Selecting the Ideal Temperature Sensor
Agenda

- Why do we need temperature sensors?
- Temperature sensing technologies
- Silicon temperature sensors
- What is the ideal solution for your application?
Why do we need Temperature Sensors?

Temperature Measurement:
- Extending IC MTBF (Arrhenius Equation)
- Processor Performance Optimization
- Fan speed control
- Temperature correction & display

Temperature Compensation:
- Power amplifier temperature compensation
- Display contrast control
- Photo diode temperature compensation

Over-temperature Detection:
- Over-temperature shutdown
- Thermostat functionality
- Battery management

The two market driving applications for temperature sensors have been PC motherboards and cellular phones. There are however numerous applications that require temperature sensing ranging from the temperature correction of a pressure sensor to the fan controlled cooling of an electronics enclosure.

Any application that requires the detection of temperature in the standard -55 to +125°C range of ICs is a good candidate for a silicon temperature sensor.

Temperature sensors are also used in conjunction with a number of other sensors to provide temperature correction. For example, relative humidity and dew point is calculated by measuring the humidity with a humidity sensor and the measurement is then adjusted to account for the ambient temperature. Another example of a duel sensor system is a thermopile. A thermopile consists of a thermocouple and a thermistor. The thermopile consists of a infrared sensitive thermocouple and a thermistor that provides cold junction compensation.
There are advantages and disadvantages with each of the five common temperature sensors, including their interface circuits. The factors which determine which sensor fits a particular application include:

- Temperature range
- External signal conditioning circuitry
- Location of the interface electronics
- Required accuracy
- Design budget

For example, thermocouples are the sensors typically used to measure engine temperatures of 1400°F. On the other hand, platinum RTDs are the standard choice for precise measurements. If the application consists of monitoring the temperature on a PCB and controlling a fan, any of these five sensors could be used.

The selection criteria for temperature sensors is driven not only by the attributes of the sensor, but also by the interface circuitry that is required. A transducer is defined as the sensor plus the signal conditioning circuitry. It is important to consider the system implications of the transducer when selecting the temperature sensor.
The main advantage of thermocouples is that they operate over a very wide temperature range. Also, thermocouples are one of the few sensors rugged enough to survive a high temperature caustic environment such as an engine.

Other advantages of thermocouples include their low cost and that they can be placed in parallel in an array or harness. A thermocouple harness provides an output that is equal to the average temperature of the individual thermocouple probes. Thermocouples can be wired in parallel because they typically fail as an open circuit.

There are several disadvantages of thermocouples. The interface circuitry must provide cold junction compensation (CJC) and the location of the cold junction circuit becomes critical to obtaining an accurate measurement.
The main advantages of thermistors are that they are very inexpensive and available in a wide variety of packages ranging from surface mount to leaded beads. Thermistors are built with semiconductor materials and can have either a positive (PTC) or a negative (NTC) temperature coefficient.

The main negative feature of thermistors is that the temperature range is relatively small and that an external circuit is needed to linearize and condition the signal. Furthermore, the low cost thermistors are usually not very accurate.

For cost sensitive applications such as battery chargers, thermistors are an excellent choice. In this application, accuracy is not important because temperature is only monitored to detect an over heating shutdown condition. Furthermore, the thermistor is available in a package that can be mounted directly on a “hot” component such as a transformer.
Thermistors are relatively non-linear, especially at cold and hot temperatures and in comparison with a RTD. Typically, thermistors must be calibrated in order to achieve a high accuracy comparable to RTD or silicon IC sensors. If the application requires high accuracy, either a RTD or a silicon sensor is usually a better design choice. RTDs are very linear and stable; therefore, they are the sensor of choice for high accuracy applications. RTDs will be discussed in more detail in future slides.

The thermistor’s non-linearity problem can be partially solved by simply using a discrete resistor and a voltage divider circuit. Many thermistor datasheets suggest a linearization network that consists of placing discrete resistors in parallel and/or series with the sensor.

The graph shows the effect of placing a resistor in series with the thermistor. The linear region is approximately 0 to 50°C and this region is linear to 10-bits. The small slope of the resistance curve for temperatures below 0°C and above 50°C produces a lower temperature resolution in bits for the thermistor at the cold and hot conditions. An analog output silicon sensor is typically a better sensor to use if the application requires accuracy at low and high temperatures.
RTDs are the standard sensor chosen for precision sensing applications. RTDs can be built using platinum, nickel or copper temperature sensitive resistive metals. Platinum (PRTD) is the temperature sensing metal that is used in most RTDs. The accuracy of the temperature coefficient is controlled by the purity of the resistive material, while the magnitude of the resistance is a function of the length of the wire.

Two types of RTDs are available, thin film and wire wound. Thin film RTDs are manufactured with a semiconductor deposition process and offer the advantage of producing sensors housed in small packages.

Wire wound RTDs are typically built by wrapping a wire around a ceramic bobbin and then covering the bobbin with a metal sheath. The thermal time constant of RTDs are a function of the thickness of the metal sheath material of the probe. Hot wire anemometers, which are used as flow sensors, achieve a response time of a few milliseconds by essentially placing a thin bare wire in the flow path.
Discrete diode sensors are limited to very low cost, low accuracy applications. In addition, these sensors have the same limited temperature range as silicon sensors.

The current to voltage relationship of a diode can be used to develop an equation where voltage is proportional to temperature. The large variation in the threshold conduction from diode to diode (i.e. “knee” of the I versus V curve) limits the accuracy of these sensors. The accuracy of diode sensors will be relatively poor unless a current ratioing method is implemented.

Discrete diode sensors were popular in the early 1970’s; however, these sensors are being replaced by analog output and remote diode silicon IC sensors in most applications. The popularity of silicon IC sensors is increasing, especially with the development of low cost CMOS silicon sensors with on-chip signal conditioning circuits.
The main advantage of silicon sensors is that the output can be directly interfaced to a processor. No linearization or external components are required. Although these sensors are more expensive than thermistors and discrete diodes, they are easy to integrate into the electronics, reduce the system component count and minimize the required design time.

The main disadvantage of silicon sensors is that they are non-contact sensors. They are available in a wide variety of standard IC packages and typically measure the temperature of the ambient temperature inside an electronics enclosure.

The first silicon IC temperature sensors were developed in the 1970s and produce an output voltage or current that is proportional to temperature. These sensors offer many advantages, including the integration of the sensor and the signal conditioning circuitry in a small IC package.

CMOS IC processes provide the digital features that make IC sensors an attractive sensor technology for a wide range of applications. CMOS technology has enabled the integration of the temperature sensor, ADC and temperature detection logic on a single chip that is connected to the processor through a serial data bus.
Silicon temperature sensors can be classified by their output signal into four main categories of sensors.

Analog sensors were the first silicon systems to be developed and their output is a voltage that is proportional to temperature in the form of a straight line where \( y = mx + b \). Note the first analog sensors developed in the 1970s had a current output.

Serial output or digital sensors were developed to take advantage of the high integration and low cost features of CMOS IC processes. Serial output sensors are typically used in microcontroller systems. These sensors measure temperature and communicate with the processor with a standard data protocol such as SPI or SMBus.

Logic output sensors are identical to analog output sensors except that the output is driven by a comparator. Logic output sensors are often used as thermostats where the temperature trip point is programmed by the selection of external resistors.

PWM output sensors provide an output where the duty cycle of a digital waveform is proportional to temperature. These sensors typically have a constant frequency and high duty time; however, it is necessary to calculate the ratio of the logic high time \( (t_1) \) divided by the logic low time \( (t_2) \) in order to maximize the accuracy.
The main advantage of analog temperature sensors is that the output can be directly interfaced to an ADC input. No linearization or external components are required. Although these sensors are more expensive than thermistors and discrete diodes for low-accuracy applications, they are easy to integrate into the electronics, reduce the system component count, minimize the required design time and reduce power consumption.
The output of an Analog Output sensor is typically measured with either a discrete or a microcontroller's internal ADC.

A simplified schematic of the ADC system is shown in this slide. The temperature sensor’s output pin is driven by an op-amp that has an output impedance ($R_{OUT}$) typically between 100 to 600$\Omega$ (the output impedance of the TC1047A is less than 1 ohm because of an on-board operational amplifier that functions as a voltage buffer). The input of a ADC consists of a simple sample and hold circuit. A switch is used to connect the signal source with a sampling capacitor and the ADC measures the $C_{SAMPLE}$ capacitor's voltage in order to determine the temperature.

The $R_{OUT}$ and $R_{SWITCH}$ resistances and the $C_{SAMPLE}$ capacitor form a time constant that must be less than the sampling rate ($T_{SAMPLE}$) of the ADC as shown.

An external capacitor in the range of 1 to 100nF sometimes is added to the output pin to provide additional filtering and to form an anti-aliasing filter for the ADC. Note that this capacitor may impact the time response of the the sensor. The user must allow time for the capacitor to charge sufficiently between ADC conversions. Also, the sensor amplifier may oscillate if the filter capacitor is too large.
Logic-output temperature sensors are the ideal solution for over- or under-temperature detection. Again, the output can be directly interfaced to a processor and no external components are required.

The output is typically not latched; thus, the switch will turn-off when the temperature falls below the temperature setpoint. Note it is necessary to have hysteresis so the switch does not “chatter” when crossing the temperature setpoint.
Logic output sensors are sometimes referred to as temperature switches, because they typically function as a thermostat to notify the system that a maximum or minimum temperature limit has been detected.

The features of logic output sensors include:

- Logic Level Output
- Notifies System when Temperature is Above (or Below) a Preset Value
- Either Factory or User-Programmable Temperature Settings
- Available in a Variety of Output Configurations

This slide shows two typical application for logic output sensors. These sensors are often used as switches to turn-on either a fan or a warning light when a high temperature condition is detected.
Serial-Output Temp Sensor

**Advantages**
- Direct Communication
- Save PCB Space
- Minimize Design Time
- Low Power

**Applications**
- Computers
- Set-top Boxes
- Office Equipment
- Wireless Handsets

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The main advantage of a digital silicon sensor is that the output can be directly interfaced to a processor. Temperature is converted to a “digital word”.

You can also see the block diagram of the TC77 serial output sensor, which integrates the temperature sensor, ADC and digital registers on a single chip. Communication with the processor is accomplished through the SPI serial bus. The SPI bus uses SCK, SI/O and CS pins to transmit and receive data. Temperature is measured by monitoring the voltage of a diode with a 13-bit ADC. The temperature data is stored in the Temperature Register. If a Temperature Register read operation occurs while an ADC conversion is in progress, the previous completed conversion will be outputted. The Configuration Register is used to select either the continuous temperature conversion or shut-down operating modes. A shutdown mode is also available to disable the temperature conversion circuitry thereby minimizing the power consumption; however, the serial I/O communication port remains active.
This slide shows the TCN75 being used in an application where temperature is sensed in many locations across a printed circuit board or from board to board. Communication between the TCN75 and the MCU is accomplished via a two-wire bus that is compatible with industry standard protocols. This permits reading the current temperature, programming the set point and hysteresis, and configuring the device.

The INT output is programmable as either a simple comparator for thermostat operation or as a temperature event interrupt. This output notifies the host controller when ambient temperature exceeds a user programmed set point.
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Practical Considerations

Define your needs
- What temperature range is needed?
- What accuracy is required?
- Are there any size limitations?
- Does the design have power constraints?
- What is the target cost?

Design your system
- Choose your sensor
- Design your analog front end
- Design your measurement system
More Information

Temperature Sensing Publications

- Sensors Magazine (www.sensorsmag.com)

Serial I/O Standards

- SMBus web site (www.smbus.org)
- SPI web site (Motorola Web site)

Grounding / Shielding and Noise Reduction


Here are some resources for additional temperature sensor related information.
For More Information

Microchip’s Web site (www.microchip.com)

- AN512 - Implementing Ohmmeter/Temperature Sensor
- AN679 - Temperature Sensing Technologies
- AN684 - Single Supply Temperature Sensing with Thermocouples
- AN871 - Temperature Sensing with the TC77
- AN895 - RTD Oscillator Circuits
- AN897 - Thermistor Sensing with a PGA
- AN938 - Interfacing the TC1047A Analog Output Temperature Sensor to a PIC® device
- TB050 - Monitoring Multiple Temperature Nodes Using TC74 Thermal Sensors and a PIC16C505
- TB052 - Multi-zone Temperature Monitoring with the TCN75

Our web site offers a lot of information about temperature sensor products and designs. Here is a list of some of the available application notes and technical briefs.
### Microchip’s Temperature Sensor ICs

**Analog Output**
- TC1046: $V_{OUT} = 6.25\text{mV/}^\circ\text{C}$
- TC1047A: $V_{OUT} = 10\text{mV/}^\circ\text{C}$

**Logic output**
- TC620/621/623: Dual Trip Point
- TC622/624: Single Trip Point
- TC6501/2/3/4: SOT-23, Selectable Hysteresis

**Serial Output**
- TC74: SOT-23, 2-Wire Digital Sensor
- TCN75: Multi-drop, 2-Wire Digital Sensor
- TC72: 3x3 DFN-8, 10-Bit SPI Digital Sensor
- TC77: SOT-23, ±1°C, 13-Bit SPI Digital Sensor

This slide shows Microchip Technology’s temperature sensor families as well as some of the key product characteristics. More information (datasheets, application notes, design guides, etc.) can be found on our web site: www.microchip.com
Thank You!

Thank you for attending this presentation. Good luck with your temperature measurements.