Technical Article

# Silicon Temperature Sensing with Precision—An Autobiographical Look at Measuring Temperature to ±0.1°C

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## Abstract

This article examines the accuracy of the latest generation of silicon temperature sensors. These sensors provide a digital output, require no linearization, are available in small package sizes, and are low power. Many can be programmed with alarm functions to alert systems of a potential malfunction.


## Introduction

The electronics industry is demanding ever more levels of accuracy, and temperature sensing is no exception. Many temperature sensing solutions exist, each with their benefits and drawbacks. Silicon temperature sensors, while being quite linear, have never offered the accuracy of other solutions. However, recent advances in silicon temperature sensing mean that high resolution and precision can now be achieved with a silicon solution.

## A New Freezer

It was March 2020 and the UK was just about to go into lockdown. The world was stocking up on food in case supermarkets closed, and the future looked uncertain. Then the freezer in the Bramble household stopped working. With the words from the Kenny Rogers song "Lucille" of "You picked a fine time to leave me …" echoing in my head, we went looking online for a new replacement.

A few days later, our new freezer arrived, complete with a digital temperature display on the front panel, as was the desire of Mrs. Bramble. The recommended setting was –18°C and, after one hour, the appliance was at the correct temperature and ready to accept food. I was skeptical of the accuracy of the temperature readout but did not care as long as it froze the food. One problem, though: an engineering mind is a restless mind and after days of the ostensibly sage digital readout unblinkingly staring at me, daring me with its confident pronouncements, I broke. I had to test the accuracy claims of this new addition to our kitchen.

## Temperature Sensors

There is a wide variety of temperature sensors used in industrial applications, each with advantages and drawbacks. Since many texts detail the operation of various temperature sensors, I don't repeat the details here, but offer a summary below.

### Thermocouples

Thermocouples provide a low cost, moderately accurate way to measure very high temperatures. They rely on a voltage being generated between two junctions, each made of dissimilar metals, held at different temperatures, as discovered by Thomas Seebeck in 1821. In the case of a K-type thermocouple (made of the alloys chromel and alumel), it outputs a voltage of about 41 µV/°C and can be used to measure temperatures in excess of 1000°C. Nevertheless, the Seebeck effect relies on a temperature difference between two junctions, so while the hot junction measures the temperature of interest, the cold junction must be kept at a known temperature. Ironically, another temperature sensor is required at the cold junction for the temperature difference to be measured and parts such as the AD8494 provide the perfect solution to do this. Since thermocouples are physically small, they have low thermal mass and give a fast response to changes in temperature.

### RTDs

To measure moderate temperatures (<500°C), resistive temperature detectors (RTDs) are widely used by industry. These devices consist of a metal element that exhibits a positive change in resistance with temperature, most commonly platinum (Pt). Indeed, the PT100 sensor is the most widely used RTD in industry and it gets its name from being made from platinum and having a resistance of 100 Ω at 0°C. While these devices do not measure to the high temperature of a thermocouple, they are highly linear and their reading is repeatable. A PT100 needs a precise driving current, which creates an accurate voltage drop across the sensor that is proportional to temperature. The resistance of the connecting wires of the PT100 creates an error in the resistance measurement of the sensor, so Kelvin sensing is typical and results in 3- or 4-wire sensors.

### Thermistors

If a low cost solution is required and the temperature range is low, a thermistor often suffices. These devices are highly nonlinear, with a characteristic based on the Steinhart Hart equation, yielding resistance reduction with increasing temperature. The benefit of a thermistor is that the change in resistance is large with small changes in temperature, so a high level of accuracy can be achieved despite its nonlinearity. Thermistors also feature a fast thermal response. Individual thermistor nonlinearities are well defined, so they can be calibrated out, using components such as the LTC2986.

## Diodes, Diodes Everywhere, but Not a ($V_{be}$) Drop to Sink ...

Finally, to test the veracity of the new member of the household, I opted for a silicon temperature sensor. They work straight out of the box, need no cold junction temperature compensation or linearization, are available with analog and digital outputs, and come precalibrated. Until recently, though, they have only offered moderate accuracy. While good enough for indicating the state of health of electronic equipment, they have never been accurate enough to measure, say, body temperature, usually requiring ±0.1°C accuracy (according to the ASTM E1112 standard). That has changed with the recent release of the ADT7422 and ADT7320 silicon temperature sensors, which can measure to resolutions of ±0.1°C and ±0.2°C, respectively.

A silicon temperature sensor exploits the temperature dependency of a transistor's $V_{be}$, as given by the Ebers-Moll equation, approximated by:

$$I_c = I_s \left[ exp\left(\frac{qV_{be}}{kT}\right) - 1 \right] \quad (1)$$

where $I_c$ is the collector current, $I_s$ is the reverse saturation current of the transistor, q is the charge on an electron ($1.602 \times 10^{-19}$ coulombs), k is Boltzmann's constant ($1.38 \times 10^{-23}$), and T is absolute temperature.

The expression for collector current in Equation 1 also holds true for the current in a diode, so why does every application circuit use a transistor and not a diode? In reality, the current in a diode also includes a recombination current resulting from the electrons recombining with holes as they pass through the depletion region of the pn junction and this presents a nonlinearity of the diode's current with $V_{be}$ and temperature. This current also appears in a bipolar transistor, but flows into the base of the transistor so it does not appear in the collector current, hence the nonlinearity is much less.

Rearranging the above gives

$$V_{be} = \frac{kT}{q} ln \left[ \frac{I_c}{I_s} + 1 \right] \quad (2)$$

$I_s$ is small compared with $I_c$, so we can ignore the 1 term in Equation 2. We can now see that $V_{be}$ changes linearly according to a logarithmic change in $I_c$. We can also see that if $I_c$ and $I_s$ are constant, then $V_{be}$ changes linearly with temperature, since k and q are also constant. It is an easy task to force a constant collector current into a transistor and measure how the $V_{be}$ changes with temperature.

$I_s$ is related to the geometry of the transistor and has a strong dependency on temperature. Like many silicon devices, its value doubles with every 10°C rise in temperature. While the effect of this change in current is reduced by the In function, we still have the problem that the absolute value of $V_{be}$ changes from transistor to transistor and thus calibration is needed. So practical silicon temperature sensors use two identical transistors and force a collector current of 1 $I_c$ into one and 10 $I_c$ into the other. Identical transistors and ratiometrically accurate currents are easy to fabricate in an integrated circuit, which is why most silicon sensors use this architecture. The logarithmic change in current causes a linear change in $V_{be}$ and the difference in the $V_{be}$'s is then measured.

From Equation 2, for two transistors held at the same temperature, the difference between their $V_{be}$'s is given by

$$\Delta V_{be} = \frac{kT}{q} ln\left[10\frac{I_c}{I_s}\right] - \frac{kT}{q} ln\left[\frac{I_c}{I_s}\right]$$

$$\Delta V_{be} = \frac{kT}{q} \left\{ ln\left[10\frac{I_c}{I_s}\right] - ln\left[\frac{I_c}{I_s}\right] \right\}$$

since

$$lnA - lnB = ln\left[\frac{A}{B}\right]$$

We can see that

$$\Delta V_{be} = \frac{kT}{q}\{ln10\}$$

By forcing different currents through each transistor and measuring the difference in $V_{be}$, we have removed the nonlinear Is term, the effect of different absolute $V_{be}$'s, and all other nonlinear effects associated with the transistor's geometry. Since k, q, and ln10 are all constant, the change in $V_{be}$ is proportional to absolute temperature (PTAT). For a 10× difference in currents, the difference in the two $V_{be}$'s changes linearly with temperature at approximately 198 µV/°C. A simplified circuit to achieve this is shown in Figure 1.

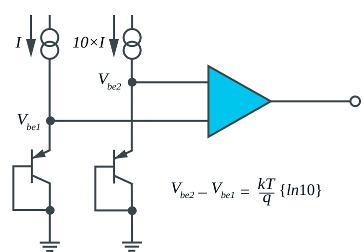


*Figure 1. A basic circuit for measuring temperature.*

The currents in Figure 1 must be carefully chosen. If the current is too high, significant self-heating and voltage drops across the internal resistances inside the transistor corrupt the result. If the current is too low, leakage currents inside the transistor add significant errors.

It should also be noted that the previous equations relate to the collector current of the transistor, whereas Figure 1 shows a constant emitter current being injected into the transistor. The transistors can be designed such that the collector to emitter current ratio is well established (and close to unity), so collector current is proportional to the emitter current.

This is only the start of the story. To get ±0.1°C accuracy with a silicon temperature sensor, extensive characterization and trimming needs to be done.

## Is It a Bird? Is It a Plane?

No, it's a super thermometer. Yes, they do exist. The uncalibrated silicon temperature sensor needs to be placed into a bath filled with silicone oil and heated to a precise temperature, measured with a super thermometer. These devices can measure to an accuracy of better than five decimal places. Fuses inside the sensor are blown to tweak the gain of the temperature sensor and thus linearize its output using the equation y = mx + C. The silicone oil provides a very uniform temperature so many devices can be calibrated in a single cycle.

The ADT7422 has an accuracy of ±0.1°C over a temperature range of 25°C to 50°C. This temperature range is centered around the typical human body temperature of 38°C, making the ADT7422 ideal for accurate vital signs monitoring. For industrial applications, the ADT7320 is trimmed so it has an accuracy of ±0.2°C, but over a wider temperature range of –10°C to +85°C.

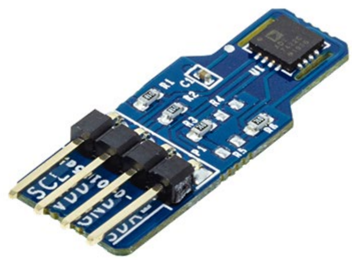


*Figure 2. The ADT7422 mounted on a 0.8 mm thick PCB.*

The calibration of the silicon temperature sensor is not the only problem, however. As with extremely precise voltage references, stresses on the die can corrupt the accuracy of the sensor and the thermal expansion of the PCB, lead frame, plastic molding, and exposed pads all need to be accounted for. The soldering process also adds its own problems. The solder reflow process increases the temperature of a part to 260°C, causing the plastic packaging to soften and the die's lead frame to distort, such that when the part cools down and the plastic hardens, a mechanical stress is locked into the die. Analog Devices' engineers expended many months of delicate experimentation to discover that a PCB thickness of 0.8 mm was the sweet spot and a ±0.1°C accuracy could be achieved, even after soldering.

## So How Cold Are My Sausages, Exactly?

I wired the ADT7320 to a microcontroller and an LCD display and wrote a few hundred lines of C code to initialize the sensor and extract the data—the part can be easily initialized by writing 32 consecutive 1s on the DIN pin. The configuration register was set to make the ADT7320 convert continuously with 16-bit accuracy. Once data is read from the ADT7320, a delay of at least 240 ms is needed to allow the next conversion to occur. To facilitate the use of very low end microcontrollers, the SPI was written manually. The ADT7320 was left inside the freezer for about 30 minutes to see what the temperature our new purchase settled at. Figure 3 shows the freezer temperature to be –18.83°C.


*Figure 3. The temperature of the freezer at –18.83°C.*

I considered this to be impressively accurate given that food does not need to be stored to this level of temperature precision. I then measured the temperature in my office on a summer's day in the UK. It was 22.87°C, as shown in Figure 4.

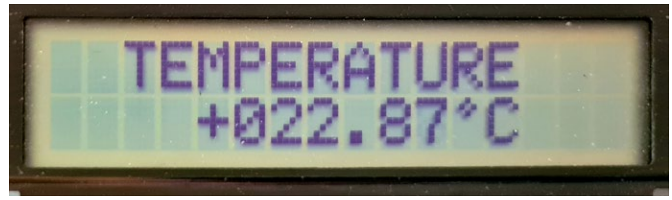


*Figure 4. The temperature of my office at 22.87°C.*

## Conclusion

Silicon temperature sensors have come a long way, becoming extremely precise to enable a high level of accuracy for vital signs monitoring. While the technology inside them is based on well-founded principles, the trimming required to get them to sub-degree accuracy levels requires significant effort. Even if this level of accuracy is achieved, mechanical stresses and soldering can easily erase gains achieved from hours of calibration.

The ADT7320 and ADT7422 represent the pinnacle of years of characterization to achieve sub-degree level precision even after being soldered onto the PCB.

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## About the Author

Simon Bramble graduated from Brunel University in London in 1991 with a degree in electrical engineering and electronics, specializing in analog electronics and power. He has spent his career in analog electronics and worked at Linear Technology (now part of Analog Devices). He can be reached at simon.bramble@analog.com.