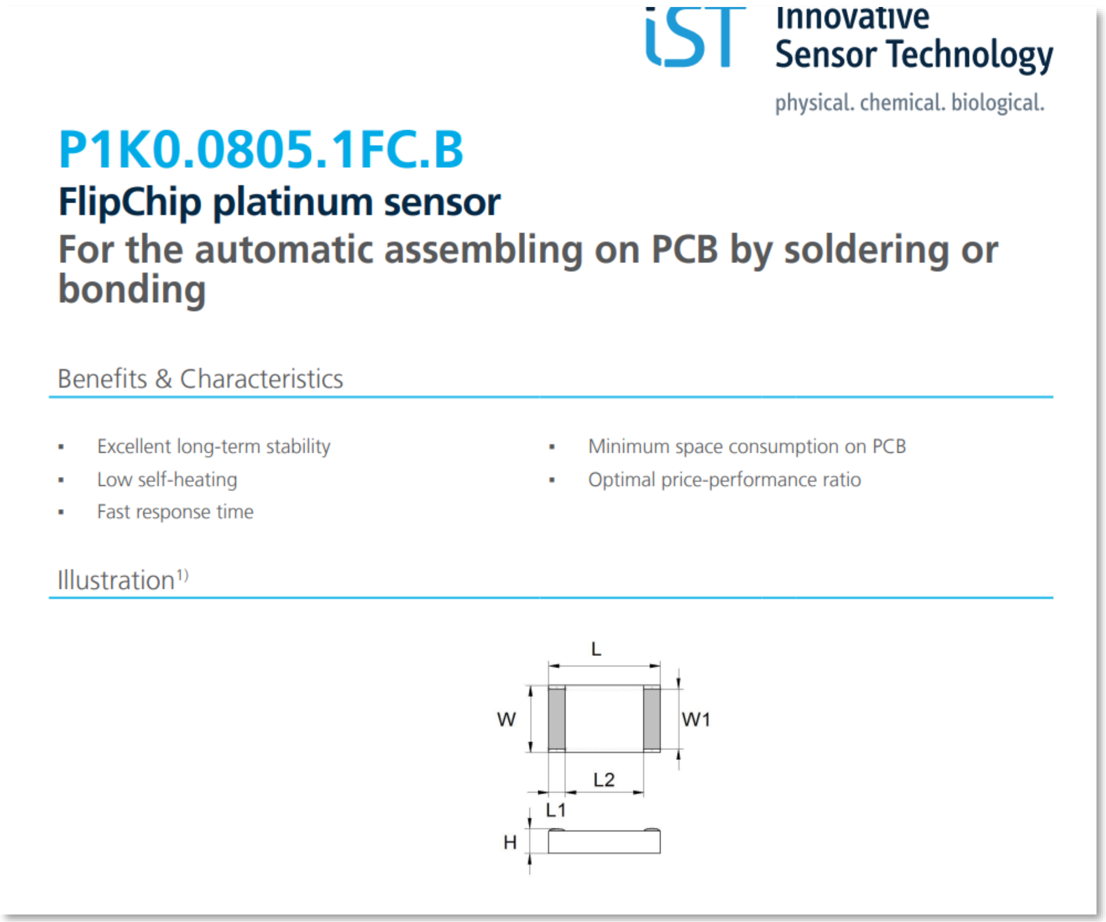
- How to convert resistance (change) into something we can act on?
- Typically we prefer to measure voltages (rather than currents)
  - Think, ADC on a MCU

➔ 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
    - *Self heating*

RTD thermistor

- RTD: resistance temperature detectors
- Pure material (like Pt)
- Available in SMT package
- Much more expensive than NTC
  - $0.9898 @1k quantities
- Broader range esp. to high temperature
- Sensitivity < NTC
- Much more linear
- 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
- Mechanism involves thermoelectricity: via connecting two materials with different thermoelectric coefficients
  - Thermoelectric = coupling between thermal (ΔT) and electric (ΔV) domains

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

- This also used (in reverse) for Peltier heaters
- Can go to **really high** temperatures (2000+ K)
- Not very common in integrated systems (put we'll see one on Tue)

Bandgap temperature sensors

- Use physics intrinsic to semiconductors

pn junction (diode) equation $I = I_0(e^{\frac{V_D}{\frac{kT}{q}}} - 1)$

- 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
- Measured via ADC, either on-chip or separate
  - ESP32C3 has two 12-bit ADCs

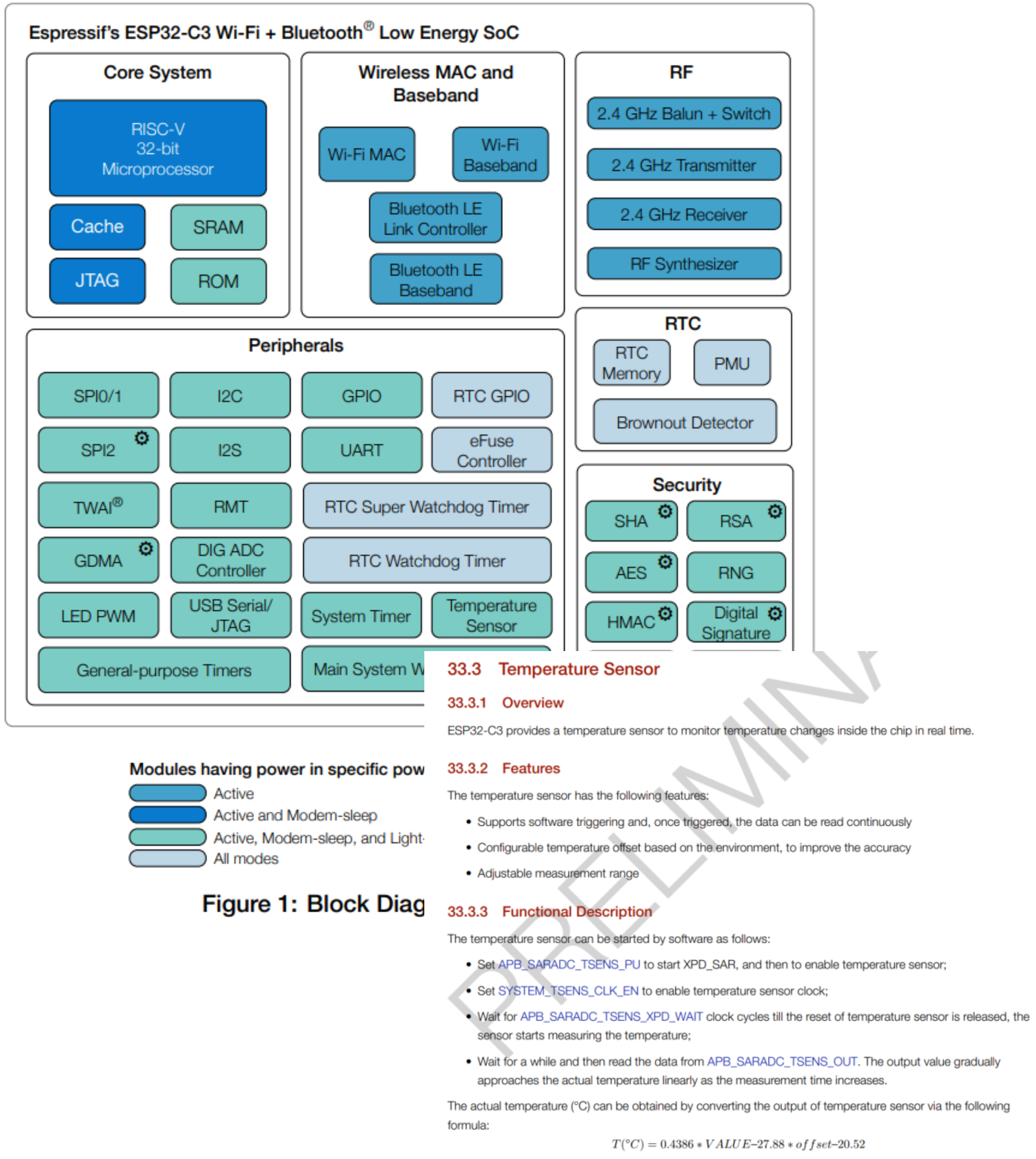


Figure 1: Block Diag

33.3 Temperature Sensor

33.3.1 Overview

ESP32-C3 provides a temperature sensor to monitor temperature changes inside the chip in real time.

33.3.2 Features

The temperature sensor has the following features:

- Supports software triggering and, once triggered, the data can be read continuously
- Configurable temperature offset based on the environment, to improve the accuracy
- Adjustable measurement range

33.3.3 Functional Description

The temperature sensor can be started by software as follows:

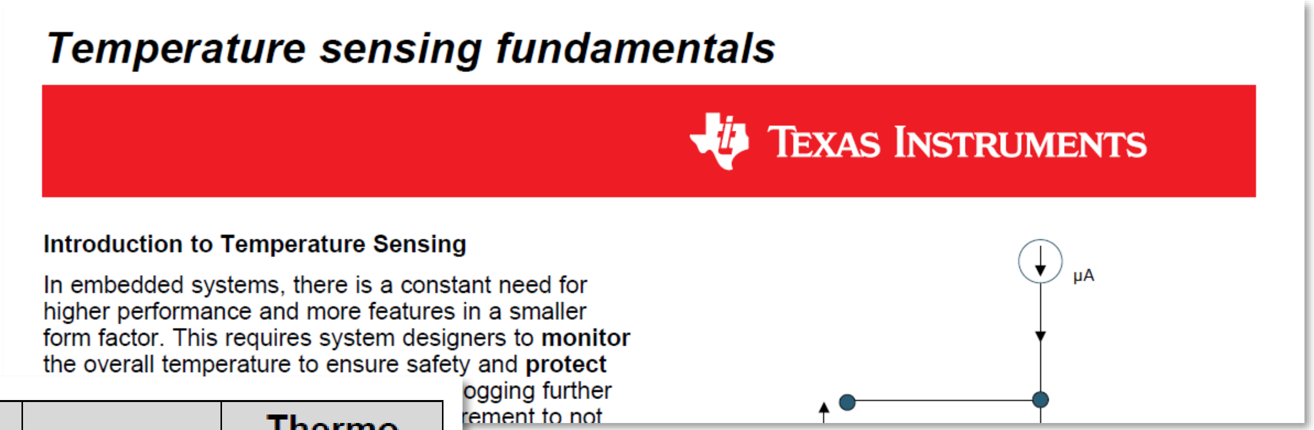
- Set APB_SARADC_TSENS_PU to start XPD_SAR, and then to enable temperature sensor;
- Set SYSTEM_TSENS_CLK_EN to enable temperature sensor clock;
- Wait for APB_SARADC_TSENS_XPD_WAIT clock cycles till the reset of temperature sensor is released, the sensor starts measuring the temperature;
- Wait for a while and then read the data from APB_SARADC_TSENS_OUT. The output value gradually approaches the actual temperature linearly as the measurement time increases.

The actual temperature (°C) can be obtained by converting the output of temperature sensor via the following formula:

$$T(°C) = 0.4386 * VALUE – 27.88 * offset – 20.52$$

Temperature sensors

- Some comparisons, from ➔



Temperature sensing fundamentals

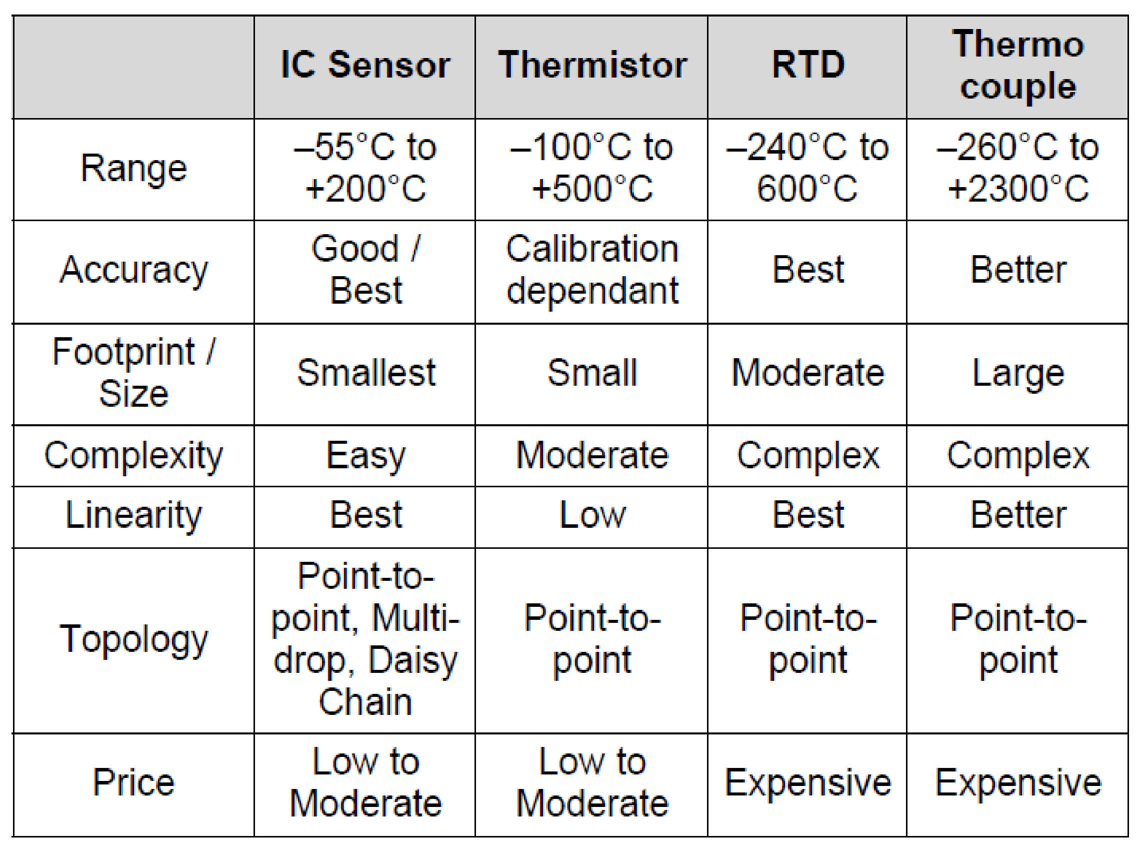
TEXAS INSTRUMENTS

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

rement to not



	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

For those who **really** care, there can be lots of specs for any particular sensor…

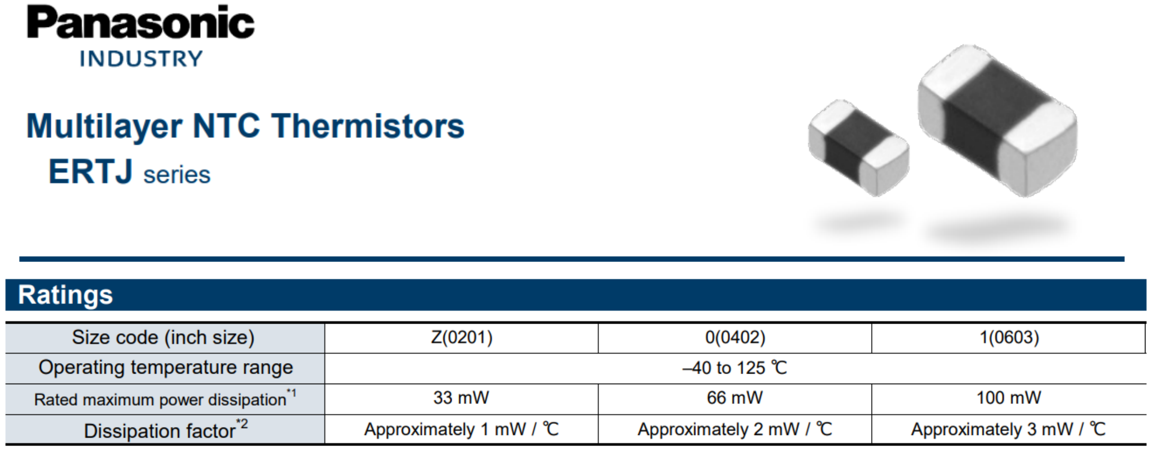
…this is one reason that data sheets can get really long

…as the designer, you need to figure out the ones you care about

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



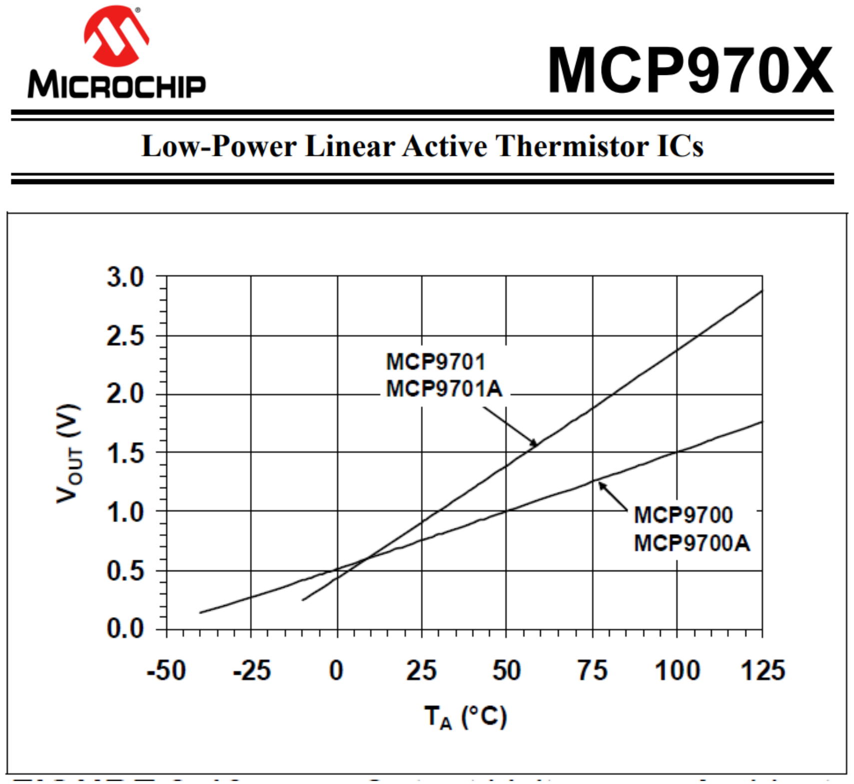
Panasonic
INDUSTRY

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 / ℃

Not a thermistor!



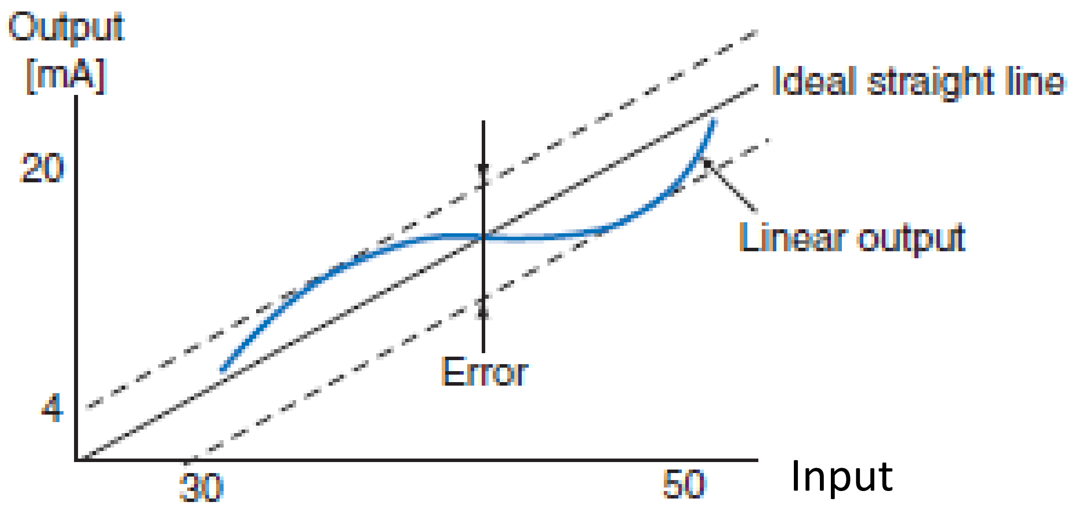
MICROCHIP **MCP970X**

Low-Power Linear Active Thermistor ICs

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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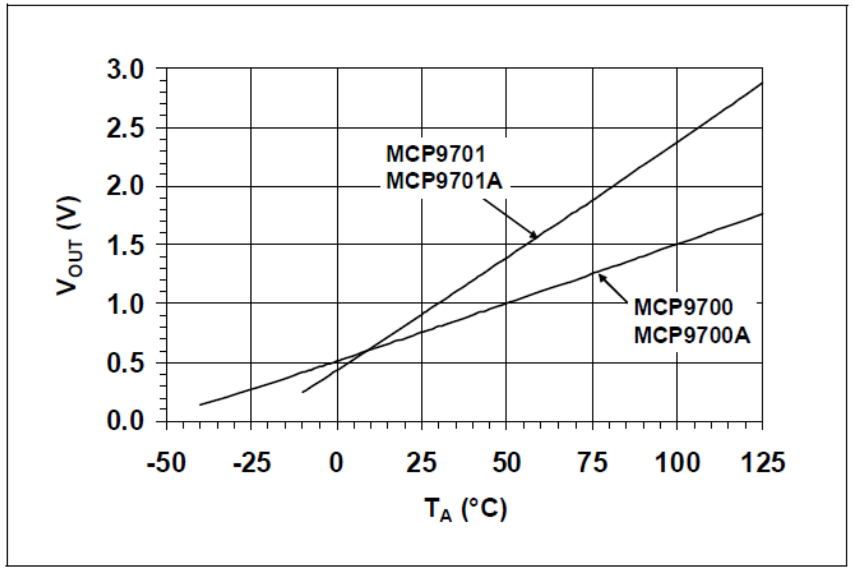
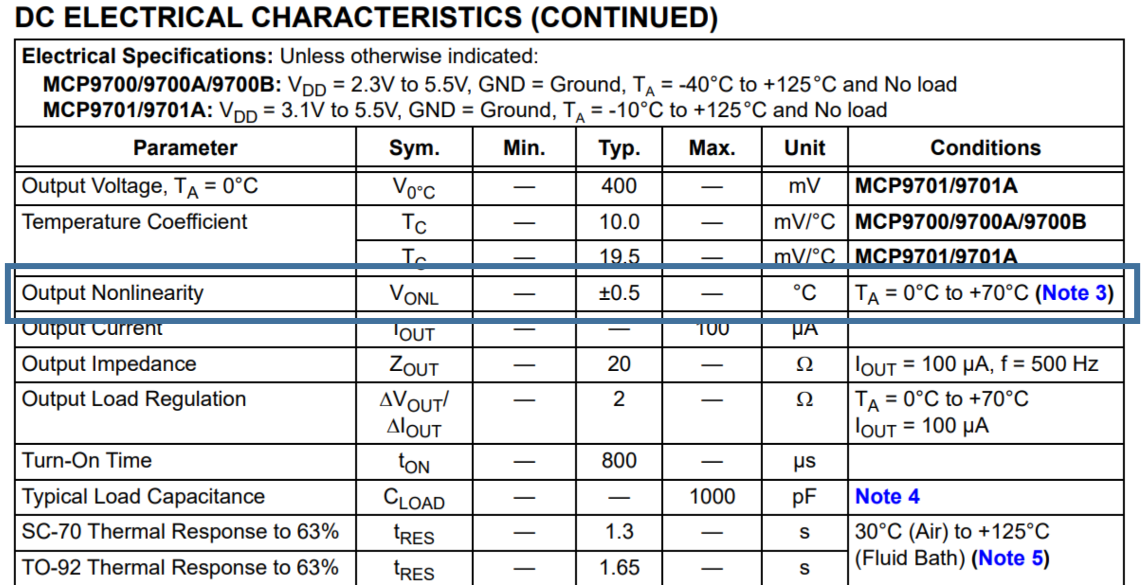




DC ELECTRICAL CHARACTERISTICS (CONTINUED)

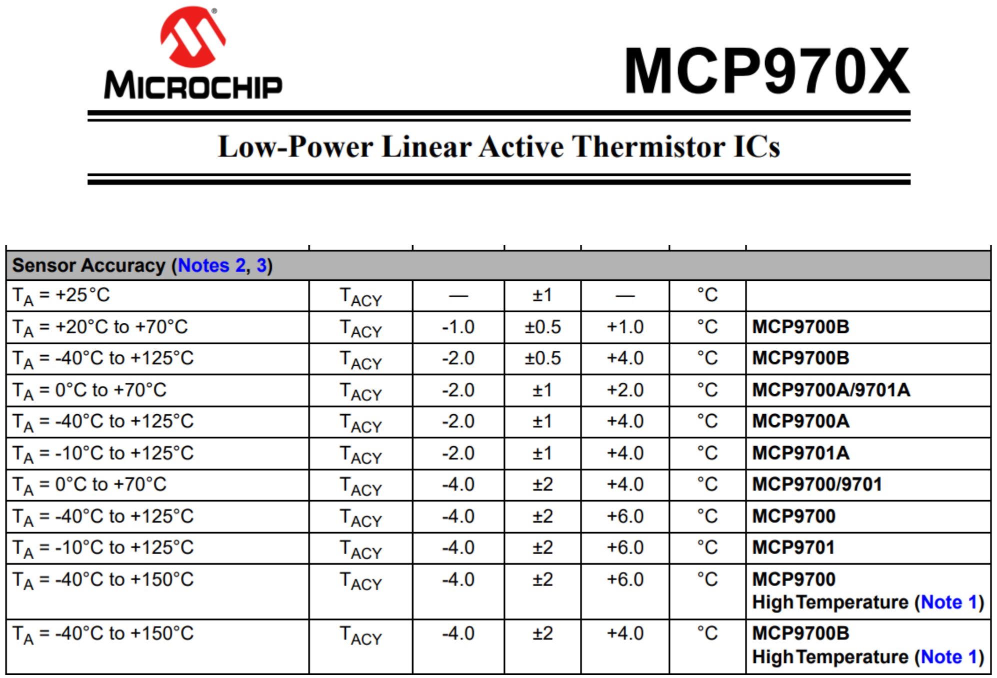
Electrical Specifications: Unless otherwise indicated:
MCP9700/9700A/9700B: V_{DD} = 2.3V to 5.5V, GND = Ground, T_A = -40°C to +125°C and No load
MCP9701/9701A: V_{DD} = 3.1V to 5.5V, GND = Ground, T_A = -10°C to +125°C and No load

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 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	

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

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)**

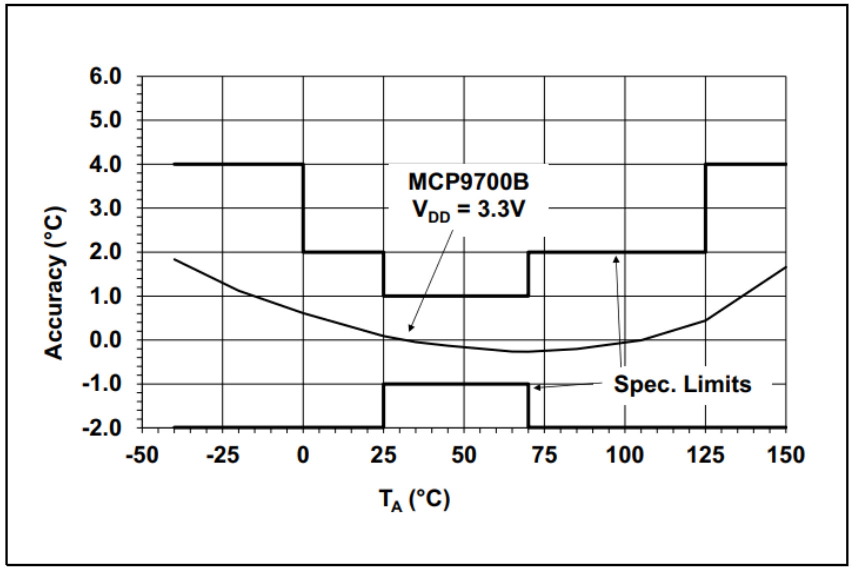
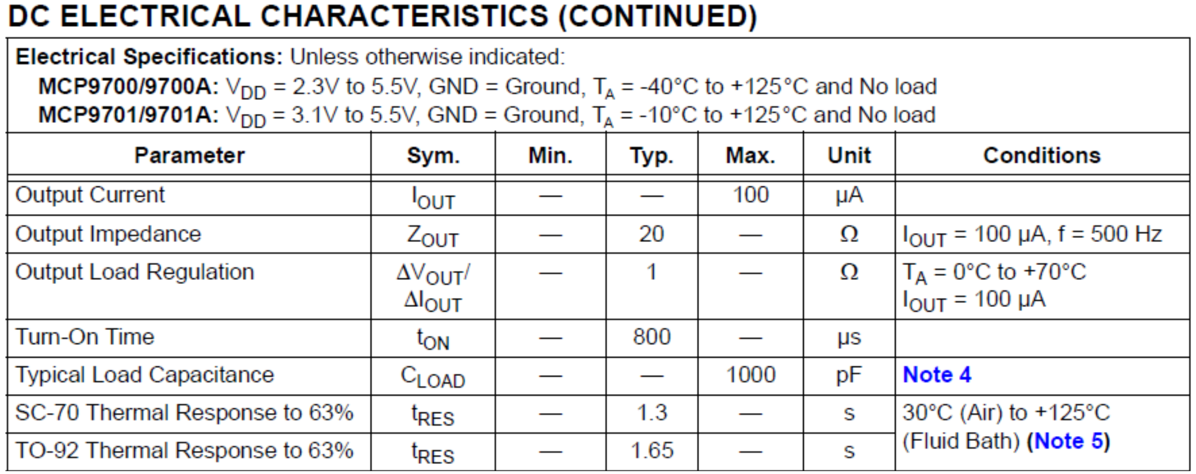


FIGURE 2-1: *Accuracy vs. Ambient Temperature (MCP9700B).*

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



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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 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	

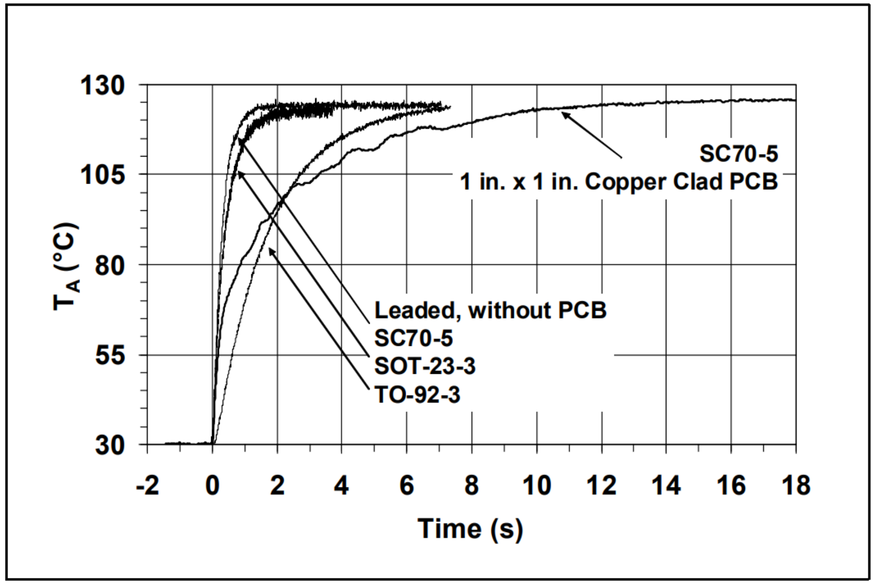
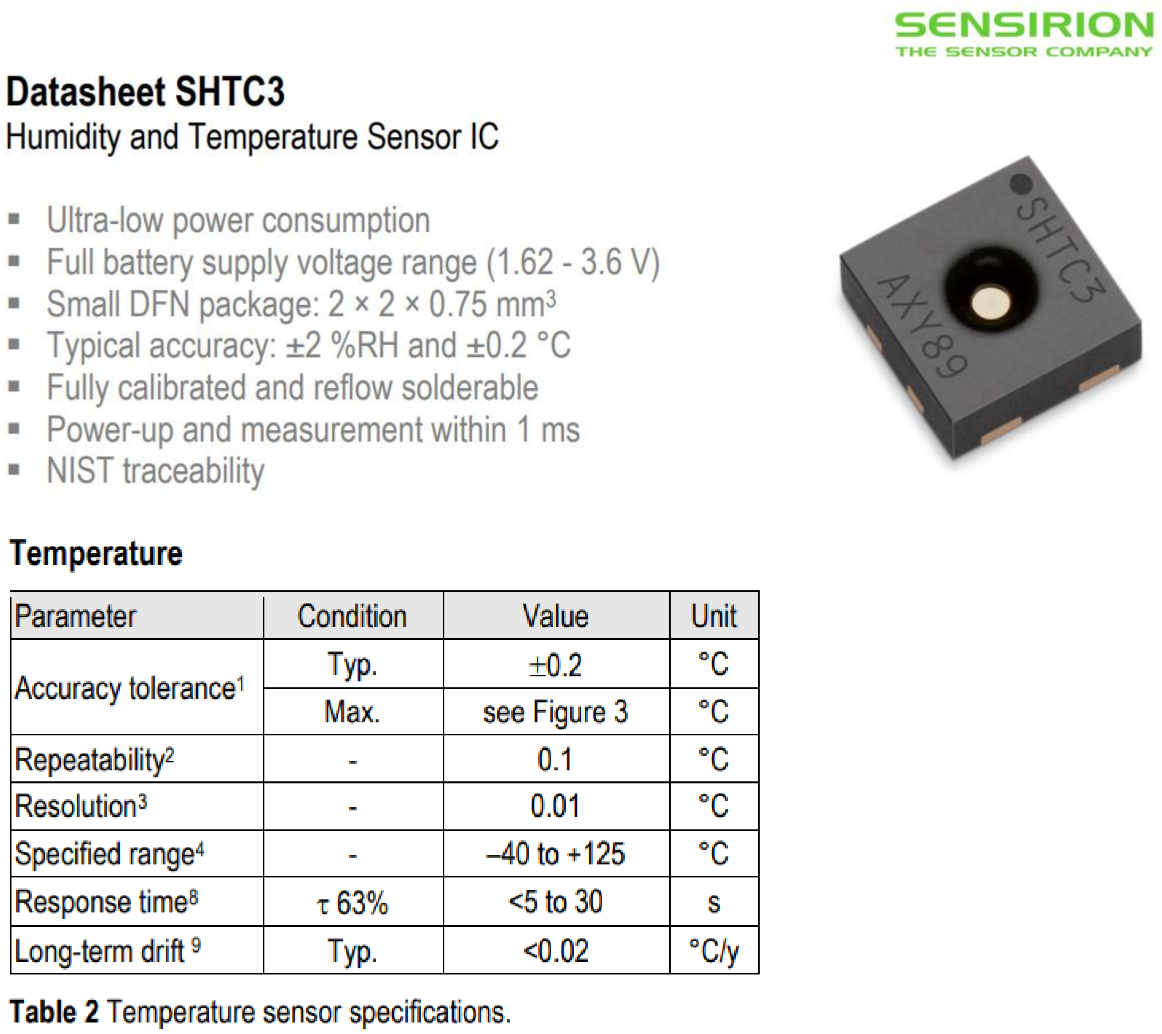


FIGURE 2-16: *Thermal Response (Air-to-Fluid Bath).*

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



SENSIRION
THE SENSOR COMPANY

Datasheet SHTC3
Humidity and Temperature Sensor IC

- Ultra-low power consumption
- Full battery supply voltage range (1.62 - 3.6 V)
- Small DFN package: 2 × 2 × 0.75 mm^3
- Typical accuracy: ±2 %RH and ±0.2 °C
- Fully calibrated and reflow solderable
- Power-up and measurement within 1 ms
- NIST traceability

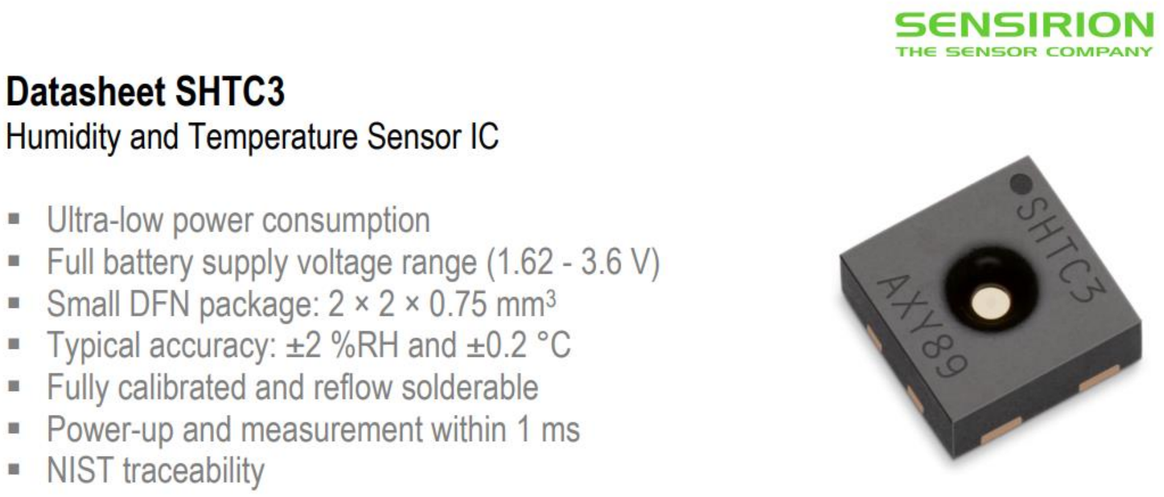
Temperature

Parameter	Condition	Value	Unit
Accuracy tolerance[1]	Typ.	±0.2	°C
	Max.	see Figure 3	°C
Repeatability[2]	-	0.1	°C
Resolution[3]	-	0.01	°C
Specified range[4]	-	–40 to +125	°C
Response time[8]	τ 63%	<5 to 30	s
Long-term drift [9]	Typ.	<0.02	°C/y

Table 2 Temperature sensor specifications.

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 a second supply voltage?



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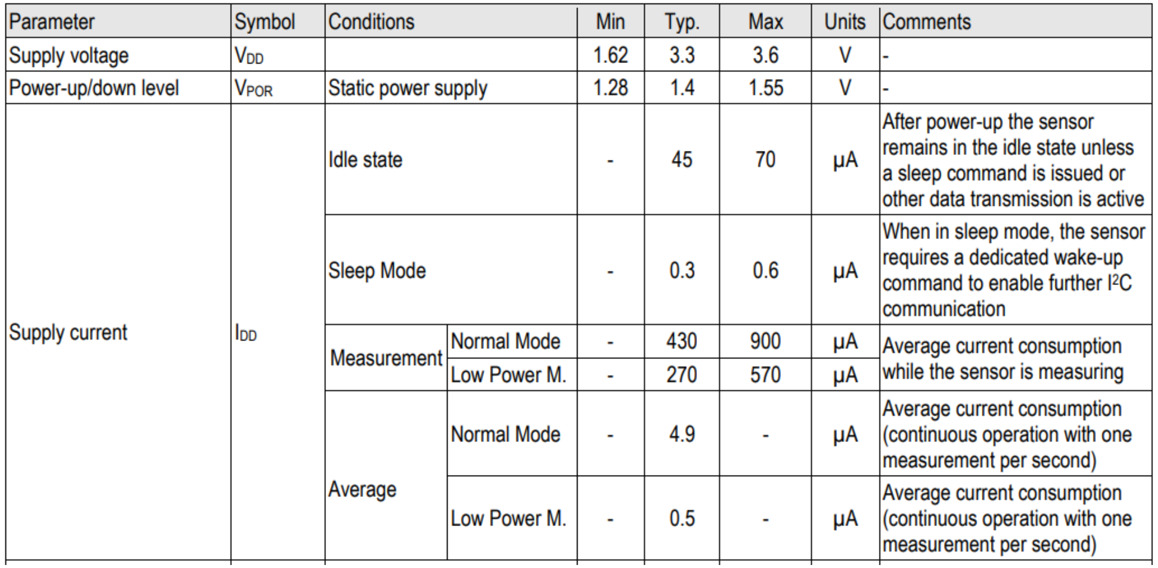
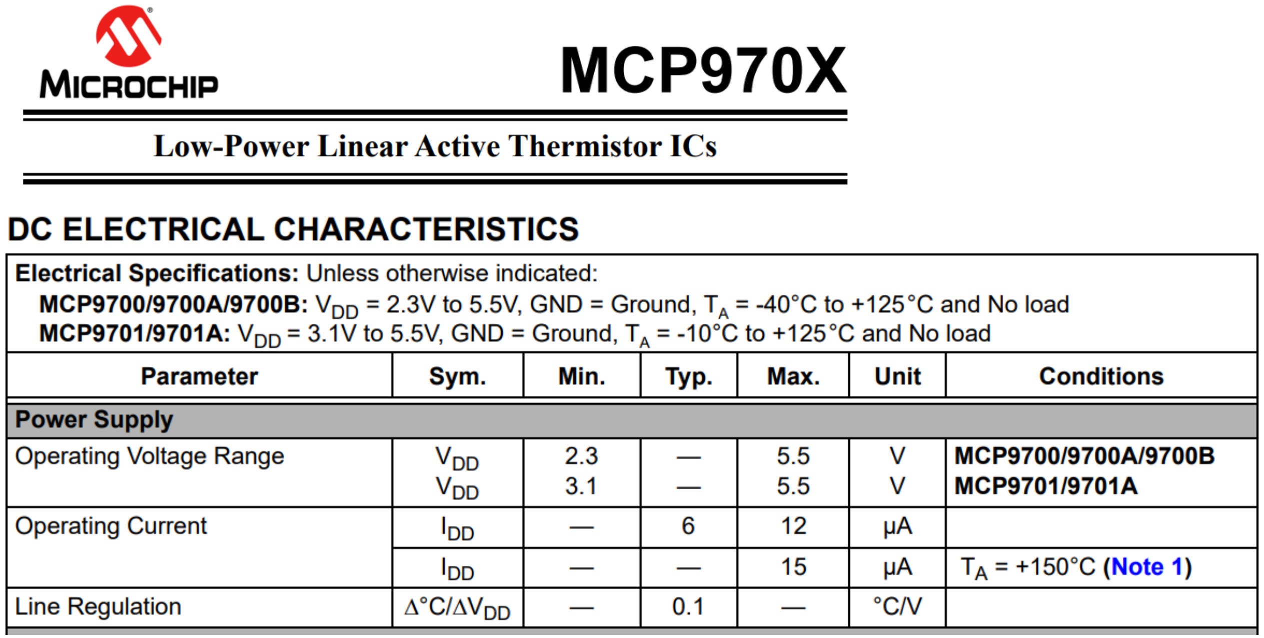


Parameter	Symbol	Conditions		Min	Typ.	Max	Units	Comments
Supply voltage	V_{DD}			1.62	3.3	3.6	V	-
Power-up/down level	V_{POR}	Static power supply		1.28	1.4	1.55	V	-
Supply current	I_{DD}	Idle state		-	45	70	μA	After power-up the sensor remains in the idle state unless a sleep command is issued or other data transmission is active
		Sleep Mode		-	0.3	0.6	μA	When in sleep mode, the sensor requires a dedicated wake-up command to enable further I^{2}C communication
		Measurement	Normal Mode	-	430	900	μA	Average current consumption while the sensor is measuring
			Low Power M.	-	270	570	μA	
		Average	Normal Mode	-	4.9	-	μA	Average current consumption (continuous operation with one measurement per second)
			Low Power M.	-	0.5	-	μA	Average current consumption (continuous operation with one measurement per second)



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} V_{DD}	2.3 3.1	— —	5.5 5.5	V V	**MCP9700/9700A/9700B** **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 variable 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

Packaging – example for SHTC3

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

1) Sensor has good access to environment

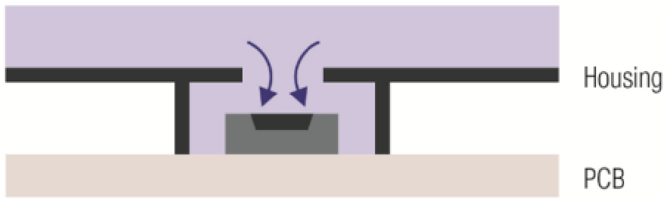


Figure 1: A large opening in the housing provides good access to environment and allows for air exchange.

2) Sensor is sealed from air entrapped in housing

Figure 2: Sealing of the sensor compartment towards the remaining housing minimizes the influence of entrapped air on the sensor.

3) Dead volume enclosed around sensor is small

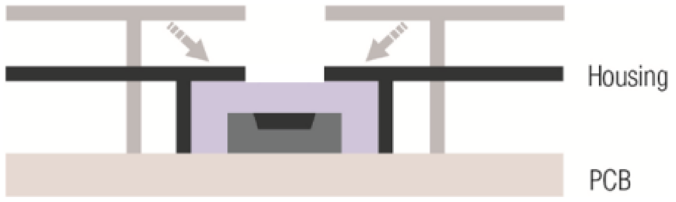


Figure 3: A small dead volume allows for rapid adaption to changes in the environment.

4) Sensor is decoupled from heat sources

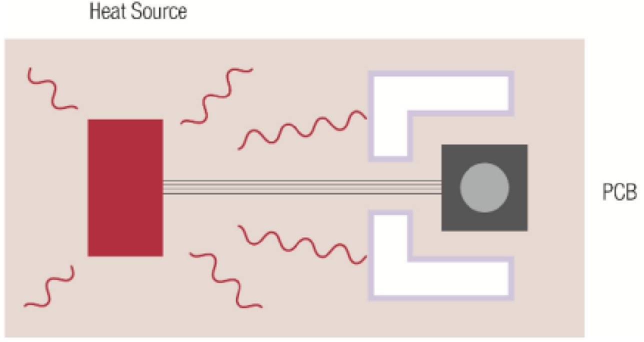


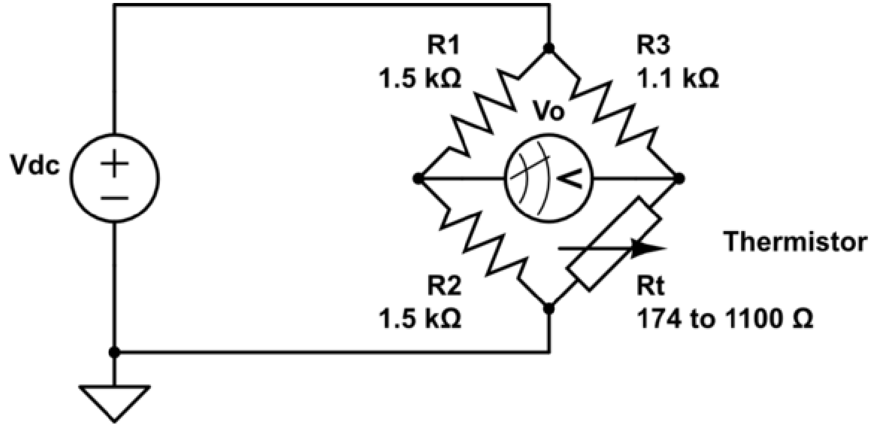
Figure 4: Decoupling of the sensor from heat sources in the PCB minimizes the influence of internal heating on the sensor.

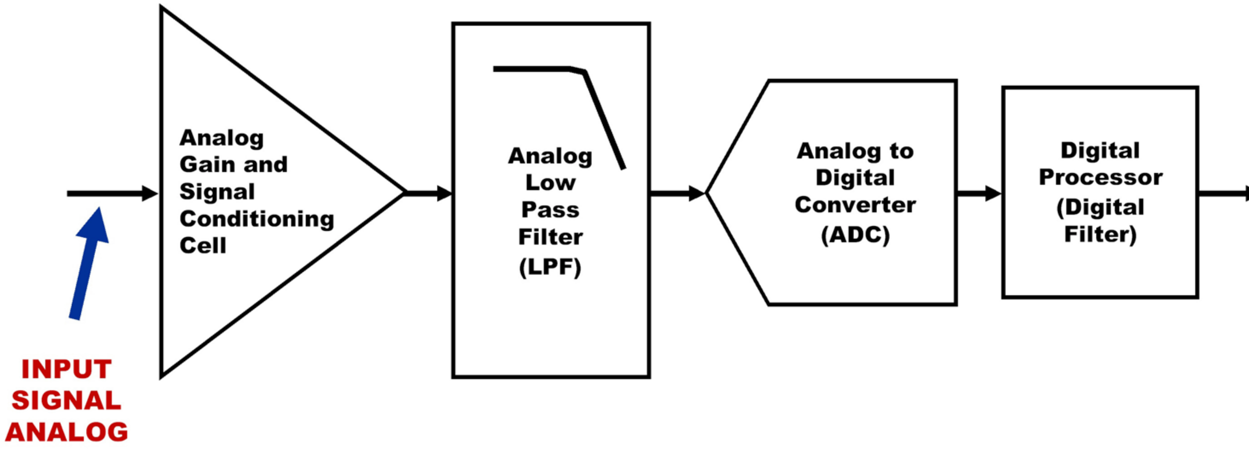
Signal conditioning and conversion

- 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]



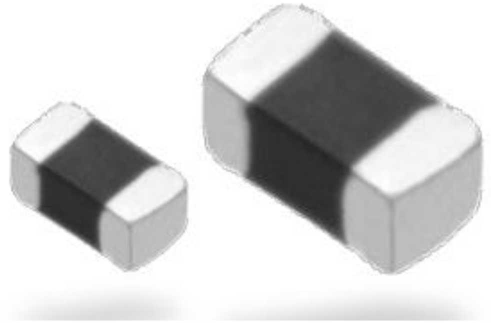


Signal conditioning and conversion

- A digital sensor will likely output via common protocol
    - I2C most common
        - Only requires 2 [extra] pins (SDA, SCL)
    - Limits on I2C
        - No more than 128 unique devices on network
        - Make sure no two devices have same address…
    - But you'll find other protocols around
        - 1-Wire, UART, SPI

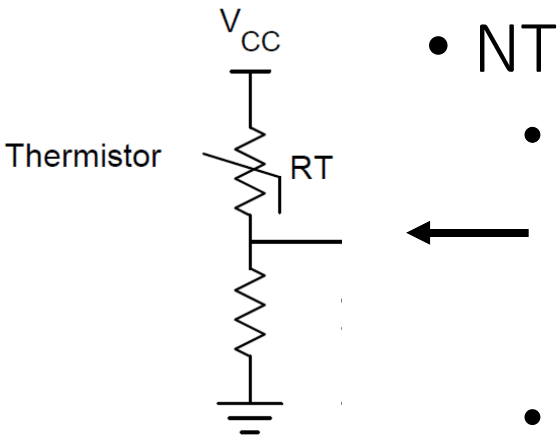
Example: compare two approaches

- 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

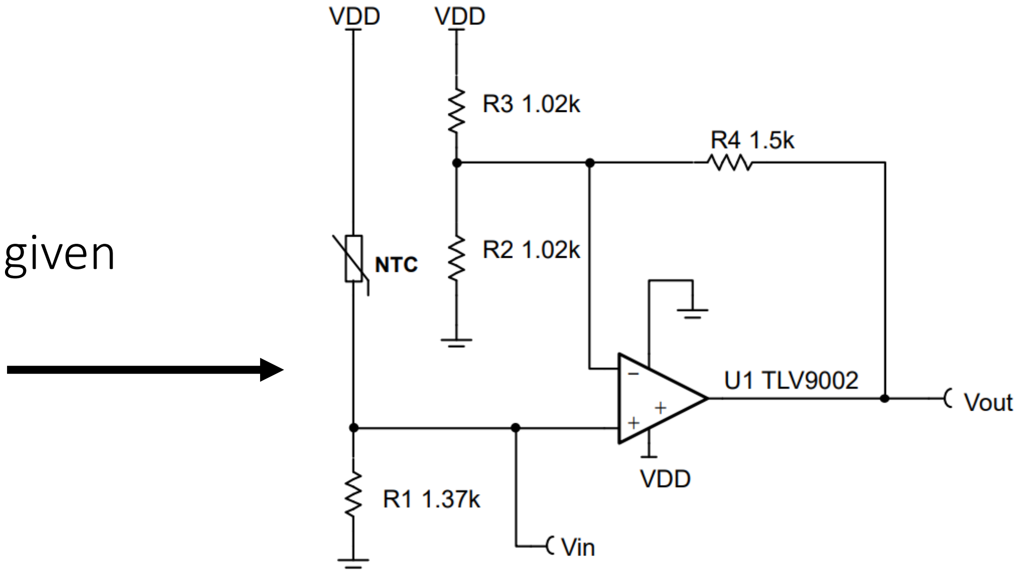


- Bandgap
  - UMW LM75BDP
  - Range -55 to 125 °C
  - I2C comms
  - Package 8-pin TSSOP [3 x 5 x 1.1 mm]
  - $0.345 @ 1k

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

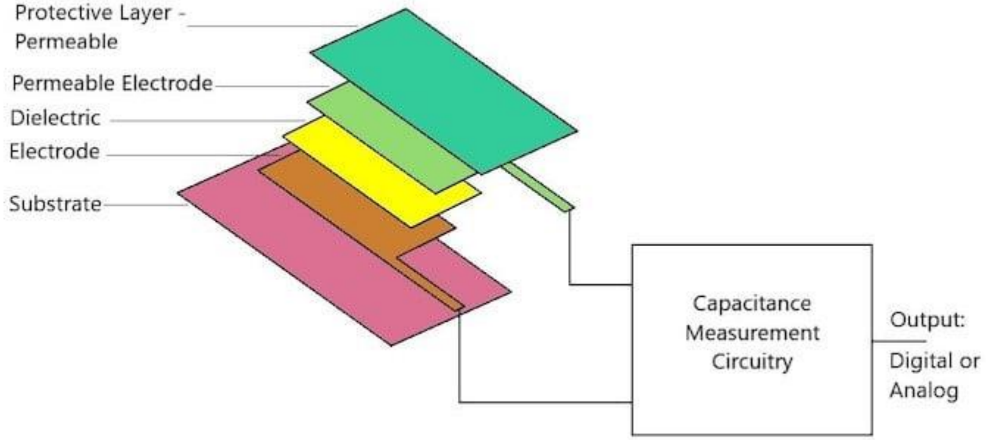
- Bandgap
    - Cost
        - $0.345 @ 1k
        - Assembly $0.0017 x 8 joints
        - Total: $0.359
    - Size
        - Package 8-pin TSSOP [3 x 5 x 1.1 mm]

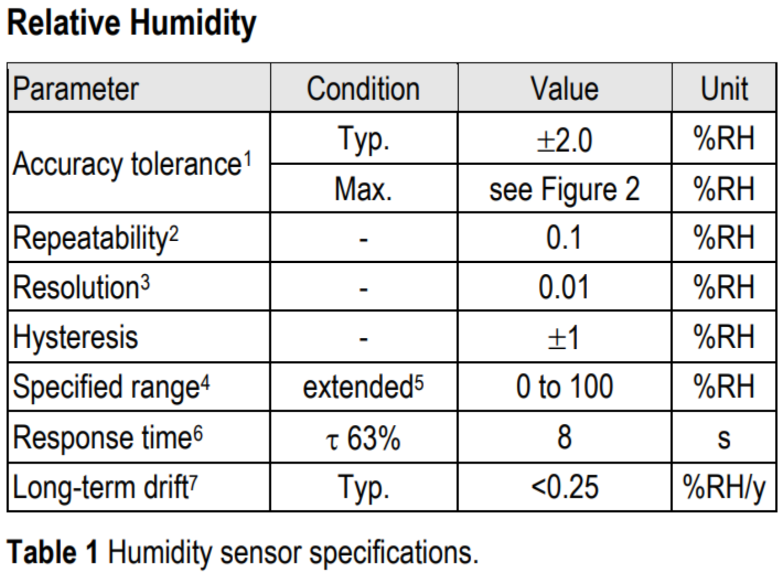
Compare two approaches

- 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

MILO sensors: humidity

- Capacitive humidity sensor (like in SHTC3)
- Parallel plate capacitor: $C = \frac{\epsilon A}{d}$
- Create capacitor with dielectric (ϵ) that absorbs water (*hygroscopic)*
  - $\epsilon_{water} \approx 80 \gg \epsilon_{dielectric}$
    ➔ $C \uparrow$ as humidity ↑
- And then we need a circuit that measures capacitance
- There are also *resistive* humidity sensors (and probably other mechanisms), but capacitive is most common





Relative Humidity

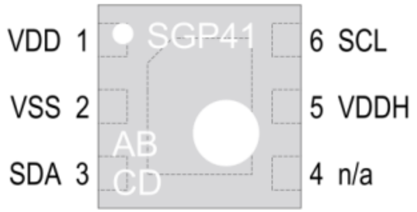
Parameter	Condition	Value	Unit
Accuracy tolerance[1]	Typ.	±2.0	%RH
	Max.	see Figure 2	%RH
Repeatability[2]	-	0.1	%RH
Resolution[3]	-	0.01	%RH
Hysteresis	-	±1	%RH
Specified range[4]	extended[5]	0 to 100	%RH
Response time[6]	τ 63%	8	s
Long-term drift[7]	Typ.	<0.25	%RH/y

Table 1 Humidity sensor specifications.

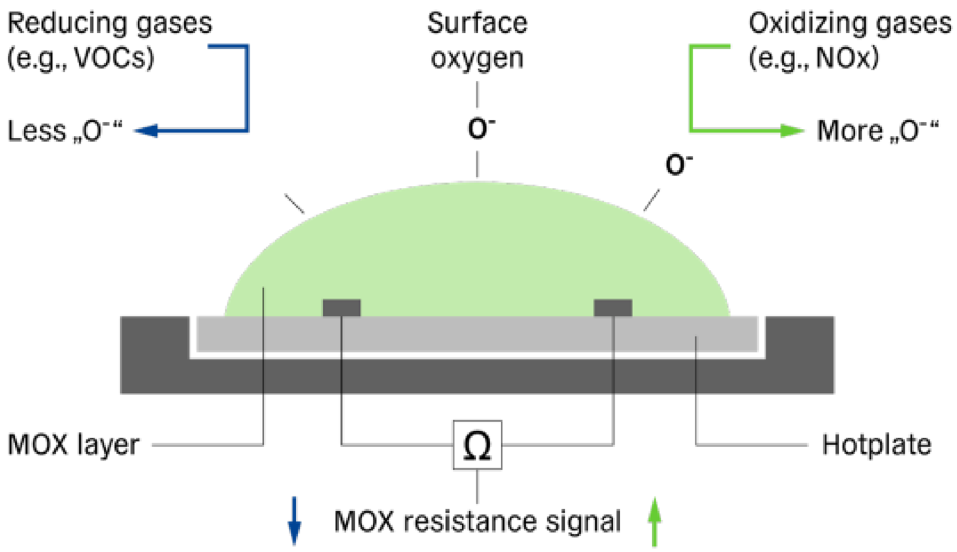
MILO sensors: VOC/NOx

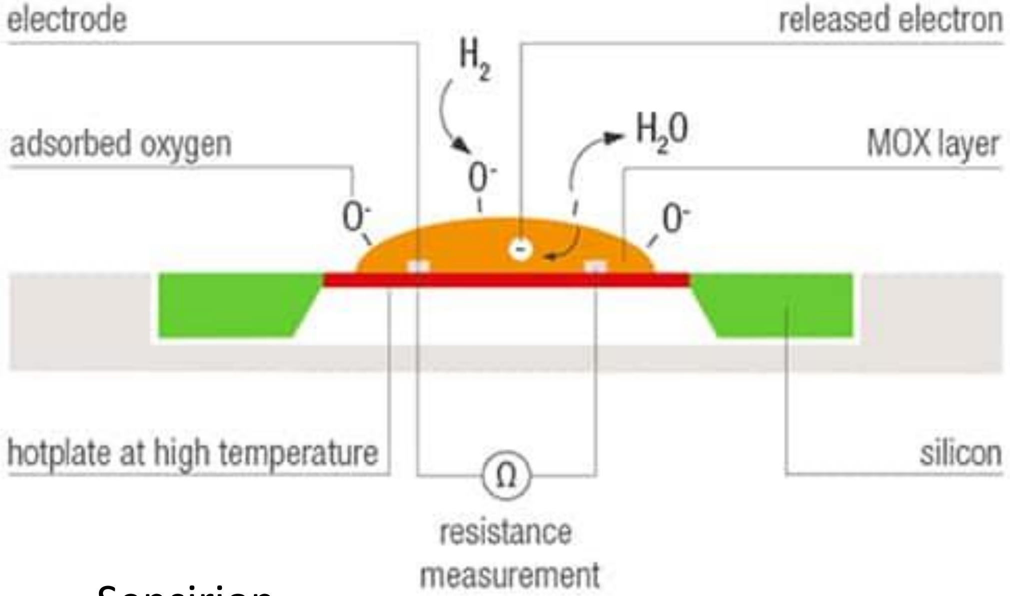
- Related to humidity sensor
- Resistive sensor (not capacitive)
- Uses metal oxide (MOX) layer
  - SnO_2 [most common], TiO_2, ZnO, In_2O_3
  - Reacts with target gas when heated to 150 °C – 400 °C
- Resistance
  - Increases due to oxidizers like NOx
  - Decreases due to reducing agents like VOCs

Pin	Name	Comments
1	VDD	Supply voltage
2	VSS	Ground
3	SDA	Serial data, bidirectional
4	n/a	Connect to ground (no electrical function)
5	VDDH	Supply voltage, hotplate
6	SCL	Serial clock, bidirectional



Sensirion SGP41

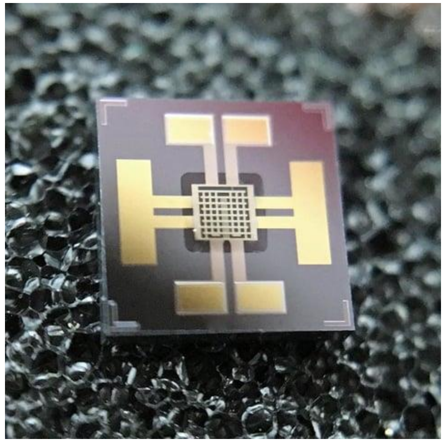




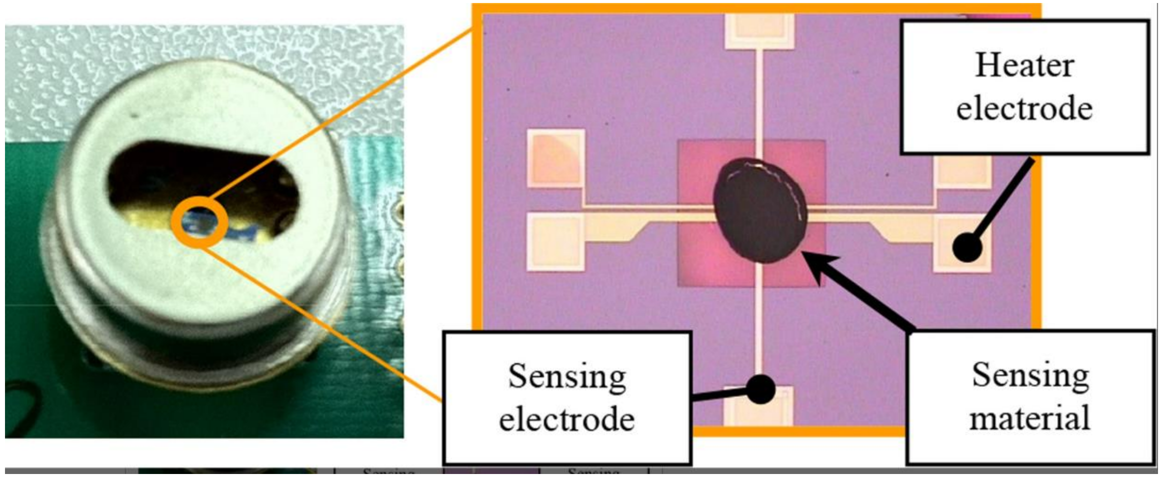
Sensirion

MILO sensors: VOC/NOx

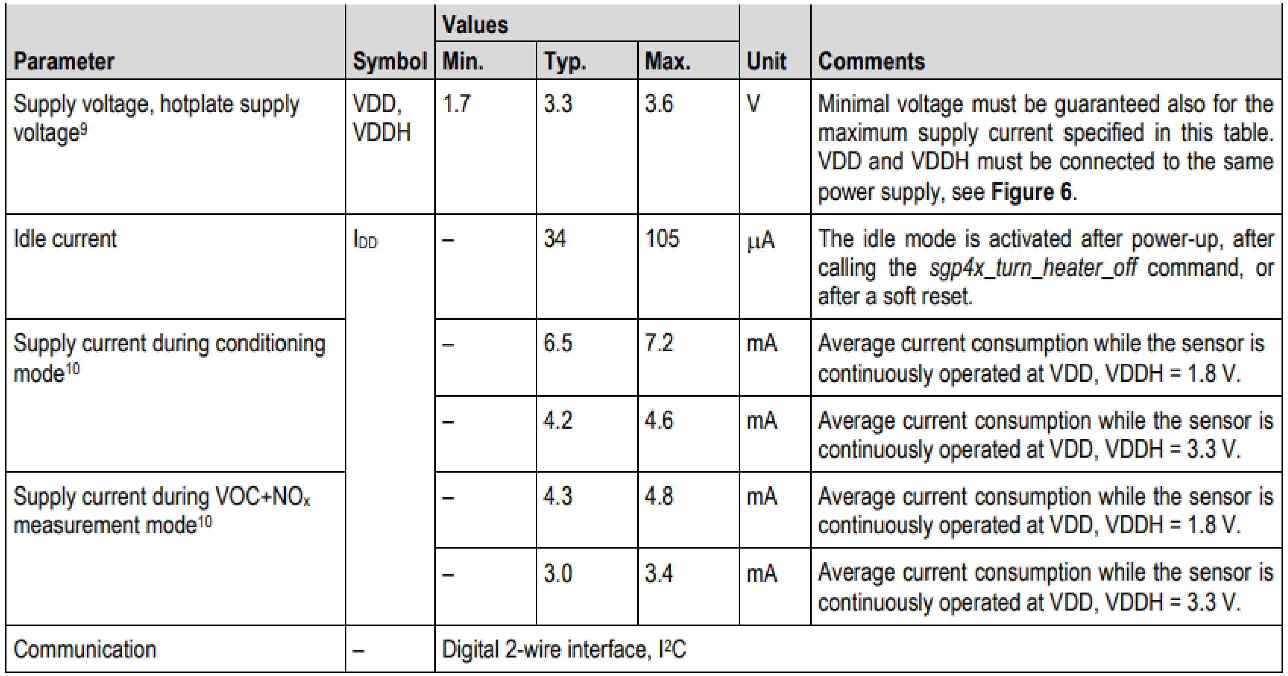
- How to heat to 100’s °C while conserving power?
  ➔ use an isolated “hotplate”
- These sensors will change resistance due to **any** reducing or oxidizing gases
  - They exhibit low **selectivity**
- SGP41 has **two** sensors (pixels), one more specific to VOC, one to NOx (details not provided!)
- SGP41 includes “conditioning” step which is likely heating the hotplate really hot to “reset”



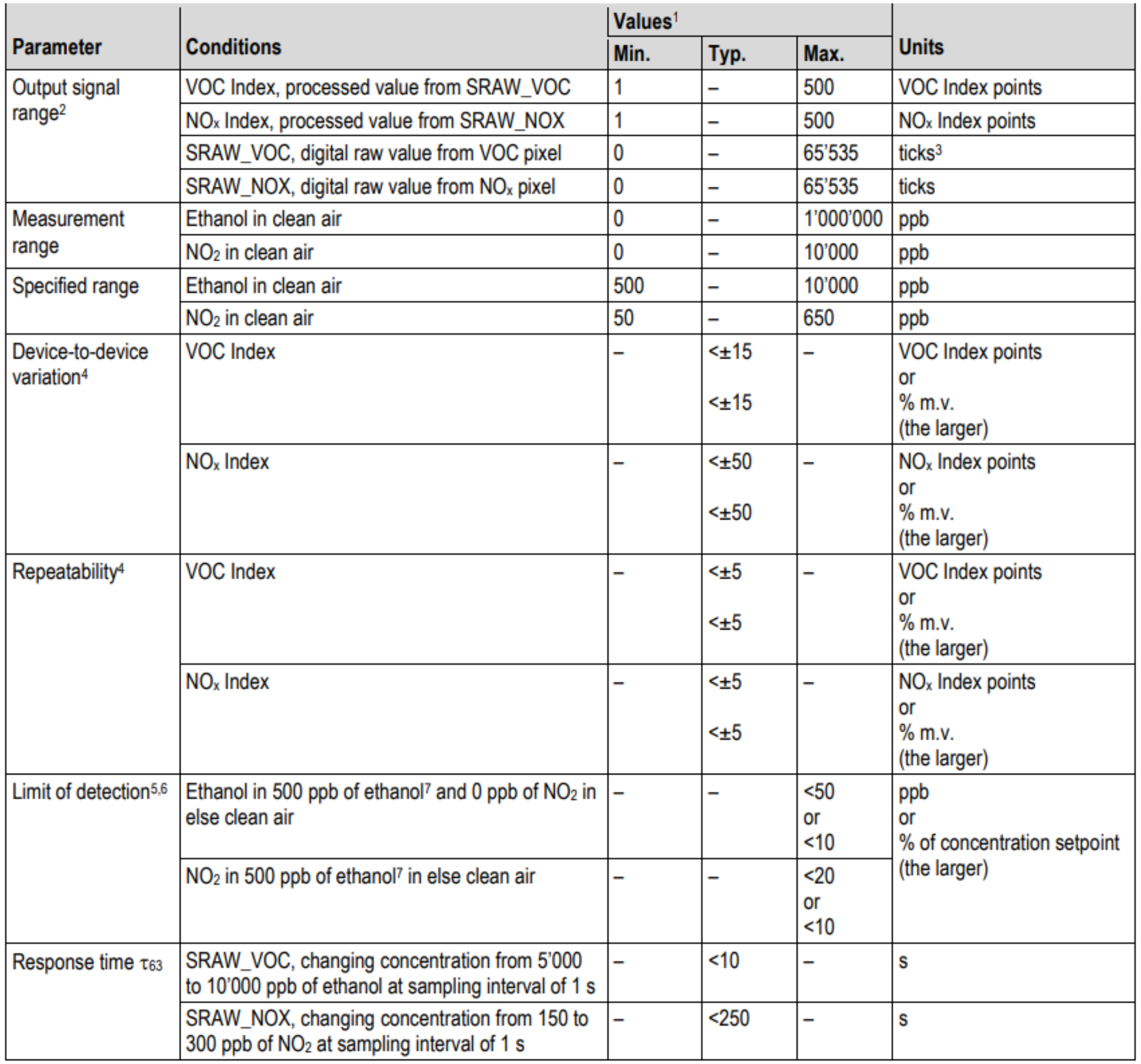
Micralyne



MILO sensors: SGP41



		Values				
Parameter	**Symbol**	**Min.**	**Typ.**	**Max.**	**Unit**	**Comments**
Supply voltage, hotplate supply voltage[9]	VDD, VDDH	1.7	3.3	3.6	V	Minimal voltage must be guaranteed also for the maximum supply current specified in this table. VDD and VDDH must be connected to the same power supply, see **Figure 6**.
Idle current	I_{DD}	–	34	105	µA	The idle mode is activated after power-up, after calling the *sgp4x_turn_heater_off* command, or after a soft reset.
Supply current during conditioning mode[10]		–	6.5	7.2	mA	Average current consumption while the sensor is continuously operated at VDD, VDDH = 1.8 V.
		–	4.2	4.6	mA	Average current consumption while the sensor is continuously operated at VDD, VDDH = 3.3 V.
Supply current during VOC+NO_x measurement mode[10]		–	4.3	4.8	mA	Average current consumption while the sensor is continuously operated at VDD, VDDH = 1.8 V.
		–	3.0	3.4	mA	Average current consumption while the sensor is continuously operated at VDD, VDDH = 3.3 V.
Communication	–	Digital 2-wire interface, I^2C				



		Values[1]			
Parameter	**Conditions**	**Min.**	**Typ.**	**Max.**	**Units**
Output signal range[2]	VOC Index, processed value from SRAW_VOC	1	–	500	VOC Index points
	NO_x Index, processed value from SRAW_NOX	1	–	500	NO_x Index points
	SRAW_VOC, digital raw value from VOC pixel	0	–	65'535	ticks[3]
	SRAW_NOX, digital raw value from NO_x pixel	0	–	65'535	ticks
Measurement range	Ethanol in clean air	0	–	1'000'000	ppb
	NO_2 in clean air	0	–	10'000	ppb
Specified range	Ethanol in clean air	500	–	10'000	ppb
	NO_2 in clean air	50	–	650	ppb
Device-to-device variation[4]	VOC Index	–	<±15 <±15	–	VOC Index points or % m.v. (the larger)
	NO_x Index	–	<±50 <±50	–	NO_x Index points or % m.v. (the larger)
Repeatability[4]	VOC Index	–	<±5 <±5	–	VOC Index points or % m.v. (the larger)
	NO_x Index	–	<±5 <±5	–	NO_x Index points or % m.v. (the larger)
Limit of detection[5,6]	Ethanol in 500 ppb of ethanol[7] and 0 ppb of NO_2 in else clean air	–	–	<50 or <10	ppb or % of concentration setpoint (the larger)
	NO_2 in 500 ppb of ethanol[7] in else clean air	–	–	<20 or <10	
Response time τ_{63}	SRAW_VOC, changing concentration from 5'000 to 10'000 ppb of ethanol at sampling interval of 1 s	–	<10	–	s
	SRAW_NOX, changing concentration from 150 to 300 ppb of NO_2 at sampling interval of 1 s	–	<250	–	s

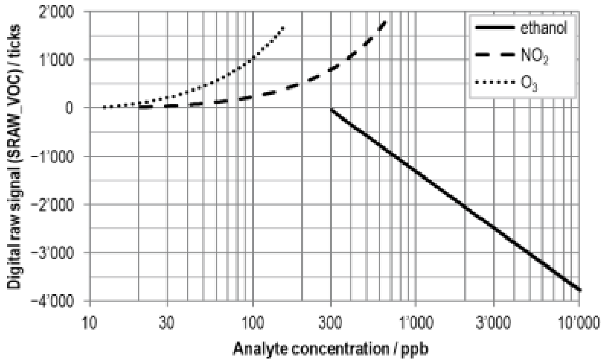


Figure 2 Typical sensor response by the VOC signal to ethanol, NO_2, and O_3 normalized to 500 ppb of H_2 + 500 ppb of ethanol. Data were recorded at 25 °C and 50 % RH and a power supply of VDD of 3.3 V.

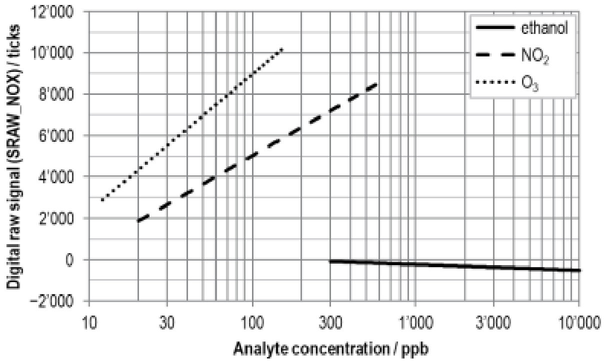
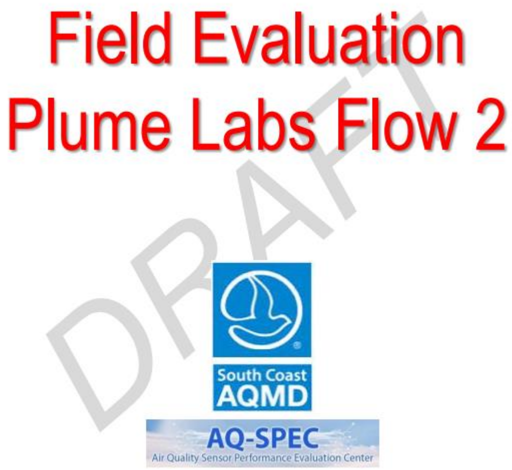


Figure 3 Typical sensor response by the NO_x signal to ethanol, NO_2, and O_3 normalized to 500 ppb of H_2 + 500 ppb of ethanol. Data were recorded at 25 °C and 50 % RH and a power supply of VDD of 3.3 V.

MILO sensors: SGP41

- There is no accuracy spec…these are not traceable, though you can calibrate them
- This is fairly notorious in consumer products…

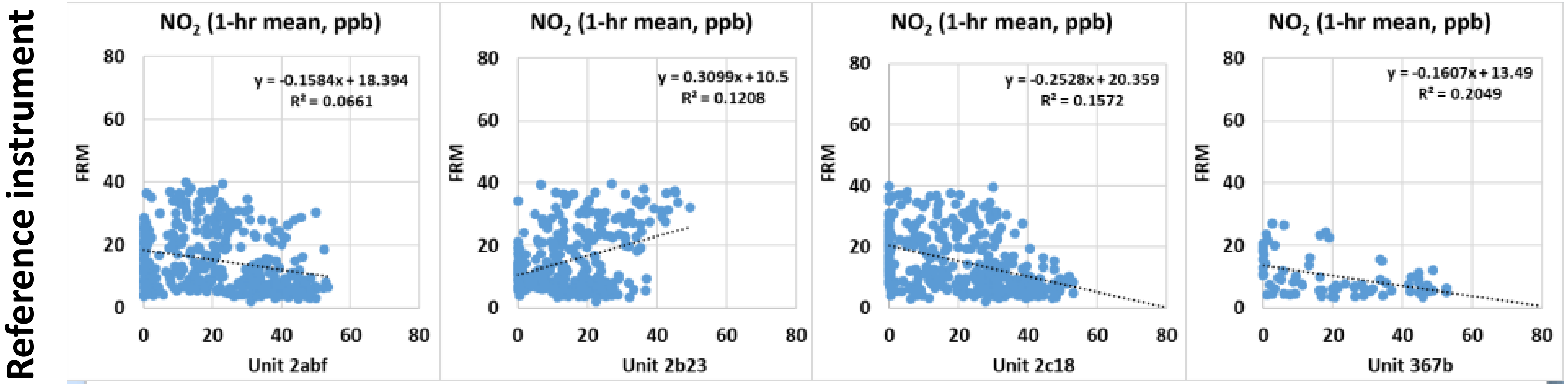
Plume Flow 2



Field Evaluation
Plume Labs Flow 2

DRAFT

South Coast AQMD
AQ-SPEC
Air Quality Sensor Performance Evaluation Center



Plume Flow 2