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Temperature Sensors Are Hot... In Circuit Design

Thermocouple, RTD, thermistor, and IC temperature sensors are vital to the performance of every electronic circuit. Before you start your next design, learn more about how they work and where they will be most effective.

As IC device dimensions shrink and heat management and dissipation become tougher-than-ever challenges, one simply cannot overestimate the importance of sensing IC temperature. In particular, temperature sensing has become ubiquitous, playing key roles in process-control, environmental, test-and-measurement, and communications applications. In addition, its use in electronic circuit design continues to expand throughout large-volume automotive, medical, and consumer applications.

Thermocouples, resistance temperature detectors (RTDs), and thermistors are the most common temperature sensors for electronic circuits *(Fig. 1)*. Mostly used in industrial measurement and control, they produce analog signal outputs that must be digitized before they're placed into computer circuits.

Semiconductor IC sensors, another common technology, dominate pc boards. They're available with analog as well as digital outputs. Besides their relatively smaller physical size, they're much more amenable for use in digital electronic circuitry, since they can be fabricated on the same piece of silicon where other electronic functions reside *(see "Typical Characteristics Of Contact Temperature Sensors" at* www.electronicdesign.com, *Drill Deeper 18912)*.

"Choosing the right sensor type and understanding its thermodynamic properties as they relate to its mounting and use are the two critical issues that determine the success or failure of the temperature sensor's application," says Jim Williams, senior scientist at Linear Technology Corp.

"Packaging and mounting of a sensor are crucial, no matter what type of sensor is used. The most common problem designers encounter is properly mounting the sensor to the measurand for optimal thermal performance," he says.

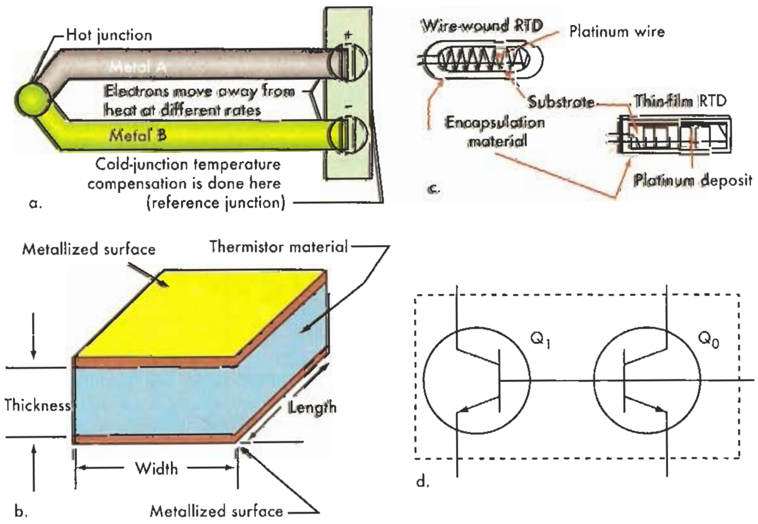
THERMOCOUPLES

Thermocouples are the most commonly used devices for temperature measurement. They operate via the Seebeck Effect in which two dissimilar metals, welded or joined together at one end, produce a voltage output at the two open ends of the metals for a given temperature. That temperature is measured at the point where the two metals are joined. A thermocouple's output voltage increases as the temperature rises.

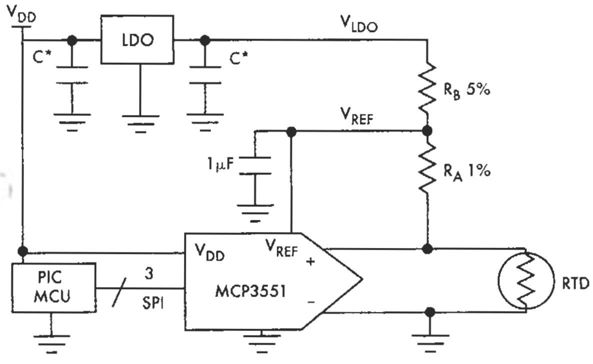
Widely used in industrial applications, their ruggedness, accuracy, and very wide temperature range are key attributes. "We still see a lot of thermocouples in heating, ventilation, and air-conditioning (HVAC) applications, an area where semiconductor IC temperature sensors are trying to compete," says Susan Pratt, an applications engineer with Analog Devices.

Thermocouples are flexible—they can be constructed in just about any manner and from many materials to suit any application. They feature many advantages over other temperature sensor types.

For example, they're very rugged, inexpensive, and highly responsive. They don't require any excitation source. And best of all, they feature the broadest temperature range of all contact-type sensors.



1. These are the four most popular types of contact temperature sensors. A thermocouple (a) uses two different metal wires, each of which moves a different quantity of electrons when heated to the same temperature. The difference between electron quantities is measured as a voltage. A wire-wound or thin-film thermistor (b) consists of resistive material that increases (positive-temperature types) or decreases (negative-temperature types) in resistance in response to increases or decreases in heat. A resistance-temperature detector, or RTD (c), acts as one leg of a Wheatstone bridge circuit in which a small amount of current produces a resistance change proportional to temperature change. Semiconductor IC temperature sensors (d) are based on silicon bandgaps in which the forward base-emitter voltage (V_{BE}) of a diode is temperature-dependent.



2. An RTD can be used with a high-resolution, delta-sigma analog-to-digital converter (ADC) like the Microchip Technology MCP3551 and two resistors to measure RTD resistance ratiometrically. Accuracy of ±0.1°C and resolution of ±0.01°C can be achieved across a temperate range of –200°C to 800°C with a single-point calibration.

Type J or iron-constantan (constantan is alloy of copper and nickel) thermocouples are the most widely used devices for thermocouple calibration. Other popular versions include types B, E, K, R, S, T, and N. The Instrument Society of America (ISA) compiled the standard ISA thermocouple calibration table.

However, thermocouples are "tip" sensitive, measuring temperature at a very small point of reference. Their outputs are also quite nonlinear, which means they require external linearization in the form of cold-junction compensation. Cold-junction compensation is crucial if accurate temperature measurements are needed.

Also, the thermocouple output voltages are quite low, in the tens to hundreds of microvolts, requiring careful wiring layout techniques to minimize noise and drift. One way to reduce noise is to place resistors in series with the thermocouple and a capacitor across the thermocouple leads to form a filter.

One common mistake with thermocouples is to use copper from the thermocouple connection to the measurement device. This introduces another thermocouple in the measurement process.

RTDS

For the most accuracy and stability, try an RTD. Most RTDs use platinum (in wire or film form) wound on a small ceramic tube, though some are made from nickel, a nickel/iron alloy, or copper.

Also, RTDs are very stable and offer fairly good linear outputs. A platinum RTD can be thermally shocked from boiling water to liquid nitrogen (–195°C) 50 times with a resulting error of less than 0.02°C. Typical RTD stabilities are on the order of ±0.5°C/year. But they do require some linearization circuitry, typically via a lookup table in a microcontroller, to correct for some nonlinearities.

RTDs are more expensive than thermistors and thermocouples, though. They require a current source to operate (a current that causes self-heating). And, they feature a low resistance-value change to temperature change, as an RTD might change by just 0.1 Ω in response to a 1°C change in temperature.

Because RTDs are self-heating devices, measurement inaccuracies can occur if the RTD self-heats under the test current. In general, currents should be kept to 1 mA or less. Self-heating errors can also be reduced by using an extremely low bias current or a 10% duty-cycle current instead of a constant bias. Too low a bias, however, introduces some noise that can affect the RTD's measurements. Nonetheless, designers can minimize this noise by using differential, ungrounded, and shielded RTDs.

Watch out for RTD connection leads, which may cause errors due to the resistance of the connecting wires, and the change in that resistance, especially when using very long leads. Utilizing three- or four-wire connections can minimize these problems.

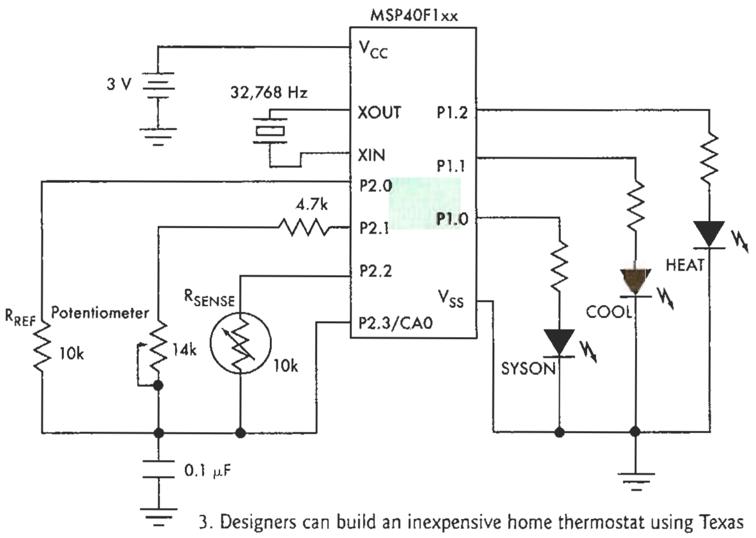
Furthermore, avoid going with an RTD beyond its specified temperature range, which is very broad compared to thermistors and IC sensors. Exceeding the specified operating temperature range may not only provide erroneous readings, it could also damage the RTD element.

Yet because of their high degree of stability, RTDs are very useful as key instrumentation elements for high-performance thermal-management applications. They can be used, for example, with a high-resolution, delta-sigma, analog-to-digital converter (ADC) like Microchip Technology's MCP3551 low-power, 22-bit unit and two resistors to measure RTD resistance ratiometrically *(Fig. 2)*. This device can achieve ±0.1°C accuracy and ±0.01°C resolution from –200°C to 800°C with a single-point calibration.

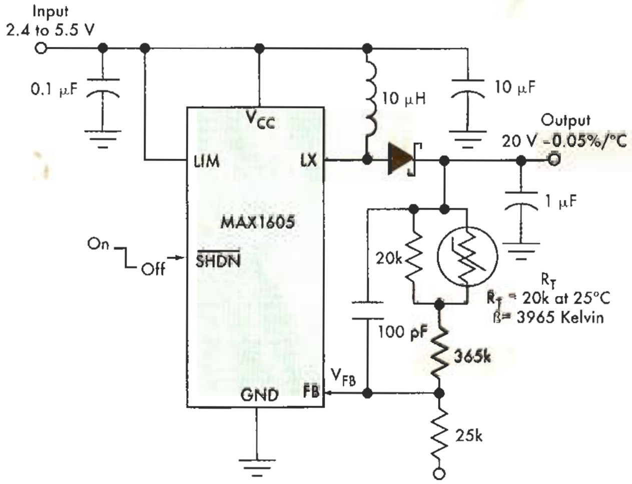
THERMISTORS

Generally, thermistors are metal-oxide ceramic semiconductor sensing elements. Like semiconductor IC temperature sensors, these relatively low-cost devices come in a small form factor. Thermistors are ideal for temperature measurements that require high accuracy as well as sensitivity over a narrow range of temperatures, typically less than 300°C.

Because they can't endure the high temperatures or stresses that thermocouples can handle, they're encased in a protective enclosure. Thermistors that can withstand the rigors of temperatures up to 1000°C are available, though they trade off this ruggedness for a slower response time. The type of protective enclosure employed also contributes to a slower response time.



3. Designers can build an inexpensive home thermostat using Texas Instruments' MSP430F111A 16-bit microcontroller and a thermistor.



4. Designers can use an NTC thermistor with the Maxim MAX1605 boost converter for resistance-mode tracking of a power supply's output.

Thermistors can be found in a wide range of applications, including use as over-temperature shutdown devices in electronic circuits. They're also integrated into a variety of systems for clinical research, such as the measurement of the flow, thermal conductivity, and diffusivity of biomaterials and the detection of liquids. With the most common type of thermistor, the negative temperature-coefficient (NTC) type, an increase in temperature results in a decrease in the thermistor's resistance.

Due to their low cost as well as other low-cost devices like microcontrollers, thermistors can be used cost-effectively in home temperature-control applications. For example, the low-cost, low-power Texas Instruments MSP430F111A 16-bit microcontroller, which includes a comparator and a timer, could be used with a thermistor to create a low-cost temp-control device.

"The MSP430F has an internal bandgap reference," says Kevin Belnap, Texas Instruments' MSP430 product manager. The device is used with a BC Components 2322-640-54103 NTC thermistor to implement a thermostat's function using slope analog-to-digital conversion *(Fig. 3)*. It dissipates a mere 160 µA at 2.2 V and 1 MHz in the active mode, 0.7 µA in the standby mode, and just 0.1 µA in the off (RAM retention) mode.

Power supplies are another important application. Simple linearization schemes make it easy to use highly nonlinear thermistors for voltage-regulator designs with temperature-dependent outputs *(Fig. 4)*. Having a temperature-dependent, power-supply output is advantageous for supplies that power LCD bias voltages. These displays feature contrast levels that vary with ambient temperature. Using a temperature-dependent bias voltage automatically cancels the LCD's temperature effects and maintains constant display contrast levels over a wide temperature range.

To improve a thermistor's poor linearity, some companies offer units with two or even three thermistors combined in a single package. These sensor networks feature highly linear response curves over a relatively wide temperature range. The tradeoff in this approach (versus a single-packaged thermistor) is an order of magnitude drop in sensitivity in temperature sensing.

Besides ordinary active-resistance passive thermistors, low-power linear active themistors like the MCP9700 and MCP9701, which operate from 2.3 to 5.5 V or 3.1 to 5.5 V at 6 µA, are available from Microchip. These analog-voltage-output sensors don't require the additional signal-conditioning circuitry required by an ordinary thermistor, and they are competitive in performance and price with regular thermistors. Linear themistors can have their outputs directly connected to the ADC input of a microcontroller.

IC SENSORS

Semiconductor IC temperature sensors have come a long way since their early days as simple devices in dual-inline packages that measured their own package temperature and generated a proportional output voltage signal. Driven by automotive, consumer, computer, medical, and many other applications, they can be found embedded in just about every printed-circuit board (PCB) and chip.

Of all contact sensor types, IC temperature sensors are the most numerous. One of their biggest assets is that they offer the best linearity in output. Since they can be made on the same chip and process as any other electronic chip function, they're easily amenable to high levels of integration.

Furthermore, they require no linearization or cold-junction compensation. They provide many useful output levels, such as logic, pulse, digital, and analog. Their good noise immunity comes from their higher output-level signals. They're readily interfacable with any other digital or analog circuit. Also, they're linear and feature a wide enough operating-temperature range to satisfy a large range of electronic circuit designs.

This extended range has opened up an entire set of new applications, such as remote sensing, airflow sensing, actuating fans, and buzzers. Modern IC temperature sensors also offer direct compatibility with many popular computer buses, including the single-wire pulse-width-modulation (PWM) bus, the two-wire I^2C bus, the three- and four-wire serial peripheral interface (SPI) bus, and the two-wire SMBus, to interface with microcontrollers and other digital systems.

Texas Instruments' TMP421 ±1°C remote and local temperature sensor monitor in an SOT23-8 case exemplifies the trend toward remote temperature measurements. It features a built-in local temperature sensor consisting of low-cost npn and pnp diode-connected transistors or diodes that are an integral part of FPGAs, microprocessors, and microcontrollers.

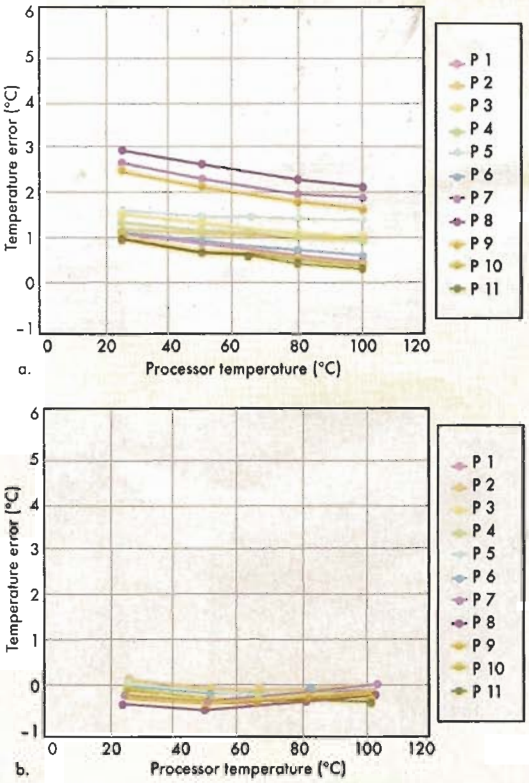
Many high-end CPUs and DSPs have specific interfaces to IC temperatures sensors to keep tabs on a processor's temperature—a critical task at gigahertz clock rates. The flexibility of an IC sensor lets users program threshold levels, hysteresis, and shutdowns. It also allows operation with digital signals coming from an ADC.

"As CPU designs approach 45-nm line widths, accurately measuring a processor's temperature becomes more challenging," says Tadija Janjic, business unit manager for TI. "A designer must know what he or she is measuring and pay attention to the sensor's package. The bigger the package, the larger the thermal constraints."

National Semiconductor uses its TruTherm technology in temperature sensors for monitoring ICs made on 90-nm processes and below. The company measured the temperature of 11 different 65-nm processors from 20°C to 100°C. Temperature errors (measurement variations) were less than 0.5°C with its TruTherm sensors versus a 3°C variation using other IC temperature sensors consisting of traditional remote diodes *(Fig. 5)*.

IC temperature sensors and their small profiles are being used in dual-inline memory modules (DIMMs), too. TI's TMP102 digital temperature sensor offers an SMBus/two-wire serial interface in an SOT563 package. According to the company, its thin profile suits it for mounting under a DIMM without compromising DIMM dimensions.

The application-specific STTS424/E02 digital sensor chips from STMicroelectronics conform to the JEDEC JC42.4 specification. The STTS424 is a standalone model, while the STTS424E02 integrates the sensor with 2 kbits of serial presence-detection EEPROM. Both interface with the I^2C bus and SMBus.



5. With its TruTherm technology, National Semiconductor says that its IC temperature sensors can lower the spread in temperature errors for 11 different 65-nm processors from 3°C (a) to 0.5°C (b).

Designers must account for two key considerations when using an IC temperature sensor. First, they must determine what quantity needs to be measured and where the object to be measured is located in the circuit. For example, the application may require the IC sensor to be mounted either close to or far away from the object. This is important for communicating with other sensors in remote locations for functions like fan-speed control and overall system temperature control.

The second consideration is measurement accuracy. Although many types of temperature sensors are available to satisfy just about every accuracy requirement, the correct temperature-sensor selection isn't so straightforward. If you choose a sensor without first understanding its basic operating principles, the measurement could suffer from inaccurate readings, or the wrong temperature zone could be monitored.

For an IC temperature sensor, the sensor's temperature is essentially that of the transistor's junction diode. So when measuring the temperature of, say, a CPU, a thermal-diode monitor that's integrated either on the sensor chip itself or on the CPU should be used for accurate measurements. This monitor can also be implemented as a discrete solution on a PCB.

GREATER ACCURACY

Semiconductor IC temperature sensors are moving toward greater accuracy of 0.5°C and better, in concert with today's shrinking IC line widths and increasing chip densities. "There's a lot of interest in very high-accuracy, low-cost IC sensors and in new applications like HVAC," says Analog Devices' Pratt. "This is the case in the food transport business of perishable goods where thermocouples are now more commonly used."

"IC temperature sensors are enabling more sophisticated sensing in terms of accuracy, ease of use, and a direct digital output for domestic and industrial HVAC applications, as well as use in white goods appliances. We might see a trend toward having an IC with an embedded temperature sensor on it, but then we're giving up the redundancy gained from a discrete approach," says Linear's Williams. "The raw measurement capability of an IC temperature sensor has not changed much. What has changed is the packaging." ED