Temperature Sensor Handbook

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Introduction

Temperature is the most-often-measured environmental quantity. This is expected since most physical, electronic, chemical, mechanical, and biological systems are affected by temperature. Some processes work well only within a narrow range of temperatures; certain chemical reactions, biological processes, and even electronic circuits perform best within limited temperature ranges. When these processes need to be optimized, control systems that keep temperature within specified limits are often used. Temperature sensors provide inputs to those control systems.

Many electronic components can be damaged by exposure to high temperatures, and some can be damaged by exposure to low temperatures. Semiconductor devices and Liquid Crystal Displays (LCDs) are examples of commonly used components that can be damaged by temperature extremes. When temperature limits are exceeded, action must be taken to protect the system. In these systems, temperature sensing helps enhance reliability. One example of such a system is a personal computer. The computer's motherboard and hard disk drive generate a great deal of heat. The internal fan helps cool the system, but if the fan fails, or if airflow is blocked, system components can be permanently damaged. By sensing the temperature inside the computer's case, high-temperature conditions can be detected and actions can be taken to reduce system temperature, or even shut the system down to avert catastrophe.

Other applications simply require temperature data so that temperature effects on a process may be taken into account. Examples are battery chargers (battery charge capacities vary with temperature, and cell temperature can help determine the optimum point at which to terminate fast charging), crystal oscillators (oscillation frequency varies with temperature), and LCDs (contrast is temperature dependent and can be compensated if the temperature is known).

This handbook provides an introduction to temperature sensing, with a focus on silicon-based sensors. Included are several application circuit examples, reprints of magazine articles on temperature sensing, and a selection guide to help you choose a silicon-based sensor that is appropriate for your application.

Temperature-Sensing Techniques

Several temperature-sensing techniques are currently in widespread usage. The most common of these are Resistance Temperature Detectors (RTDs), thermocouples, thermistors, and semiconductor integrated-circuit sensors. The right one for your application depends on the required temperature range, linearity, accuracy, cost, features, and ease of designing the necessary support circuitry. In this section, we discuss the characteristics of the most common temperature-sensing techniques.

1.1 RTDs

Resistive sensors use a sensing element whose resistance varies with temperature. A platinum RTD or the more popular Platinum Resistive Thermometers (PRTs) consist of a coil of platinum wire wound around a bobbin, or a film of platinum deposited on a substrate. In either case, the sensor's resistance-temperature curve is a nearly-linear function, as shown in ***Figure 1-1.*** The RTD's resistance curve is the lower one; a straight line is also shown for reference. Nonlinearity is several degrees at temperature extremes, but is highly predictable and repeatable. Correction of this nonlinearity may be performed with a linearizing circuit or by digitizing the measured resistance value and using a lookup table to apply correction factors. Because of the curve's high degree of repeatability over a wide temperature range (roughly -250° C to +750° C) and platinum's stability (even when hot), RTDs are found in a variety of precision-sensing applications.

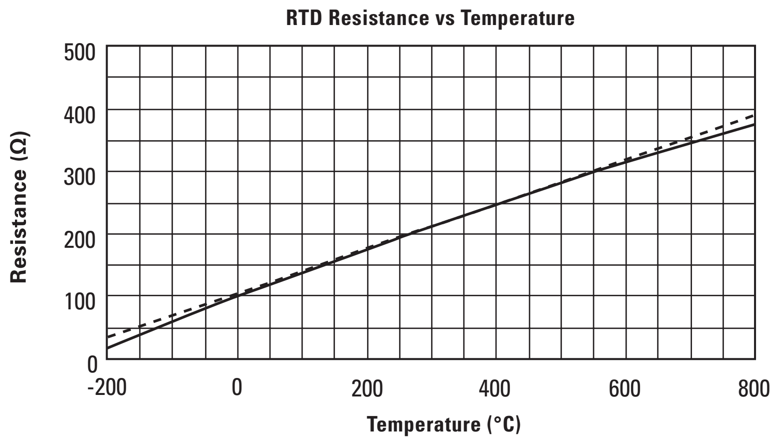


Figure 1-1. RTD Resistance vs Temperature. The Upper Curve is a Straight Line for Reference.

The complexity of RTD-signal-processing circuitry varies substantially depending on the application. Usually a known, accurate current is forced through the sensor, and the voltage across the sensor is measured. Several components, each of which generates its own errors, are necessary. When leads to the sensor are long, 4-wire connections to the sensor can eliminate the effects of lead resistance, but this may increase the circuit's complexity.

Low-voltage operation is possible with resistive sensors as there are no inherent minimum voltage limitations on these devices, and there are enough precision low-voltage amplifiers available to make low-voltage operation reasonable to achieve. Low-power operation is a little tougher, but it can be accomplished at the expense of complexity by using intermittent power techniques. By energizing the sensor only when a measurement needs to be made, power consumption can be minimized.

RTDs have drawbacks in some applications. For example, the cost of a wire-wound platinum RTD tends to be relatively high. On the other hand, thin-film RTDs and sensors made from other metals can cost as little as a few dollars. Also, self-heating can occur in these devices. The power required to energize the sensor raises its temperature, which affects measurement accuracy. Circuits that drive the sensor with a few mA of current can develop self-heating errors of several degrees. The nonlinearity of the resistance-vs-temperature curve is a disadvantage in some applications, but it is very predictable and therefore correctable.

1.2 Thermistors

Another type of resistive sensor is the thermistor. Low-cost thermistors often perform simple measurement or trip-point-detection functions in low-cost systems. Low-precision thermistors are very inexpensive; at higher price points, they can be selected for better precision at a single temperature. A thermistor's resistance-temperature function is nonlinear as can be seen in ***Figure 1-2***. Therefore, if measuring a wide range of temperatures is desired, it is necessary to perform substantial linearization. An alternative is to purchase linearized devices, which generally consist of an array of two thermistors with some fixed resistors. These devices are much more expensive and less sensitive than single thermistors, but they tend to have excellent accuracy. Simple set point-thermostat or controller applications can be implemented using thermistors, but they require multiple components like a comparator, reference, and discrete resistors.

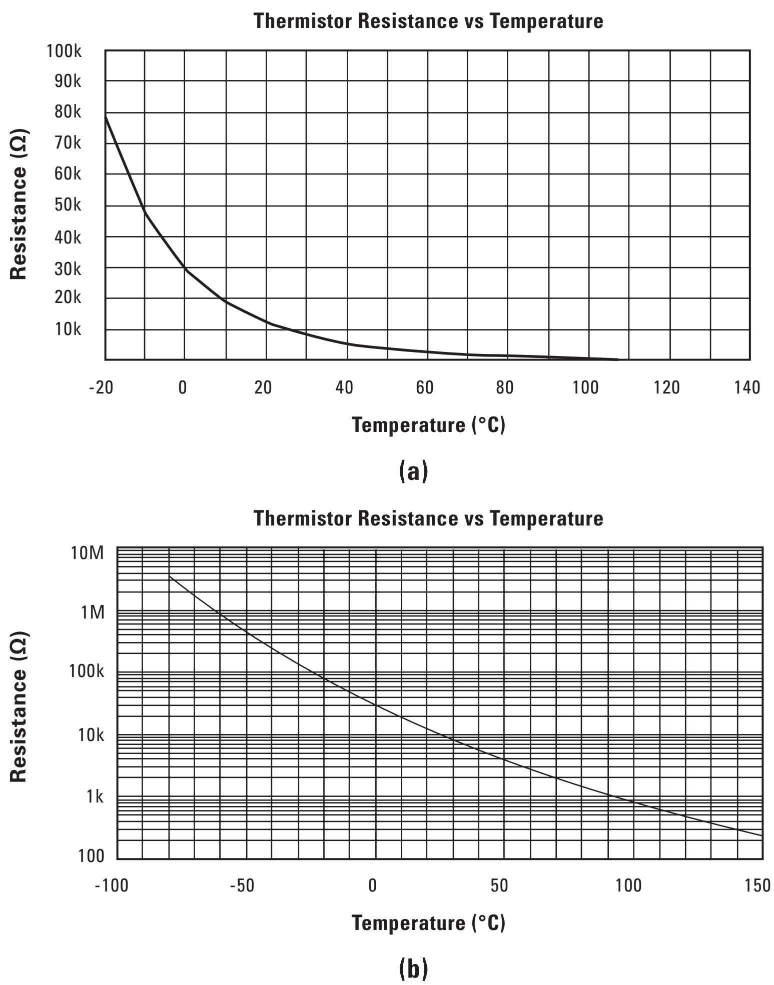


Figure 1-2. Thermistor Resistance vs Temperature. (a) Linear Scale. (b) Logarithmic Scale.

When functionality requirements are even more involved (for example, if multiple trip points or analog-to-digital conversion is necessary), external circuitry and cost increase quickly. Consequently, low-cost thermistors will typically only be used in applications with minimal functionality requirements. Thermistors can be affected by self-heating, usually at higher temperatures where their resistances are lower. As with RTDs, there are no fundamental reasons why thermistors shouldn't be used on low supply voltages. External active components such as comparators or amplifiers will usually limit the low end of the supply voltage range. Low-power applications require increased circuit complexity to compensate for the nature of high impedances to be sensitive to noise-induced errors. You can find thermistors that will work over a temperature range from about -100°C to +550°C although most are rated for maximum operating temperatures from 100°C to 150°C.

1.3 Thermocouples

A thermocouple consists of a junction of two wires made of different materials. For example, a Type J thermocouple is made from iron and constantan wires, as shown in ***Figure 1-3***. Junction 1 is at the temperature to be measured. Junctions 2 and 3 are kept at a different, known temperature. The output voltage is approximately proportional to the difference in temperature between junction 1 and junctions 2 and 3. Typically, the temperature of junctions 2 and 3 with a second sensor will be measured, as shown in the figure. This second sensor enables the ability to develop an output voltage proportional to an appropriate scale (for example, in °C), by adding a voltage to the thermocouple output that has the same slope as that of the thermocouple, but is related to the temperature of junctions 2 and 3.

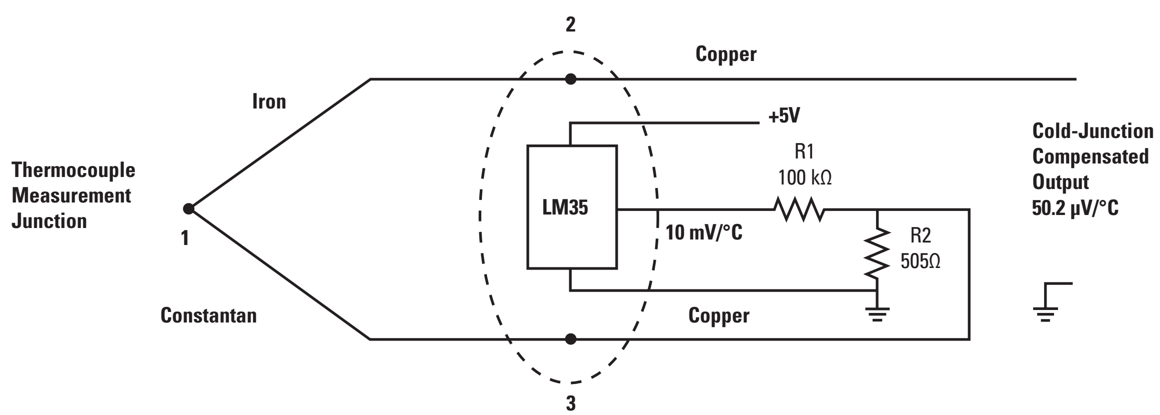


Figure 1-3. Using the LM35 for Thermocouple Cold-Junction Compensation

Because a thermocouple's "sensitivity" (as reflected in its Seebeck coefficient) is rather small — on the order of tens of microvolts per °C — a low-offset amplifier to produce a usable output voltage is required. Nonlinearities in the temperature-to-voltage transfer function (shown in ***Figure 1-4***) amount to many degrees over a thermocouple's operating range and, as with RTDs and thermocouples, often necessitate compensation circuits or lookup tables. In spite of these drawbacks, however, thermocouples are very popular, in part because of their low thermal mass and wide operating temperature range, which can extend to about 1700°C with common types. ***Table 1-5*** shows Seebeck coefficients and temperature ranges for a few types of thermocouples.

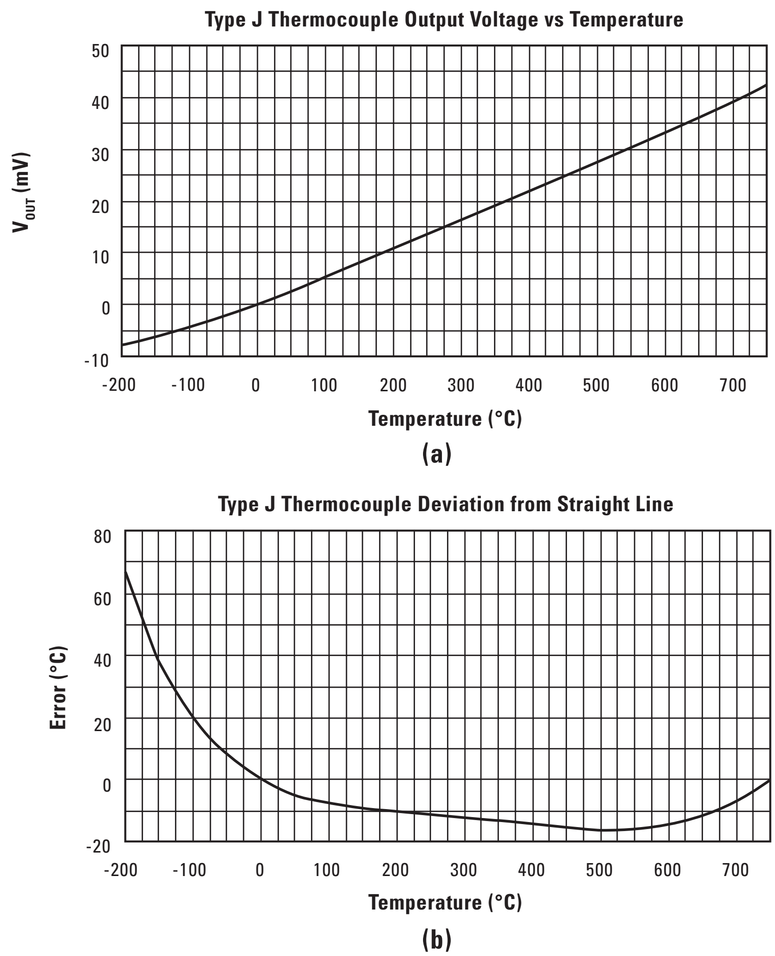


Figure 1-4. a) Output Voltage as a Function of Temperature for a Type J Thermocouple.
b) Approximate Error in °C vs a Straight Line That Passes Through the Curve at 0°C and 750°C.

Table 1-5. Using the LM35 for Thermocouple Cold-Junction Compensation

Type	Seebeck Coefficient µV/°C	Temperature Range (°C)
E	58.5 @ 0°C	0 to 1700
J	50.2 @ 0°C	0 to 750
K	39.4 @ 0°C	-200 to +1250
R	11.5 @ 0°C	0 to 1450

1.4 Silicon Temperature Sensors

IC temperature sensors differ significantly from the other types of sensors in a couple of important ways. The first is operating temperature range. A temperature-sensor IC can operate over the nominal IC temperature range of -55°C to +150°C. Some devices go beyond this range, while others, because of package or cost constraints, operate over a narrower range. The second major difference is functionality. A silicon temperature sensor is an integrated circuit, and can therefore include extensive signal-processing circuitry within the same package as the sensor. In addition, a simple silicon sensor can be included as a remote diode to easily measure a highly-integrated digital IC (for example, a processor or field-programmable gate array, FPGA) junction temperature remotely. It is not necessary to design cold-junction compensation or linearization circuits for temperature-sensor ICs, and unless there are extremely specialized system requirements, there is no need to design comparator or analog-to-digital converter (ADC) circuits to convert their analog outputs to logic levels or digital codes. Those functions are already built into several commercial ICs.

IC temperature sensors vary widely in terms of complexity, ranging from simple analog-output sensors to digital sensors with many other integrated features. National's offerings in this area are described in the next section.

National builds a wide variety of temperature-sensor ICs that are intended to simplify the broadest possible range of temperature-sensing challenges. Some of these are analog circuits, with either voltage or current output. Others combine analog-sensing circuits with voltage comparators to provide “thermostat” or “alarm” functions. Still other sensor ICs combine analog-sensing circuitry with digital I/O and control registers providing simple digital solutions for highly-integrated systems. Even greater integration is achieved by including remote-diode sensing, voltage monitoring, and fan-control functions, making them an ideal solution for microprocessor-based systems, from embedded-microcontroller-based systems to personal computers that require autonomous fan control for acoustical noise minimization.

Other applications simply require temperature data so that the temperature’s effect on a process may be accounted for. Some examples include battery chargers (batteries’ charge capacities vary with temperature and cell temperature can help determine the optimum point at which to terminate fast charging), crystal oscillators (oscillation frequency varies with temperature), and LCDs (contrast is temperature dependent and can be compensated if the temperature is known).

Following is a summary of National’s sensor products as of January 2008. Unless noted otherwise, the specifications listed in this section are the guaranteed limits for the best grade device.

2.1 Voltage-Output Analog Temperature Sensors

LM94022 Selectable-Gain Analog Temperature Sensor

The LM94022 is a precision analog-output CMOS temperature sensor that delivers a voltage inversely proportional to temperature. This sensor has a maximum error of ±1.5°C from 20°C to 40°C measured temperature and ±1.8°C from 0°C to 70°C measured temperature. It operates at a supply voltage as low as 1.5V and as high as 5.5V. It is the next generation of the industry-standard LM20 device. The LM94022 sensor’s low supply current and small SC-70 package make it ideal for portable systems as well as general temperature-sensing applications.

Two logic inputs, Gain Select 1 (GS1) and Gain Select 0 (GS0), select the gain of the very linear (only slightly parabolic) temperature-to-voltage output transfer function. Four gains (slopes) are selectable: –5.5 mV/°C, –8.2 mV/°C, –10.9 mV/°C, and –13.6 mV/°C. In the lowest gain configuration (GS1 and GS0 both tied low), the LM94022 sensor can operate with a 1.5V supply while measuring temperature over the full –50°C to +150°C operating range. For high supply voltages, a higher gain can be selected to optimize temperature sensitivity and system noise immunity.

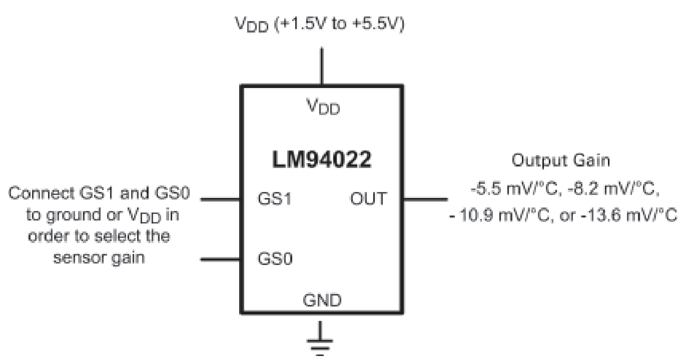


Figure 2-1. The LM94022 Sensor has Selectable Gain to Maximize the Sensitivity and the Temperature Range at a Given Supply Voltage

Many analog temperature-sensor applications use an ADC to sample the analog-temperature proportional-voltage output. These ADCs may be discrete or may be integrated into a processor or a microcontroller. The LM94022 device's output is optimized for driving the input stage of an ADC and the filter capacitor that is often located at the ADC input. The LM94022 device can drive a high 1100 pF maximum load capacitance (like a filter capacitor as large as 1 nF ±10%) without requiring an external series resistor to stabilize its output. Additionally, the robust ±50 µA of source and sink current is designed to drive the input current requirements of the ADC's switched capacitive input without requiring a buffer. Eliminating these extra components saves system cost and valuable board space.

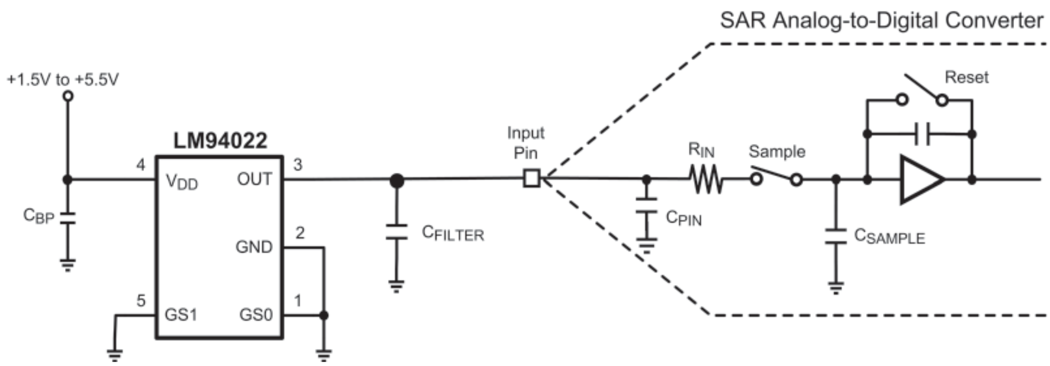


Figure 2-2. The LM94022 Temperature Sensor is Ideal for Driving the Input to an ADC Circuit

LM20 Temperature Sensor

The LM20 device has long been an industry standard in temperature sensing. It is a precision CMOS temperature sensor that outputs a voltage which is inversely proportional to temperature. The analog output is predominately linear, with a very minor parabolic shape and a nominal gain of -11.7 mV/°C. The LM20 sensor can measure a wide operating temperature of -55°C to +130°C with a single supply voltage, which can range from 2.7V to 5.5V. The LM20 device is ideally suited for a wide range of systems and applications. The LM20 sensor is available in tiny SC70-5 and miniature 4-bump micro-SMD packages.

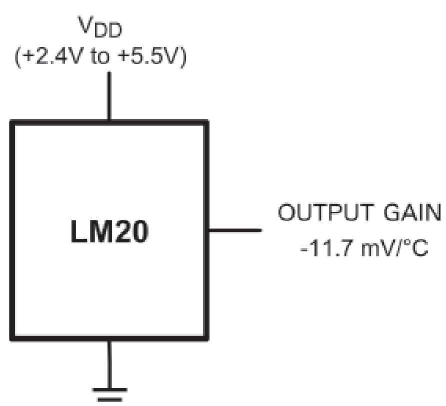


Figure 2-3. LM20 Connections. Three Connections Provide a Linear Analog Voltage Output.

LM135, LM235, LM335 Kelvin Sensors

The LM135, LM235, and LM335 sensors develop an output voltage proportional to absolute temperature with a nominal positive temperature coefficient of 10 mV/K. The nominal output voltage is therefore 2.73V at 0°C and 3.73V at 100°C. The sensors in this family operate like two-terminal shunt-voltage references and are nominally connected as shown in ***Figure 2-4***. The third terminal allows the adjustment of accuracy using a trim pot as shown in the figure. The error of an untrimmed LM135A sensor over the full -55°C to +150°C range is less than ±2.7°C. Using an external trim pot to adjust accuracy reduces error to less than ±1°C over the same temperature range. The sensors in this family are available in plastic TO-92 and SO-8 packages and in a TO-46 metal can.

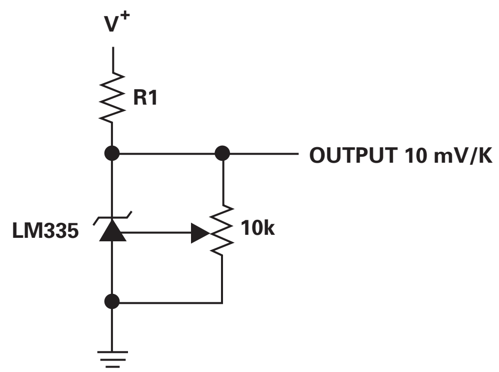


Figure 2-4. Typical Connection for LM135, LM235, and LM335 Sensors

LM35 and LM45 Celsius Sensors

The LM35 and LM45 sensors are three-terminal devices that produce output voltages proportional to °C (10 mV/°C), so the nominal output voltage is 250 mV at 25°C and 1.000V at 100°C. These sensors can measure temperatures below 0°C by using a pull-down resistor from the output pin to a voltage below the "ground" pin (see **Application Hints**, **Section 3.2**). The LM35 sensor is more accurate (±1°C from -55°C to +150°C vs. ±3°C from -20°C to +100°C), while the LM45 device is available in a smaller SOT-23 package. The LM35 device is available in plastic TO-92 and SO-8 packages and in a TO-46 metal can.

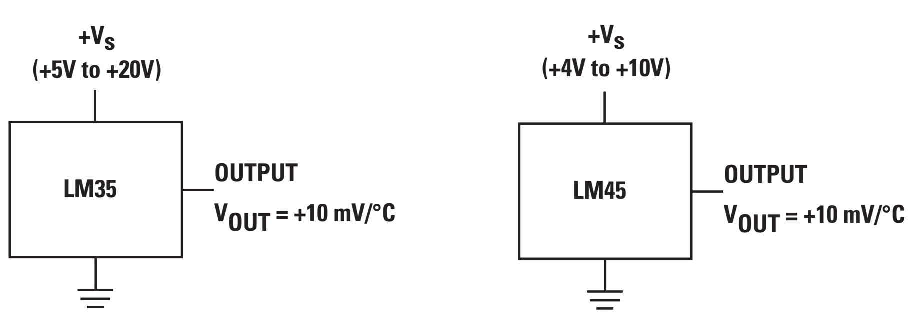


Figure 2-5. LM35 and LM45 Typical Connections. Each IC is essentially a 3-terminal device (supply, ground, and output), although some are available in packages with more pins.

LM34 Fahrenheit Sensor

The LM34 sensor is similar to the LM35 sensor, but its output voltage is proportional to °F (10 mV/°F). Its accuracy is similar to the LM35 device (±2°F from -50°F to +300°F), and it is available in the same packages as the LM35 device: TO-92, SO-8, and TO-46.

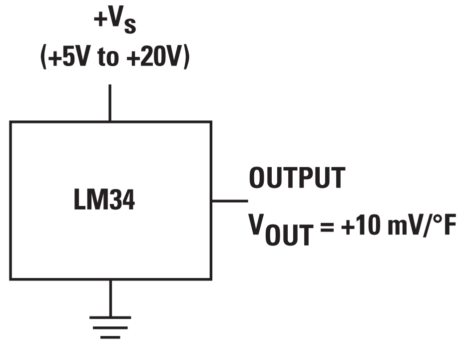


Figure 2-6. LM34 Typical Connection

LM50 Single-Supply Celsius Sensor

The LM50 sensor is called a single-supply Celsius sensor because, unlike the LM35 and LM45 sensors, it can measure negative temperatures without taking its output pin below its ground pin (see **Application Hints**, **Section 3.2**). This can simplify external circuitry in some applications. The LM50 device's output voltage has a 10 mV/°C slope and a 500 mV "offset". Thus, the output voltage is 500 mV at 0°C, 100 mV at -40°C, and 1.5V at +100°C. Accuracy is within 3°C over the full -40°C to +125°C operating temperature range. The LM50 sensor is available in a SOT-23 package.

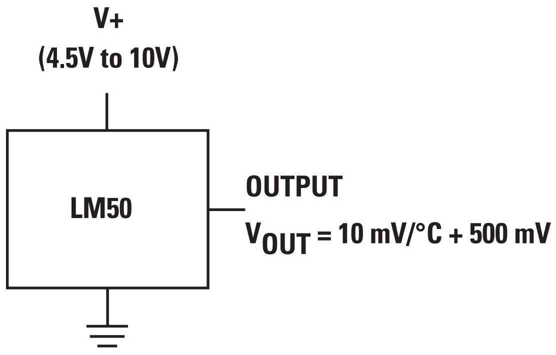


Figure 2-7. LM50 Typical Connection

LM60 2.7V Single-Supply Celsius Sensor

The LM60 sensor is similar to the LM50 sensor, but it is intended for use in applications with supply voltages as low as 2.7V. Its 110 µA supply-current drain is low enough to make the LM60 sensor an ideal device in battery-powered systems. The LM60 sensor's output voltage has a 6.25 mV/°C slope and a 424 mV "offset". This results in output voltages of 424 mV at 0°C, 174 mV at -40°C, and 1.049V at 100°C. The LM60 device is available in a SOT-23 package.

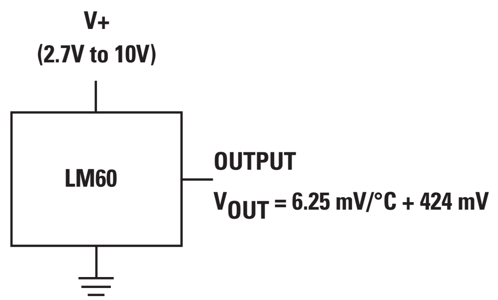


Figure 2-8. LM60 Typical Connection

2.2 Current-Output Analog Sensors

LM134, LM234, and LM334 Current-Output Temperature Sensors

Although its datasheet calls it an "adjustable current source", the LM134/LM234/LM334 is also a current-output temperature sensor with an output current proportional to absolute temperature. The sensitivity is set using a single external resistor. Typical sensitivities are in the 1 µA/°C to 3 µA/°C range, with 1 µA/°C being a good nominal value. By adjusting the value of the external resistor, the sensitivity can be trimmed for good accuracy over the full operating temperature range (-55°C to +125°C for the LM134, -25°C to +100°C for the LM234, and 0°C to +70°C for the LM334). The LM134/LM234/LM334 typically needs only 1.2V supply voltage, so it can be useful in applications with very limited voltage headroom. Devices in this family are available in SO-8 and TO-92 plastic packaging and a TO-46 metal can.

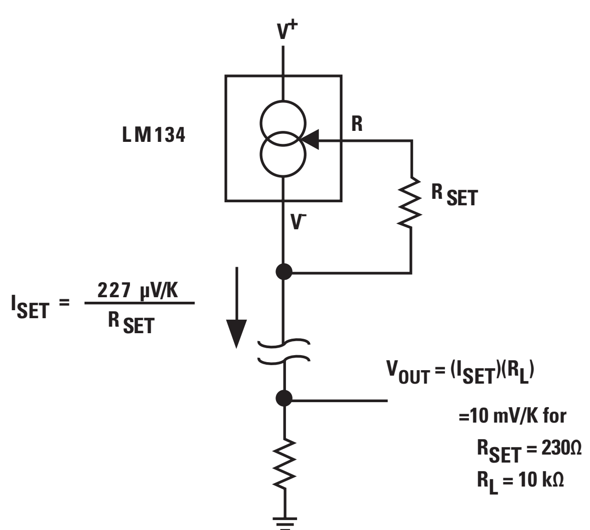


Figure 2-9. LM134 Typical Connection. R_{SET} Controls the Ratio of Output Current to Temperature.

2.3 Comparator-Output Temperature Sensors

LM26LV Precision Low-Voltage Temperature Switch

The LM26LV is a low-voltage, precision analog sensor and a temperature switch in a small 2.2 mm x 2.5 mm package. Operating on a supply voltage as low as 1.6V and as high as 5.5V, it includes an analog temperature sensor (similar to the LM94022 sensor) which outputs a temperature inversely proportional to measured temperature. It also features a temperature switch, with both active-high and active-low outputs, which goes active when the measured temperature exceeds a specified trip temperature (***Figure 2-10***).

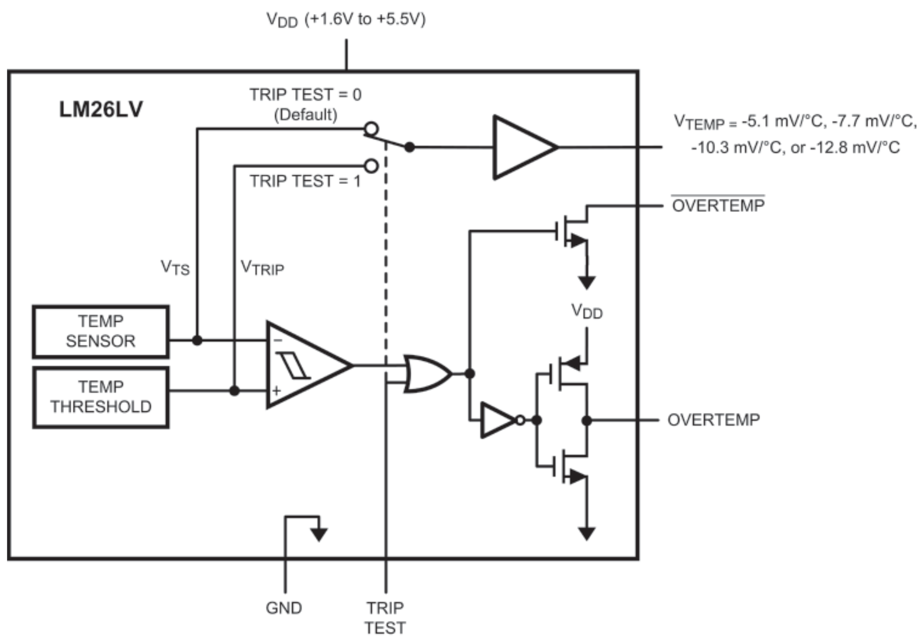


Figure 2-10. The LM26LV features a Temperature Switch and an Analog Temperature Output

The trip temperature is preset at the factory for any temperature in the range of 0°C to 150°C, in increments of 1°C. Once the LM26LV sensor is installed, it can be tested while in the system by driving the TRIP TEST input pin high (***Figure 2-11***). This test forces the outputs to go active, verifying the proper function of the internal comparator. As a low-voltage, next-generation successor to the very popular LM26 and LM27 sensors, the LM26LV device is well suited for applications where the current temperature must be monitored and where an over-temperature alarm is necessary. In addition to low-voltage operation, it also has an improved analog output. The V_{TEMP} output has a strong source and sink current and can drive large capacitive loads, optimizing it for driving the input to an ADC. Application examples include systems where the analog output is read by an ADC in a processor and the over-temperature-switch output is read by a digital input to signal when the system needs to reduce power or perhaps shut down to protect the system from damage due to extreme temperature.

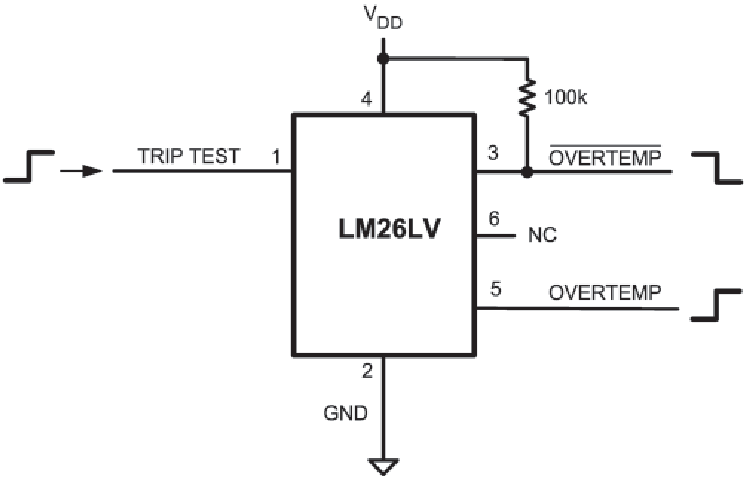


Figure 2-11. The LM26LV TRIP TEST Input Allows Easy Testing of OVERTEMP Outputs

LM26 and LM27 Temperature Switches

The LM26 and LM27 are highly-integrated precision temperature switches. Both devices are available in a leaded SOT-23 package. The trip points are preset at the factory. The LM26 switch has a wide operating range from -55°C to +125°C. The LM27 switch will operate from -40°C to +150°C and is optimized for trip points from 120°C to 150°C. The single logic output can be ordered as an over-temperature or under-temperature output; it can also be ordered as an active-low open-drain or an active-high push-pull output. The HYST digital input allows for the selection of the hysteresis value of either 2°C (connect to V_{DD}) or 10°C (connect to GND). The analog temperature sensor output (V_{TEMP}) delivers a voltage that is inversely proportional to measured temperature. This output has very weak drive capability that can be overdriven by 1.5 mA. Therefore, one can simply force the V_{TEMP} voltage to cause the digital output to change state(s), thereby verifying that the comparator and output circuitry function after assembly.

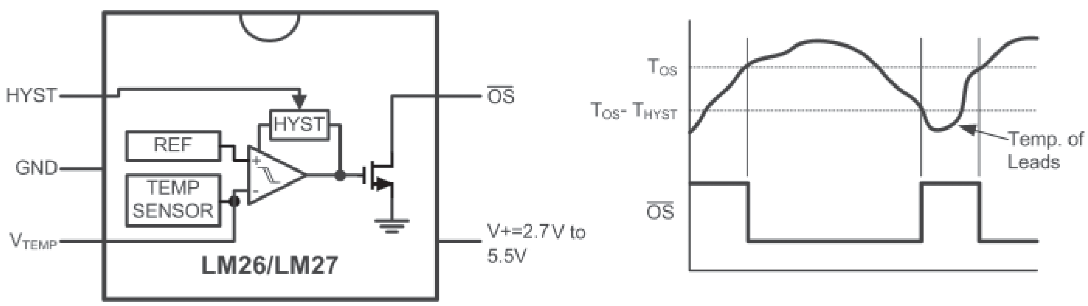
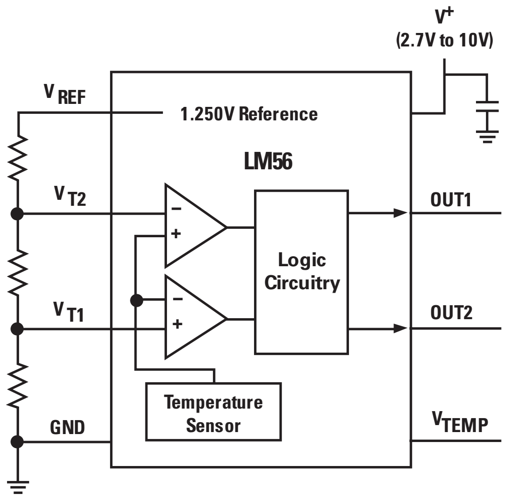


Figure 2-12. The LM26 and LM27 Sensors Integrate a Temperature Switch and an Analog Temperature Sensor. The Hysteresis Magnitude is Selected by the Digital HYST Input.

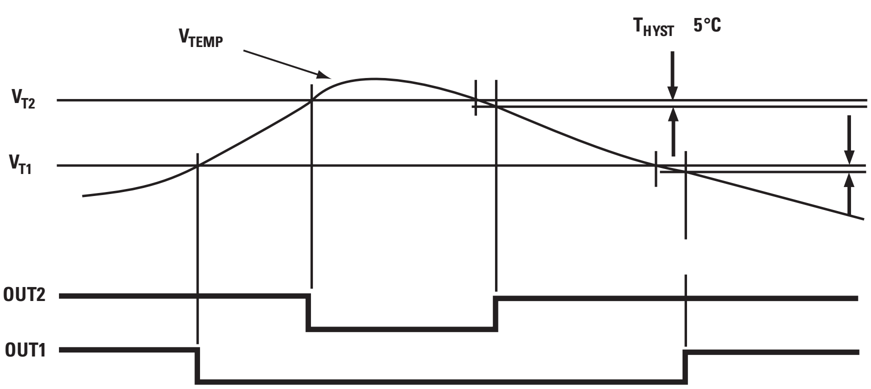
LM56 Low-Power Thermostat

The LM56 thermostat includes a temperature sensor (similar to the LM60 device), a 1.25V voltage reference, and two comparators with preset hysteresis. It will operate from power supply voltages between 2.7V and 10V, and draws a maximum of 200 µA from the power supply. The operating temperature range is -40°C to +125°C. Comparator trip point tolerance, including all sensor, reference, and comparator errors (but not including external resistor errors), is 2°C from 25°C to 85°C and 3°C from -40°C to +125°C.

The internal temperature sensor develops an output voltage of 6.2 mV x T(°C) + 395 mV. Three external resistors set the thresholds for the two comparators.



(a)



(b)

Figure 2-13. LM56 Dual-Output, Low-Power Thermostat.
a) LM56 Simplified Block Diagram. b) LM56 Temperature Response Curve.

2.4 Digital Output Sensors

LM73 High-Accuracy Digital Temperature Sensor with 2-Wire Interface

The LM73 is a precision integrated-circuit digital temperature sensor. The 2-wire interface is compatible with SMBus and I^2C interfaces. The excellent accuracy of ±1°C from -10°C to +80°C and wide operating range of -40°C to +150°C make it ideal for a wide variety of temperature-sensing applications. A single address-select pin makes the LM73 sensor configurable to any of three unique device addresses by simply floating the pin, connecting it to ground, or connecting it to V_{DD}.

The LM73 sensor has programmable resolution. By simply writing two bits in the Control/Status Register, the resolution can be optimized between a minimum of 0.25°C/LSB, for a fast conversion time of 14 ms, to a maximum resolution 0.03°C/LSB for the greatest sensitivity. This excellent sensitivity allows the LM73 device to sense very small changes in temperature, allowing the host processor to determine the direction and rate of temperature change and respond very quickly. Both the SMBus-Interface Clock Signal (SMBCLK) and the SMBus-Interface Data Signal (SMBDAT) lines feature integrated low-pass filters and a timeout feature, which increase the LM73 device's ability to tolerate noise on the bus. The LM73 sensor continually converts temperature into a digital code and the temperature data can be read at any time. A shutdown mode is available, and while in this mode, a single conversion can be initiated at any time, allowing the system to perform a conversion only as needed, thereby minimizing power requirements and conserving battery charge.

The ALERT# output functions as a temperature switch. It goes active when the temperature exceeds a system-programmable temperature limit (which is programmed into the T_{HIGH} register). The T_{LOW} register provides system-programmable hysteresis. Crossing the T_{LOW} value resets the ALERT# output (for hysteresis with T_{HIGH}) and also sets a register flag to indicate to the system that the measured temperature has gone below that value. All of this functionality is integrated into a small SOT23-6 package.

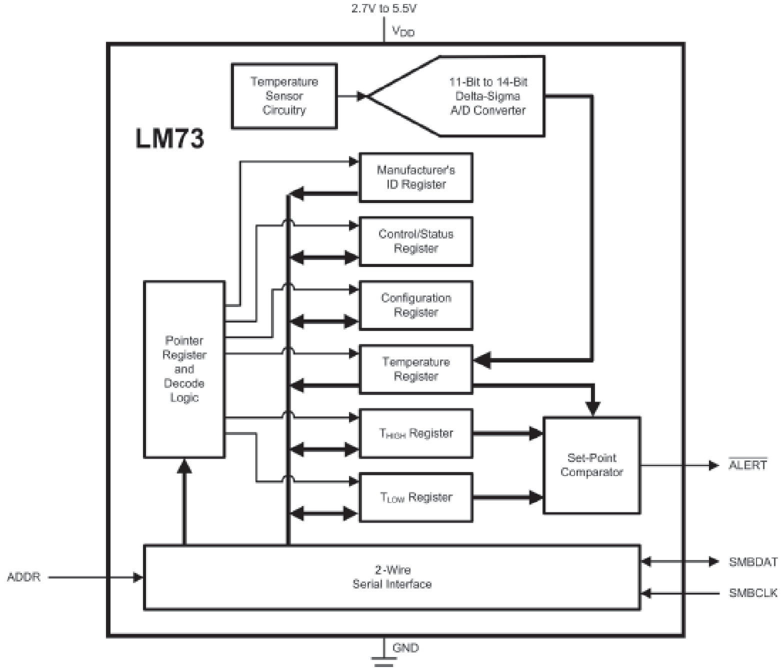


Figure 2-14. The LM73 is a Highly-Integrated Digital Temperature Sensor with an Analog Temperature Sensor, Delta-Sigma ADC, and Many Digital Features such as an ALERT# Output, Programmable Resolution, and a 2-Wire Interface

LM92 High-Accuracy Temperature Sensor and Thermal Window Comparator with 2-Wire Interface

The LM92 is a digital temperature sensor with a thermal window comparator. It is extremely accurate with a maximum error of ±0.33°C at 30°C and ±0.50°C from 10°C to 50°C.

The window-comparator feature of the LM92 sensor eases the design of temperature control systems. The open-drain Interrupt (INT) output becomes active when the temperature goes outside the values which define a programmable window (stored in the T_{HIGH} and T_{LOW} registers). A separate Critical Temperature Alarm (T_CRIT_A) line will go active if the measured temperature exceeds the value stored in the T_CRIT register. The INT output can operate in either a comparator or event mode. The T_CRIT_A output operates in comparator mode only. Communicating through the popular I^2C 2-wire serial-bus interface, the host can program both the upper and lower limits of the window as well as the critical temperature limit. Programmable hysteresis as well as a fault queue is available to minimize false tripping.

Two pins (A0, A1) are available for address selection. The LM92 device's 2.7V to 5.5V supply voltage range, serial-bus interface, 12-bit + sign output, and wide operating temperature make it ideal for a wide range of applications. These include thermal management and protection applications in personal computers, electronic test equipment, office electronics, automotive, medical, and HVAC applications.

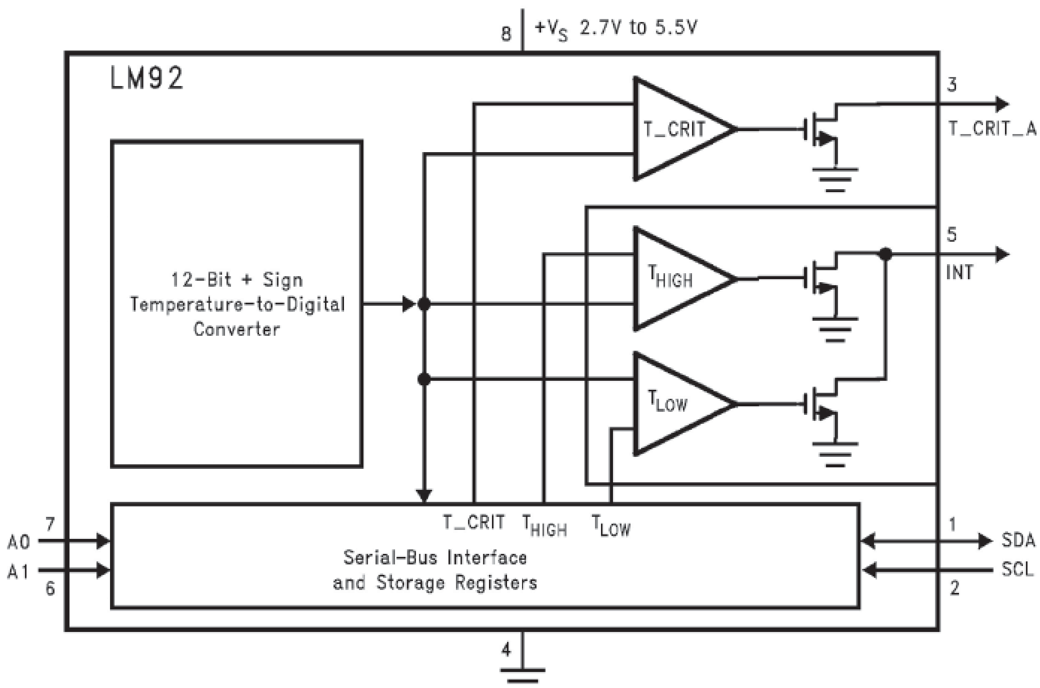


Figure 2-15. The LM92 Sensor is a Very Accurate and Highly-Integrated Digital Temperature Sensor with a Window Comparator and a Critical-Temperature Output

LM75 Digital Temperature Sensor and Thermal WATCHDOG with 2-Wire Interface

National's LM75 sensor is an industry-standard integrated-circuit digital temperature sensor. The LM75 device contains a temperature sensor, a delta-sigma ADC, a 2-wire digital interface, and registers for controlling the IC's operation. The 2-wire interface follows the I^2C protocol.

Three pins (A0, A1, and A2) are available for selection of eight possible I^2C addresses. Temperature is continuously being measured, and can be read at any time. The host processor can instruct the LM75 sensor to monitor temperature and take the OS output pin high or low (the sign is programmable) if the temperature exceeds a programmed limit. A second, lower threshold temperature can also be programmed so the host can be notified when temperature has dropped below this threshold. The OS function supports both Comparator and Interrupt modes. Thus, the LM75 device is the heart of a temperature monitoring and control subsystem for microprocessor-based systems such as personal computers. Temperature data is represented by a 9-bit word (1 sign and 8 magnitude bits in 2's complement format), resulting in 0.5°C resolution. Accuracy is ±2°C from -25°C to +100°C and ±3°C from -55°C to +125°C.

The LM75 sensor is available in an SO-8 package or the smaller MSOP-8 package. The LM75B version includes low-pass filters on the clock and data lines to make the communications robust against the effects of system-induced noise on the lines. It also features a time-out timer on the data line so, if the I^2C bus gets stuck low by any component on the bus, it will reset the interface and wait for the beginning of the next communication. This method can also be used to reset the interface externally.

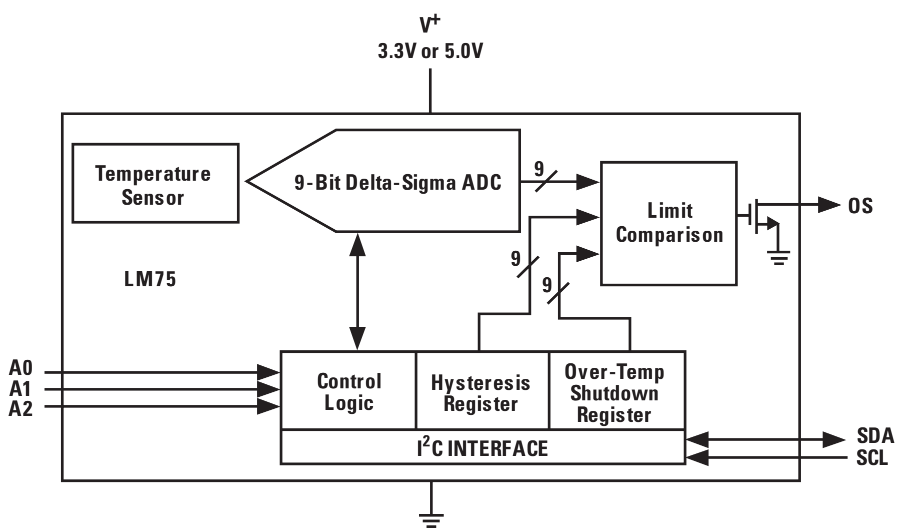


Figure 2-16. LM75 Block Diagram

LM95071 High-Accuracy Digital Temperature Sensor with SPI/MICROWIRE® Interface

The LM95071 sensor continues the tradition of National's digital temperature sensors that are compatible with the SPI/ MICROWIRE® interface. Following up on the success of the LM74 and LM70 sensors, the LM95071 sensor provides excellent accuracy over a wide operating temperature and large supply voltage range in a small SOT-23 package. Its easy-to-use 3-wire interface connects easily to the GPIO pins of a processor or ASIC, with minimal interface programming effort. The host can query the LM95071 sensor at any time to read temperature. A shutdown mode is available for reduced power consumption. Excellent accuracy of ±1°C from 0°C to 70°C and ±2°C over the full operating temperature range of -40°C to +150°C make the LM95071 device ideal for a wide range of electronic system applications.

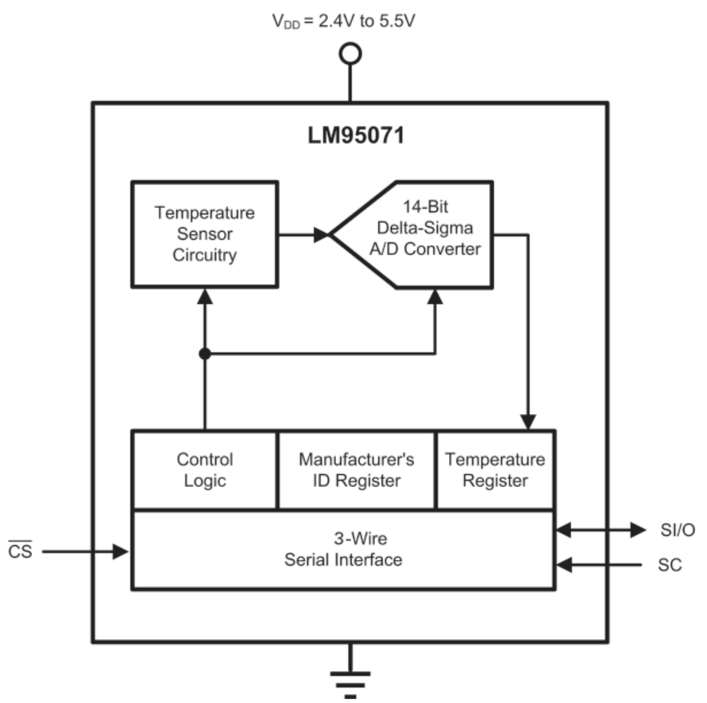


Figure 2-17. The LM95071 features an Analog Temperature Sensor, a High-Resolution Delta-Sigma ADC, and an Easy-to-Use 3-Wire Interface

Like the LM73 sensor, the LM95071 sensor provides an extremely stable digital output (***Figure 2-18***). For a given measured temperature, the data that is read has very little variance from one reading to the next – generally less than 1 LSB. This means there is generally no need to filter the output data. The LM95071 and LM73 sensors are ideal for applications requiring stable repetitive temperature readings, like temperature compensation of a crystal oscillator.

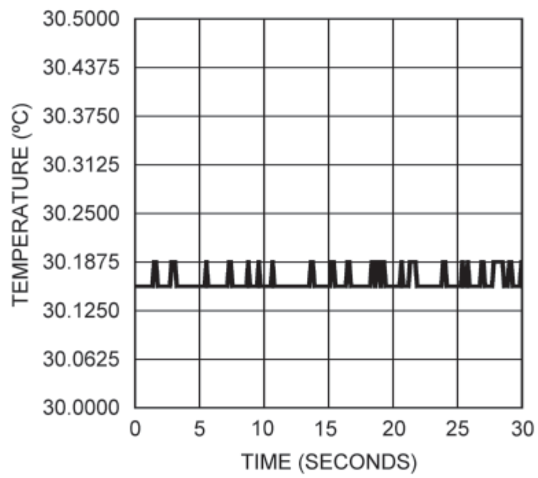


Figure 2-18. Even at Very High Resolution, the LM95071 Sensor Exhibits a Very Stable Digital Output

LM70 SPI/MICROWIRE 11-Bit Digital Temperature Sensor

The LM70 sensor integrates a temperature sensor and a delta-sigma ADC. It communicates with a host processor over the 3-wire SPI/MICROWIRE serial communications bus. Temperature readings from -50°C to +150°C are reported in a simple 2's-complement format with a resolution of 0.25°C per LSB. The LM70 sensor also features a shutdown mode that can be enabled by a write command from the system host. This allows the system to save power when continuous temperature measurements are not required.

The LM70 sensor is available in either an MSOP-8 package or an 8-pin leadless leadframe package (LLP®). The LLP features an exposed die-attach pad for improved heat transfer (low thermal resistance) between the printed circuit board and the die of the LM70 device.

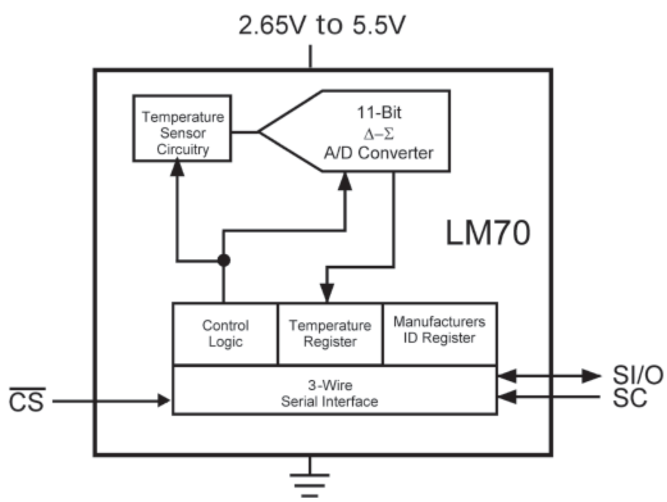


Figure 2-19. The LM70 Sensor features an Analog Temperature Sensor, a Delta-Sigma ADC, and an Easy-to-Use 3-Wire Digital Interface

LM74 SPI/MICROWIRE 13-Bit Digital Temperature Sensor

Like the LM70 sensor, the LM74 sensor integrates a temperature sensor and a delta-sigma ADC. It communicates with a host processor over a 3-wire SPI/MICROWIRE serial communications bus. The resolution of this digital temperature sensor is 0.0625°C per LSB, making it able to sense and report very small changes in temperature. Temperature readings from -50°C to +150°C are reported in a simple 2's-complement format. The LM74 sensor also features a shutdown mode that can be enabled by a write command from the system host. This allows the system to save power when continuous temperature measurements are not required. The LM74 sensor is available in either an MSOP-8 or a 5-bump microSMD package. The small 1.6 mm x 1.6 mm microSMD package makes the LM74 sensor ideally suited for a broad range of applications including portable systems and other systems where reducing required board area is critical.

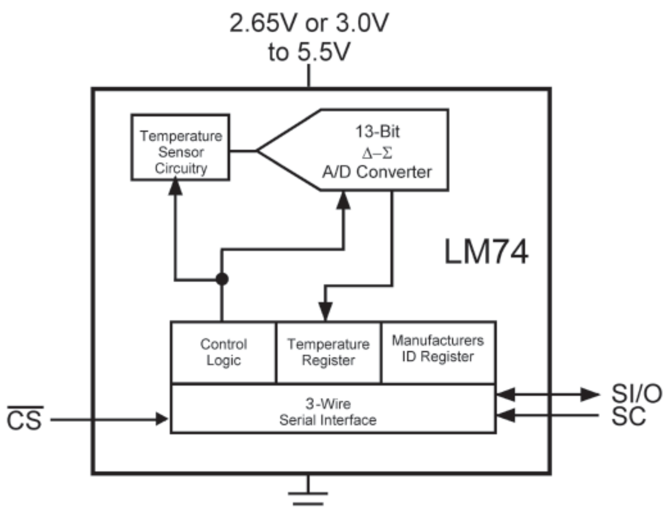


Figure 2-20. The LM70 features an Analog Temperature Sensor, a Delta-Sigma ADC, and an Easy-to-Use 3-Wire Interface

2.5 Remote-Diode Digital Sensors

Remote-diode digital sensors sense the temperature of a remote diode implemented in another IC such as a processor, ASIC, or FPGA. The "remote diode" is actually a PNP transistor with its collector tied to the device's substrate. This PNP is inherently available in most CMOS processes and therefore can be easily implemented in any complex, power-hungry circuit that can easily overheat. For a cost-effective system approach where ambient temperature is required, a 2N3904 transistor can also be used. A traditional diode-sensing approach was first established by a number of semiconductor vendors. In deep sub-micron geometries (90 nm or less), readings will vary greatly between individual processors or FPGAs when the traditional approach is used. Therefore, a new approach was invented by National Semiconductor called TruTherm® BTJ/Transistor beta-compensation technology. For a more detailed discussion on remote-diode temperature sensing, see **Section 3.** This section provides a brief overview of the less complicated devices National offers that support these functions. National's lines of hardware monitors also support remote-diode temperature sensing; however they will not be covered in this section. For more information, see **Section 2.6.**

The LM86, LM89, LM90, and LM99 Traditional Single-Channel Remote-Diode Temperature Sensors with SMBus Interface, T_CRIT, and ALERT Outputs

The LM86, LM89, LM90, and LM99 are a family of traditional remote-diode digital sensors. As can be seen in ***Figure 2-21***, the block diagram shows that in addition to a 2-wire System Management Bus (SMBus) serial interface these devices also provide ALERT and T_CRIT_A digital outputs. These outputs can be used in conjunction with set-point registers to inform a controller of an error event. Activation of the ALERT output occurs when any temperature goes outside a preprogrammed window set by the HIGH and LOW temperature-limit registers or exceeds the T_CRIT temperature limit. Activation of the T_CRIT_A occurs when any temperature exceeds the T_CRIT programmed limit. The T_CRIT limit has a programmable hysteresis register. Differences between these devices are shown in ***Table 2-22***.

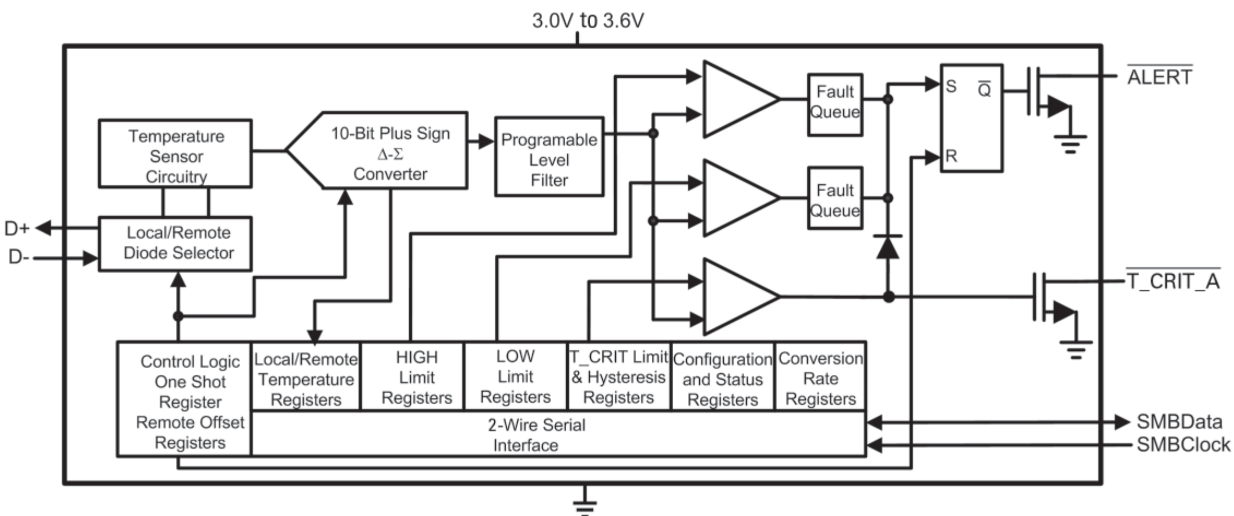


Figure 2-21. Block Diagram for the LM86 Family of Traditional Remote-Diode Digital Sensors

Table 2-22. Summary of Differences between the LM86, LM89, LM90, and LM99 Sensors

	LM86	LM89	LM90	LM99
Remote-Diode Accuracy	±0.75°C	±0.75°C	±3.0°C	±1.0°C
Remote-Diode Target Ideality	1.008	1.0021	1.008	NVIDIA GeForceFX
Remote-Diode Target Series Resistance	0Ω	3.64Ω	0Ω	
Default T_CRIT Setpoint	+85°C	+110°C	+85°C	+126°C
Default ALERT High Setpoint	+70°C	+70°C	+70°C	+86°C
Remote-Temperature-Reading Offset	0°C	0°C	0°C	-16°C
SMBus Device Address	4Ch	4Ch and 4Dh	4Ch	4Ch and 4Dh
Packages	MSOP-8, SOIC-8	MSOP-8, SOIC-8	MSOP-8	MSOP-8

For remote temperature readings, a digital filter can be invoked to filter out digital or thermal noise injected into the remote diode. To prevent false triggering of the ALERT output, a digital fault queue can be invoked that requires consecutive events to occur before triggering of these outputs.

LM95235 and LM95245 TruTherm® Single-Channel Remote-Diode Temperature Sensor with SMBus Interface, T_CRIT, and ALERT Outputs

The LM95235 and LM95245 sensors have a new TruTherm® BJT/Transistor beta-compensation analog front end (AFE) for measuring remote-diode temperature sensors. They are pin-, function-, and register-compatible with the LM89 family of products. The LM95235/LM95245 also has an improved traditional remote-diode AFE and extended temperature resolution for resolving temperatures above 127.875°C with two different formats for the -128°C/+127.875°C and 0°C/+255°C ranges. The LM95235 and LM95245 sensors contain a diode-model selection bit to select between a typical Intel processor or MMBT3904 transistor, as well as an offset register for maximum flexibility and best accuracy. The LM95235 sensor is targeted for a typical Intel processor on a 65 nm or 90 nm process while the LM95245 sensor is targeted for 45 nm, 65 nm, or 90 nm processes. The LM95235 sensor powers up in the TruTherm mode and automatically detects whether a processor diode or an MMBT3904 remote transistor is connected. Upon detecting the MMBT3904 transistor, it automatically switches modes of operation. The LM95245 sensor does not support this function and only powers up in the TruTherm mode. The ALERT pin function has been modified to a dual function pin with over-temperature shutdown (OS) and Address Select functions. The Address Select function allows up to three devices to be placed on a single bus using a simple hardware option. The LM89 family supports different device addresses with different part number ordering options, while with the LM95235 only one order number need be supported for systems that use multiple devices. The OS function is sacrificed when the address selection is used. The T_CRIT and OS outputs are asserted when either unmasked channel exceeds its programmed limit and can be used to shut down the system, to turn on the system fans, or as a microcontroller-interrupt function. The current status of the T_CRIT and OS pins can be read back from the status registers via the SMBus interface. All limits have a shared programmable hysteresis register. The digital filter function has been improved in the LM95235 sensor with an enhanced digital filter with better spike rejection. The LM95235 and LM95245 sensors include power-saving functions such as programmable conversion rate, one-shot conversion mode, and shutdown mode.

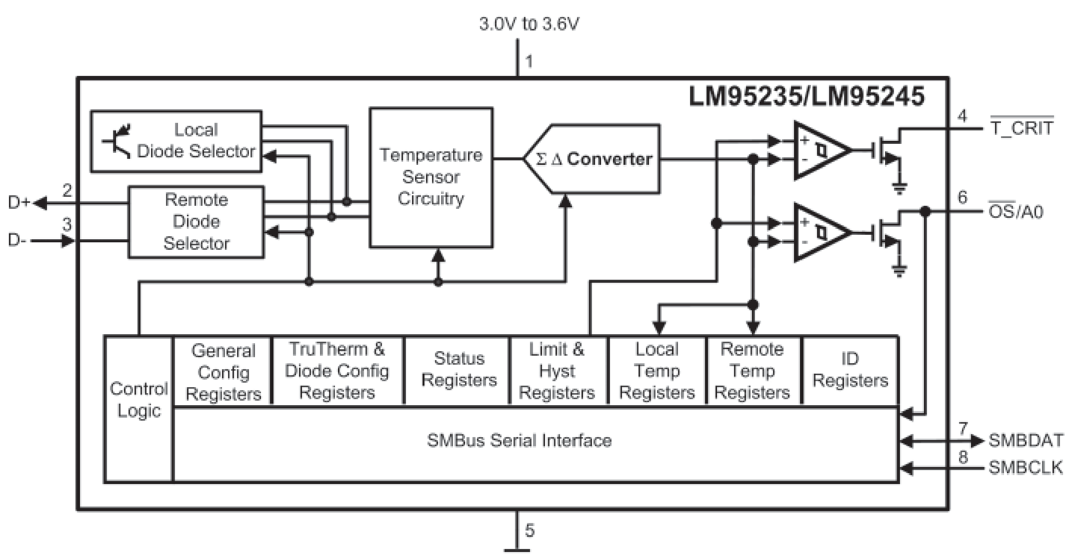


Figure 2-23. LM95235/LM95245 Block Diagram

The LM95221 Traditional Dual-Channel Remote-Diode Temperature Sensor with SMBus Interface

The LM95221 is a basic remote-diode digital sensor with two remote input channels and a local sensor that only supports the traditional mode of sensing the thermal diode temperature. It includes a Status Register that reports when a diode is missing or misconnected. The analog core of this device is an improvement over the LM89 family of sensors. The LM95221 sensor includes programmable conversion rates, one-shot conversion mode, and shutdown mode for minimization of power consumption when temperature data is not required. The remote-diode temperature readings have a resolution of 0.125°C, with a signed digital format for resolving positive or negative temperatures and an unsigned digital format for resolving temperature above 127.875 °C. The local temperature resolution is 0.25°C. The accuracy of this device is ±1°C for a temperature of +45°C to +85°C when using a thermal diode with an ideality of 1.008 and a series resistance of 2.7Ω. For more information on thermal-diode ideality and series resistance, see **Section 3.6.**

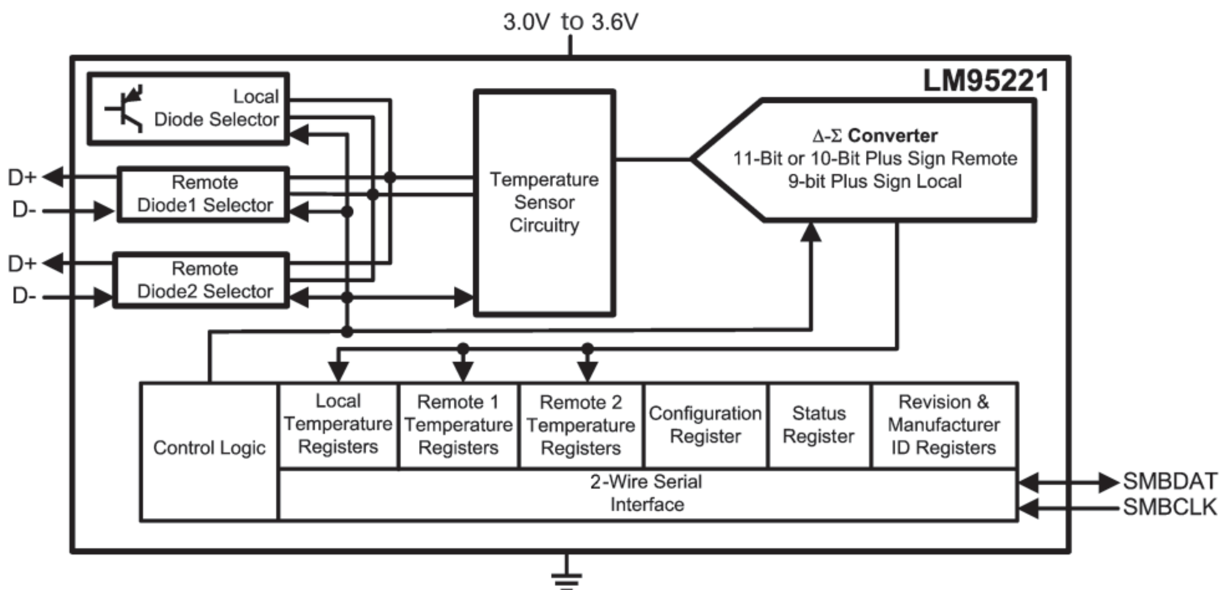


Figure 2-24. LM95221 Block Diagram

LM95231 and LM95241 TruTherm Dual-Channel Remote-Diode Temperature Sensors with SMBus Interface

The LM95231 and LM95241 sensors are register- and pin-compatible to the LM95221 sensor. They build upon the functions in the LM95221 sensor with the addition of a digital-spike, clamping and smoothing filter, diode-model selection bit, and TruTherm BJT/Transistor beta-compensation technology. The LM95231 sensor was National's first TruTherm device and is targeted for Intel processors on 90 nm processes. The LM95241 sensor is targeted for Intel processors on the 65 nm process but also works well with their processors on 90 nm processes when offset compensation is used. The LM95241 and LM95231 model-selection bit also allows them to accurately sense an MMBT3904 transistor without any offset compensation. For more information on TruTherm technology, see **Section 3.6.**

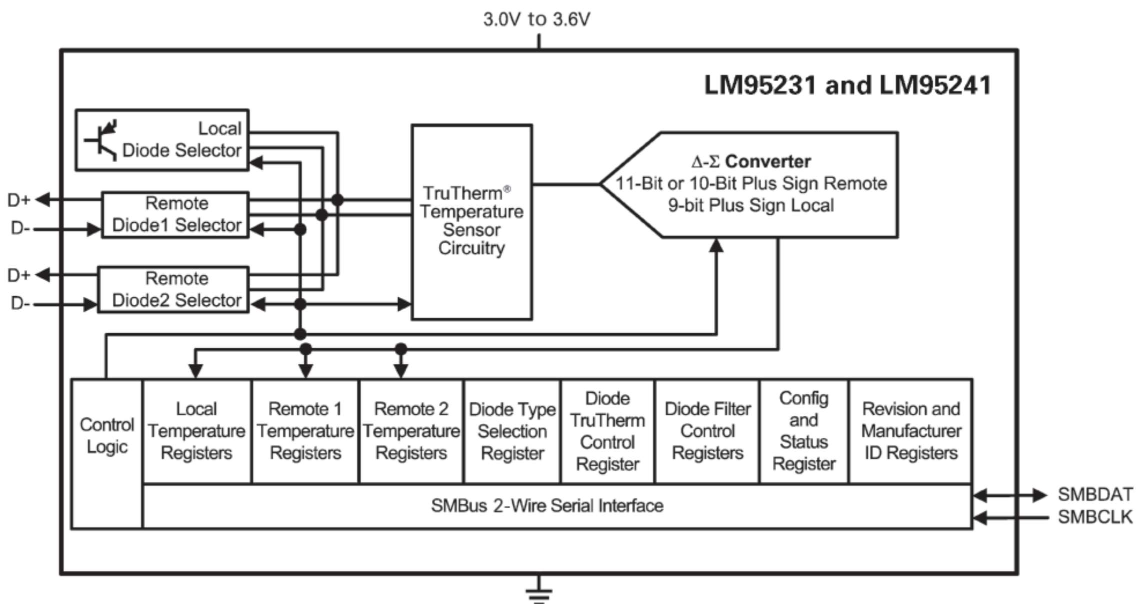


Figure 2-25. LM95231 and LM95241 Block Diagram

The LM95233 and LM95234 Dual/Quad Remote-Diode and Local Temperature Sensor with SMBus Interface and TruTherm Technology

The LM95233 and LM95234 devices are 11-bit digital temperature sensors with 2-wire SMBus interfaces that can accurately (±0.875°C) monitor the temperature of multiple remote diodes as well as their own temperature. The LM95233 sensor can be used to monitor the temperature very accurately of up to two external devices such as microprocessors, graphics processors, or diode-connected 2N3904 transistors. The LM95234 sensor can be used to monitor the temperature very accurately of up to four of these external devices. For optimum flexibility and accuracy, each of the LM95233 or LM95234 sensor's remote channels includes registers for BJT (sub-micron process) or 2N3904 diode-model selection as well as offset correction. The LM95233 and LM95234 sensors utilize TruTherm BJT/Transistor beta-compensation technology for improved sensing accuracy of sub 90 nm process thermal diodes. Please refer to **Section 3.6** for more information on the modes of thermal-diode sensing. Temperature is reported in two different formats for the -128°C /+127.875°C and 0°C/+255°C ranges. The LM95233 and LM95234 sensors provide T_CRIT1, T_CRIT2, and T_CRIT3 outputs which are triggered when any unmasked channel exceeds its corresponding programmable limit and can be used to shut down the system, to turn on the system fans, or as a microcontroller-interrupt function. The current status of the T_CRIT1, T_CRIT2, and T_CRIT3 pins can be read back from the status registers. Mask registers are available for further control of the T_CRIT outputs. All remote temperature channels employ analog filters, minimizing the need for additional external filter components. Both of the LM95233 sensor's remote temperature channels have programmable digital filters to minimize unwanted T_CRIT events when temperature spikes are encountered. Two of the LM95234 sensor's remote temperature channels have programmable digital filters while the other two remote channels utilize a fault queue to minimize unwanted T_CRIT events when temperature spikes are encountered. A three-level address pin allows connection of up to three LM95233 sensors or three LM95234 sensors to the same SMBus master. The addresses of the LM95233 and LM95234 sensors are not all the same, allowing up to five of these devices to be combined on the same SMBus. The LM95233 and LM95234 sensors include power-saving functions such as programmable conversion rate, one-shot conversion mode, shutdown mode, and the ability to turn off unused channels.

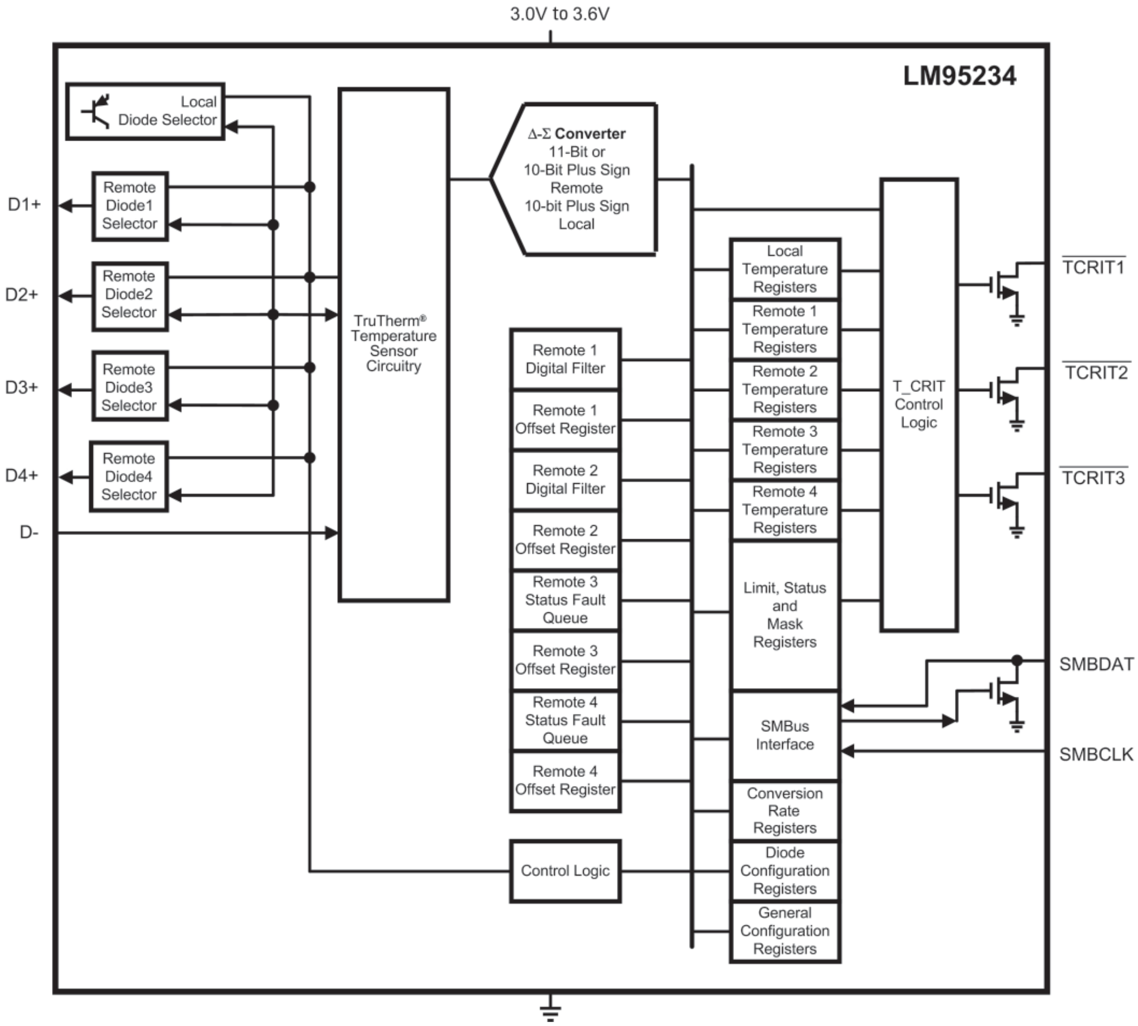


Figure 2-26. LM95234 Block Diagram

LM95213 and LM95214 Dual/Quad Remote-Diode and Local Digital Temperature Sensors with 2-Wire/SMBus Interface and T_CRIT Outputs

The LM95213 and LM95214 devices are 11-bit digital temperature sensors with a 2-wire SMBus interface that can accurately (±1.1°C) monitor the temperature of multiple remote diodes as well as their own temperature. The LM95213 sensor can be used to monitor the temperature very accurately of up to two external devices such as microprocessors, graphics processors, or a diode-connected 2N3904 transistor. The LM95214 sensor can be used to monitor the temperature very accurately of up to four of these devices. Temperature is reported in two different formats for -128°C /+127.875°C and 0°C/+255°C ranges. The T_CRIT1, T_CRIT2, and T_CRIT3 outputs are triggered when any unmasked channel exceeds its corresponding programmable limit and can be used to shut down the system, to turn on the system fans, or as a microcontroller-interrupt function. The current status of the T_CRIT1, T_CRIT2, and T_CRIT3 pins can be read back from the status registers. Mask registers are available for further control of the T_CRIT outputs. The LM95213 sensor's remote temperature channels have programmable digital filters to minimize unwanted T_CRIT events when temperature spikes are encountered. Two LM95214 remote temperature channels have programmable digital filters while the other two remote channels utilize a fault queue to minimize unwanted T_CRIT events when temperature spikes are encountered. For optimum flexibility and accuracy, each remote-diode channel includes offset correction registers for targeting diodes other than the 2N3904 transistor. A three-level address pin allows connection of up to three LM95213 sensors or three LM95214 sensors to the same SMBus master. The addresses of the LM95213 and LM95214 sensors are not all the same, allowing up to five of these devices to be combined on the same SMBus. The LM95213 and LM95214 sensors include power-saving functions such as programmable conversion rate, shutdown mode, and the ability to turn off unused channels.

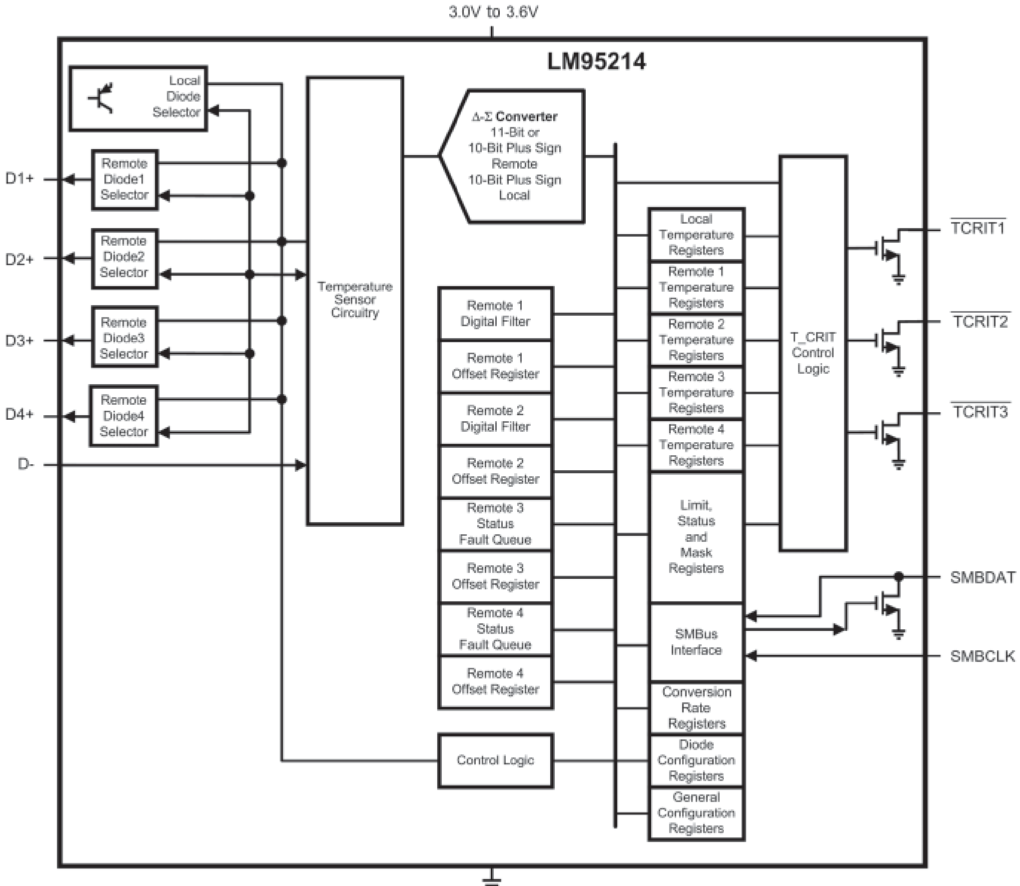


Figure 2-27. LM95214 Block Diagram

2.6 Hardware Monitors

National's final product family is the System Hardware Monitor family or Hardware Monitors, for short. These devices take standard and remote-diode digital temperature sensors of the previous families and integrate more functionality. Besides sensing temperature, hardware monitors are used to monitor fan speed, detect impending failure, control fan speed for noise abatement, optimize system efficiency, monitor supply voltages, detect chassis intrusion, monitor key processor digital signals associated with system thermal performance, and monitor and report the state of the core voltage of the system in question.

LM63 and LM64 Remote-Diode Input Digital Temperature Sensors with Integrated Fan Control

The LM63 is an 8-pin digital temperature sensor with integrated fan control. It features a 2-wire digital interface compatible with SMBus 2.0 and supports the Alert Response Address Protocol. Using a ΔΣ ADC, the LM63 sensor measures its own temperature as well as an external device such as a microprocessor, a graphics processor, or a diode-connected 2N3904 transistor. It comes with a tachometer input for fan speed monitoring and an open-drain pulse-width modulation (PWM) output for fan speed control. The LM63 controls fan speed based on remote-diode input temperature and has a built-in digital filter that can suppress erroneous temperature measurements. Its 8-step lookup table supports non-linear temperature versus fan-speed transfer functions, and therefore provides system designers the flexibility to reduce fan acoustic noise. The PWM output is compatible with the 4-pin fans and can output high- or low-frequency PWM signals.

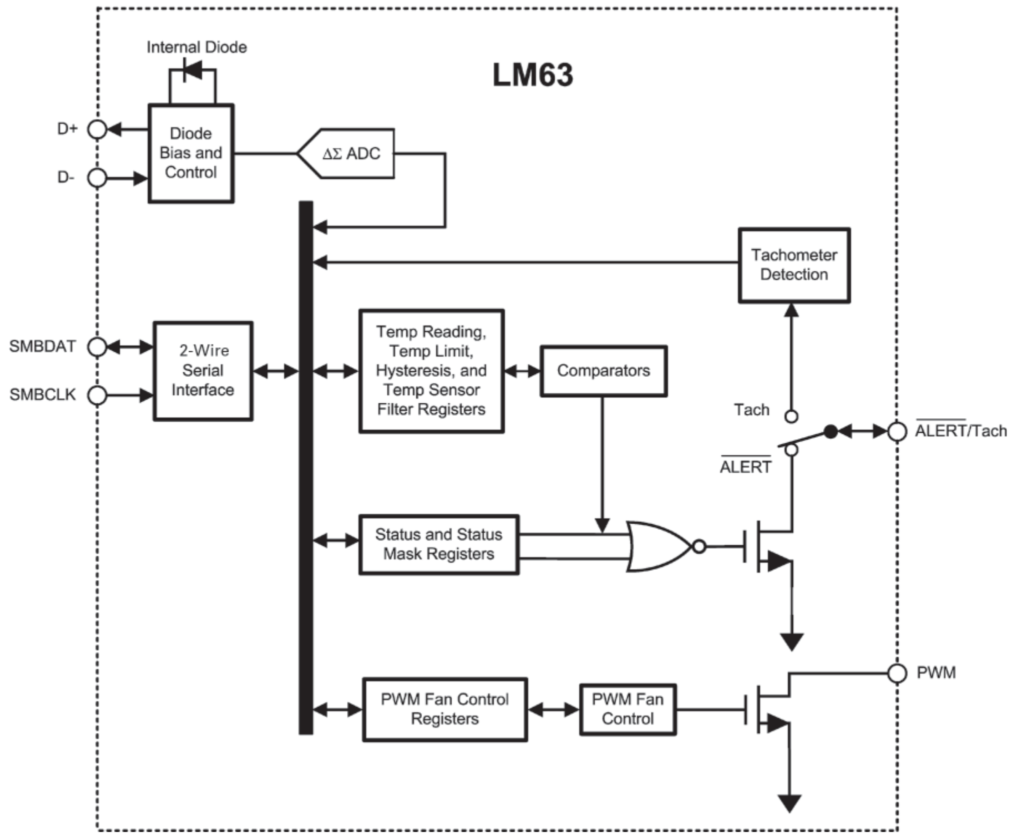


Figure 2-28. LM63 Block Diagram

The LM64 sensor is available in a small 4 mm x 5 mm LLP-24 package, and it includes all of the features that the LM63 sensor offers. In addition to the LM63 sensor's functions, the LM64 sensor resolves remote-measured temperature up to 143.875°C and features a dedicated critical temperature (T_CRIT) output for system shutdown. While the LM63 has a shared pin for the tachometer input and the ALERT output, the LM64 has individual pins for each function. Moreover, it has five general-purpose I/Os (GPIO) with power-on defaults configurable at the five general-purpose default (GPD) inputs. Finally, the LM64 sensor comes with an address (A0) input so that two LM64 sensors can reside on the same bus.

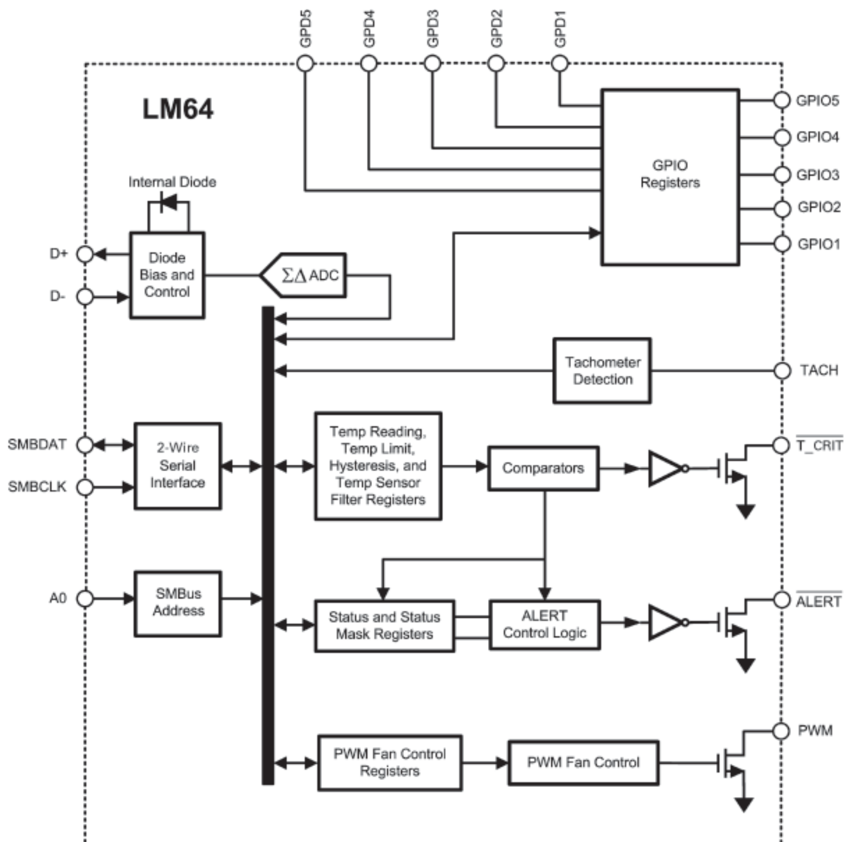


Figure 2-29. LM64 Block Diagram

For remote temperature readings, a digital filter can be invoked to filter out digital or thermal noise injected into the remote diode. To prevent false triggering of the ALERT output, a digital fault queue can be invoked that requires multiple events to occur before triggering of these outputs.

LM80 System Hardware Monitor with 2-Wire Serial Interface

The LM80 hardware monitor, with a power supply range of 2.8V to 5.75V and low supply current, offers the basics for system hardware monitoring and protection applications. It measures seven positive input voltages, its own temperature, and two fan speed inputs on an I²C interface. The LM80 monitor performs limit comparisons on all measured values and an open-drain interrupt (INT#) output is asserted when any value exceeds its corresponding programmed limits.

The LM80 device is commonly used for monitoring various power supplies on a system. In addition, it is especially well suited to interface to both analog and digital temperature sensors. The 2.56V input range is ideal for inputs from analog sensors such as the LM20 and LM50 devices. Also, the digital outputs of additional temperature sensors such as the LM26, LM56, LM75, and LM95245 devices, can be connected to the board temperature interrupt (BTI#) input of the LM80 monitor. The INT_IN# input allows propagation of the interrupts from other devices to the LM80 device. They can be observed at the INT# output of the LM80 monitor. The chassis intrusion (CI) pin is provided to monitor and reset an external circuit designed to latch a chassis intrusion event. Also, a reset output (RST_OUT#) can be generated via the serial interface.

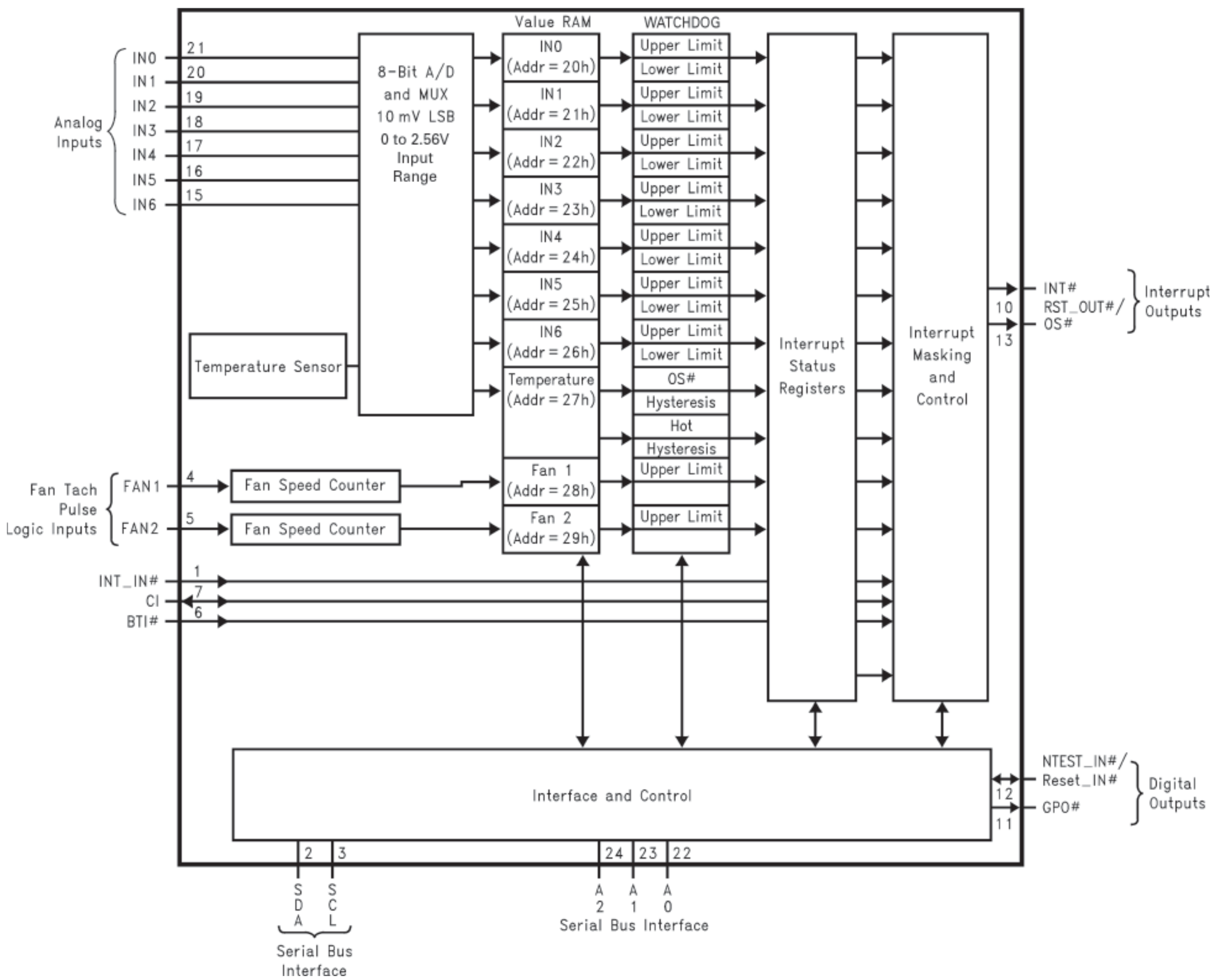


Figure 2-30. LM80 Block Diagram

LM81B System Hardware Monitor and Fan Control with 2-Wire Serial Interface

The LM81B is a system hardware monitor and fan control with a serial interface compatible with SMBus and I²C for microprocessor-based systems. It measures its own temperature, six power supply voltages, and two fan speeds. As an enhanced version of the LM80 monitor, the LM81B device has internal scaling dividers for commonly found power supplies such as 2.5V, 3.3V, 5V, and 12V so that they can be directly connected to the LM81B monitor. In addition, it offers a 1.25V range digital-to-analog converter (DAC) output for fan control.

The LM81B monitor performs limit comparisons on all measured values. When a limit is exceeded, the interrupt (INT) output will be asserted. In addition, the LM81B features a dedicated critical temperature output (T_CRIT_A) and can be used for over-temperature shutdown. Additional features include the five voltage identity (VID) input pins that can also be used as general-purpose inputs. The chassis intrusion pin can be used to monitor and reset an external circuit that detects a chassis intrusion event. The reset (RESET) pin can be used as an active-low input as well as a reset output.

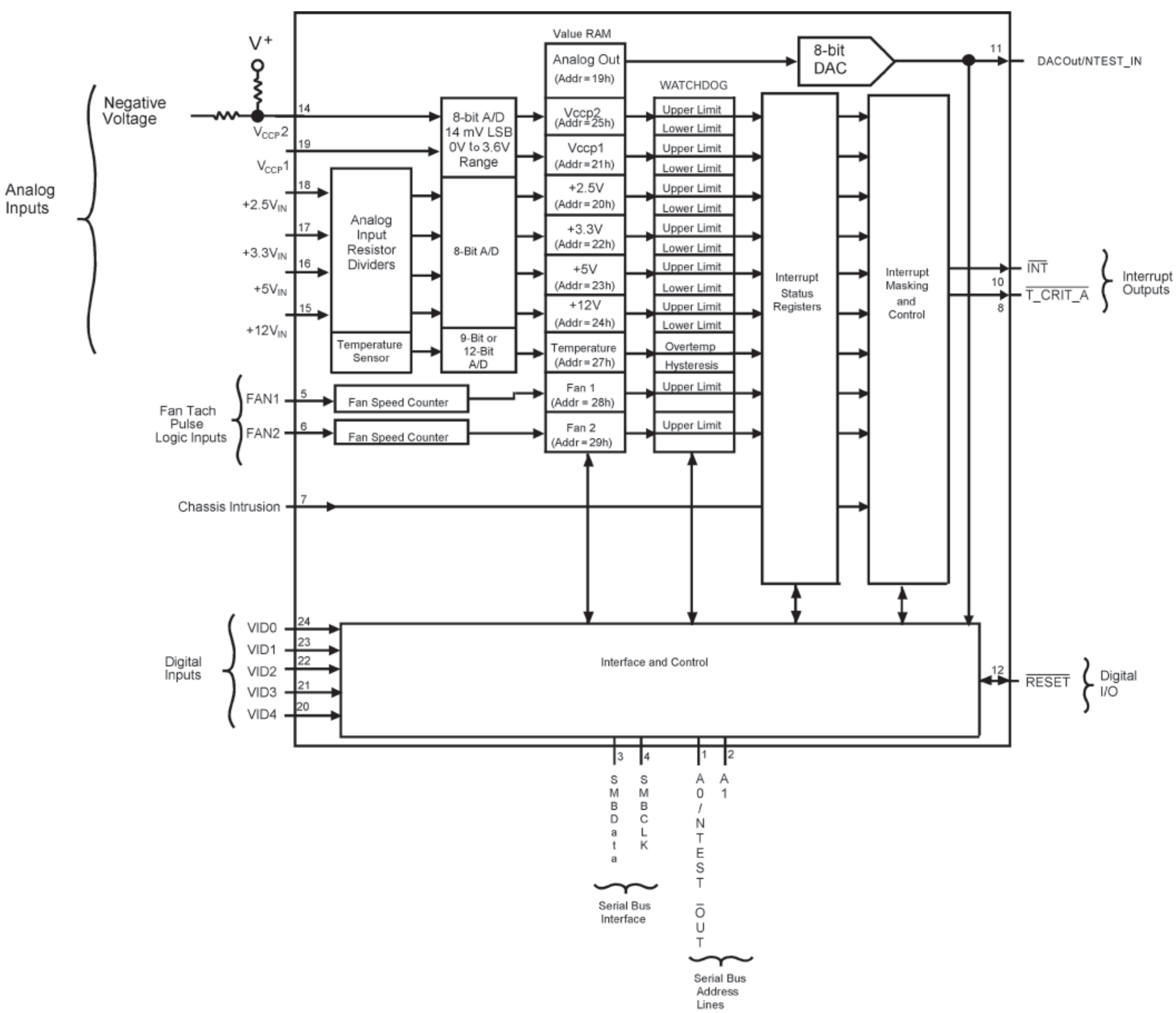


Figure 2-31. LM81 Block Diagram

LM87 2-Wire Serial Interface System Hardware Monitor with Remote-Diode Temperature Sensing and Fan Control

The LM87 device is a highly-integrated hardware monitor for virtually any microprocessor-based system including personal computers and servers. It features two remote-diode temperature monitors and utilizes a $\Sigma\Delta$ ADC architecture that allows stable measurement of signals in an extremely noisy environment. It also offers the general-system hardware-monitor functions such as its own temperature, power supplies with internal scaling resistors, and fan speed measurements. In addition, the DAC with a 2.5V output voltage range can be used for fan speed control.

The LM87 monitor performs a limit comparison on all measured values and triggers a fully programmable and maskable interrupt system with two outputs, INT# and THERM#. The chassis intrusion (CI) input allows the LM87 device to monitor and reset an external chassis intrusion detection circuit. The five voltage identification (VID) inputs are digitally programmable to monitor the VID outputs of a microprocessor, and they can be used also as IRQ or general-purpose inputs. The LM87 monitor comes with a 2-wire serial interface that is compatible with SMBus and I^{2}C and it also supports the SMBus Alert Response Address Protocol.

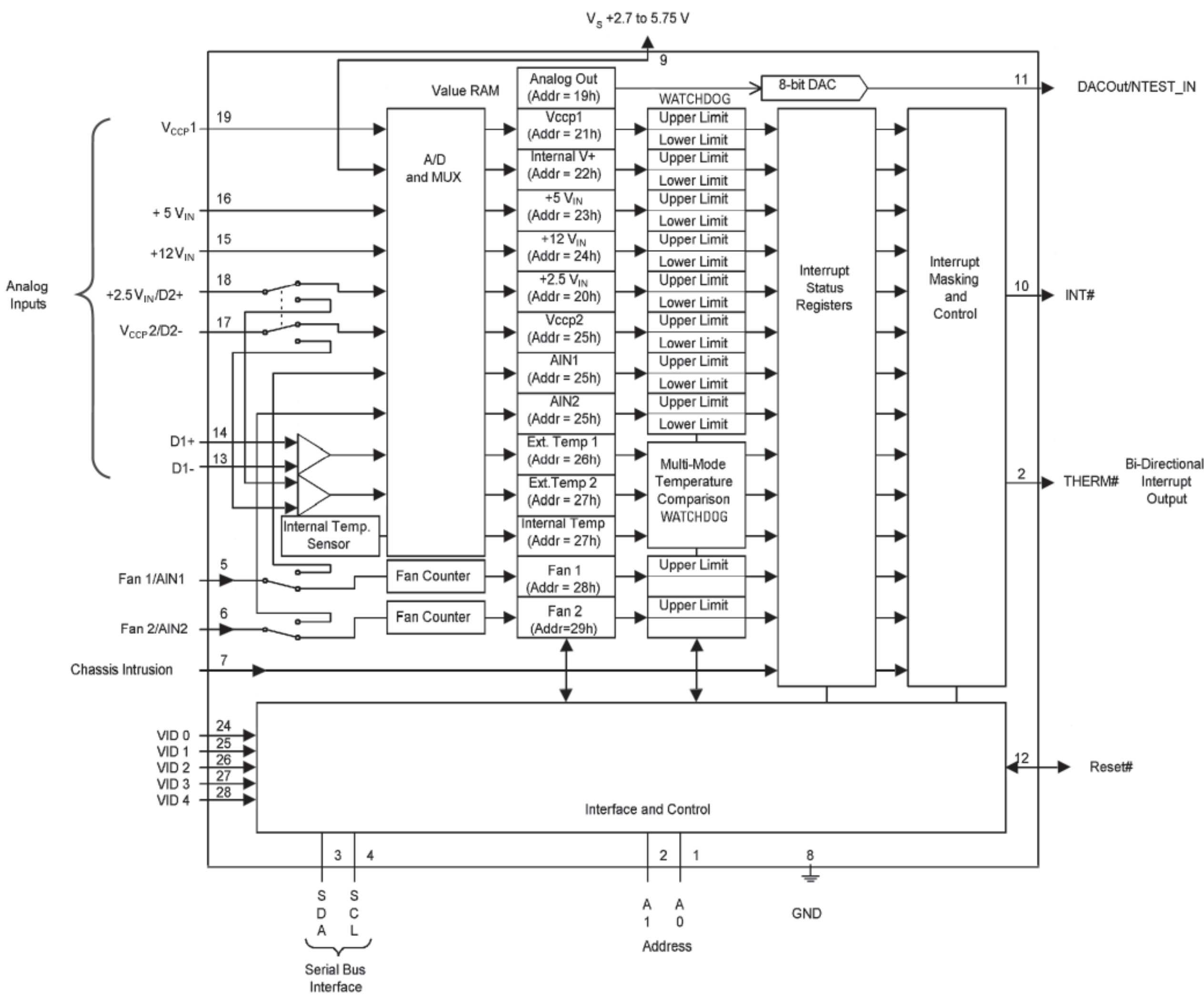


Figure 2-32. LM87 Block Diagram

LM96000 2-Wire Serial Interface Hardware Monitor with Integrated Fan Controls

The LM96000 is a highly-integrated hardware monitor with fan control capabilities for common microprocessor-based systems including personal computers and servers. Sitting on a 2-wire serial bus that is compatible with SMBus 2.0 and I^2C, it accurately measures two remote-diode temperatures, its own temperature, four fan speeds, and five power supplies. It also performs limit comparisons on all measured values and the status can be read via the serial interface.

As an enhanced version of the LM87, the LM96000 has a fully-programmable fan control system based on temperature zones. It provides four fan tachometer inputs and three pulse-width modulation (PWM) outputs for fan speed control. The PWMs can be independently controlled by up to three temperature zones, whichever one reports the hottest temperature. In addition, it digitally filters the two remote-diode temperature measurements for better control of fan speeds. Also, the LM96000 monitor not only has the low-PWM frequency support, but also the high-PWM frequency support that is essential for 4-pin fans.

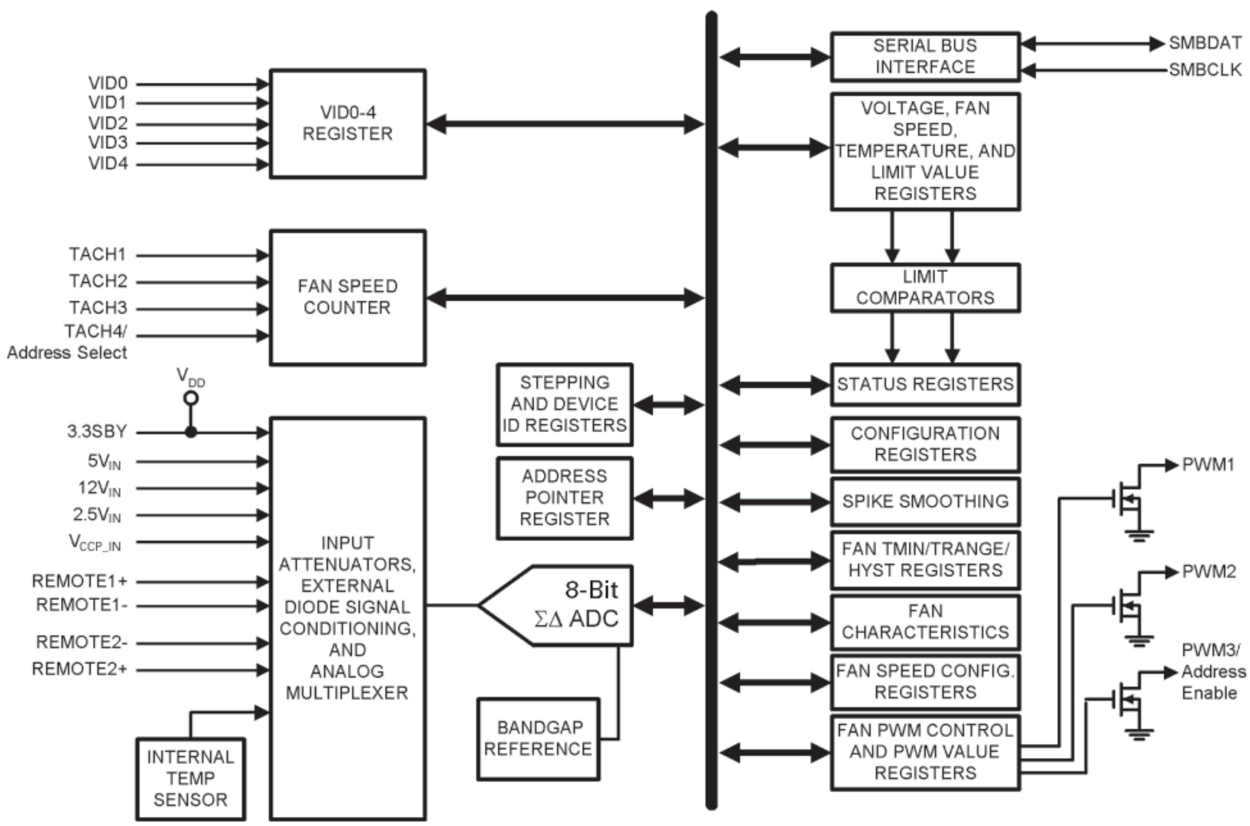


Figure 2-33. LM96000 Block Diagram

LM93 Hardware Monitor with Integrated Fan Control for Server Management

The LM93 IC is a hardware monitor with a 2-wire digital interface compatible with SMBus 2.0. Using a ΔΣ ADC, the LM93 monitor measures the temperature of its own die as well as two external devices such as processor thermal diodes or diode-connected transistors and 16 power supply voltages. All of the temperature information can be fed into the multiple lookup table (LUT)-based fan-control algorithm to set the fan speed with the two PWM outputs. The LM93 monitor includes digital filters that can be invoked to smooth temperature readings for better control of fan speed. The LM93 device has four tachometer inputs to measure fan speed. Limit and status registers for all measured values are included. The LM93 monitor includes several advanced hardware management and monitoring functions such as smart tachometer mode, dual dynamic V_{CCP} monitoring, dual PROCHOT measurements, GPIO and dual VID support, voltage reference output, and more. It is designed to monitor a dual processor motherboard with a minimum of external components.

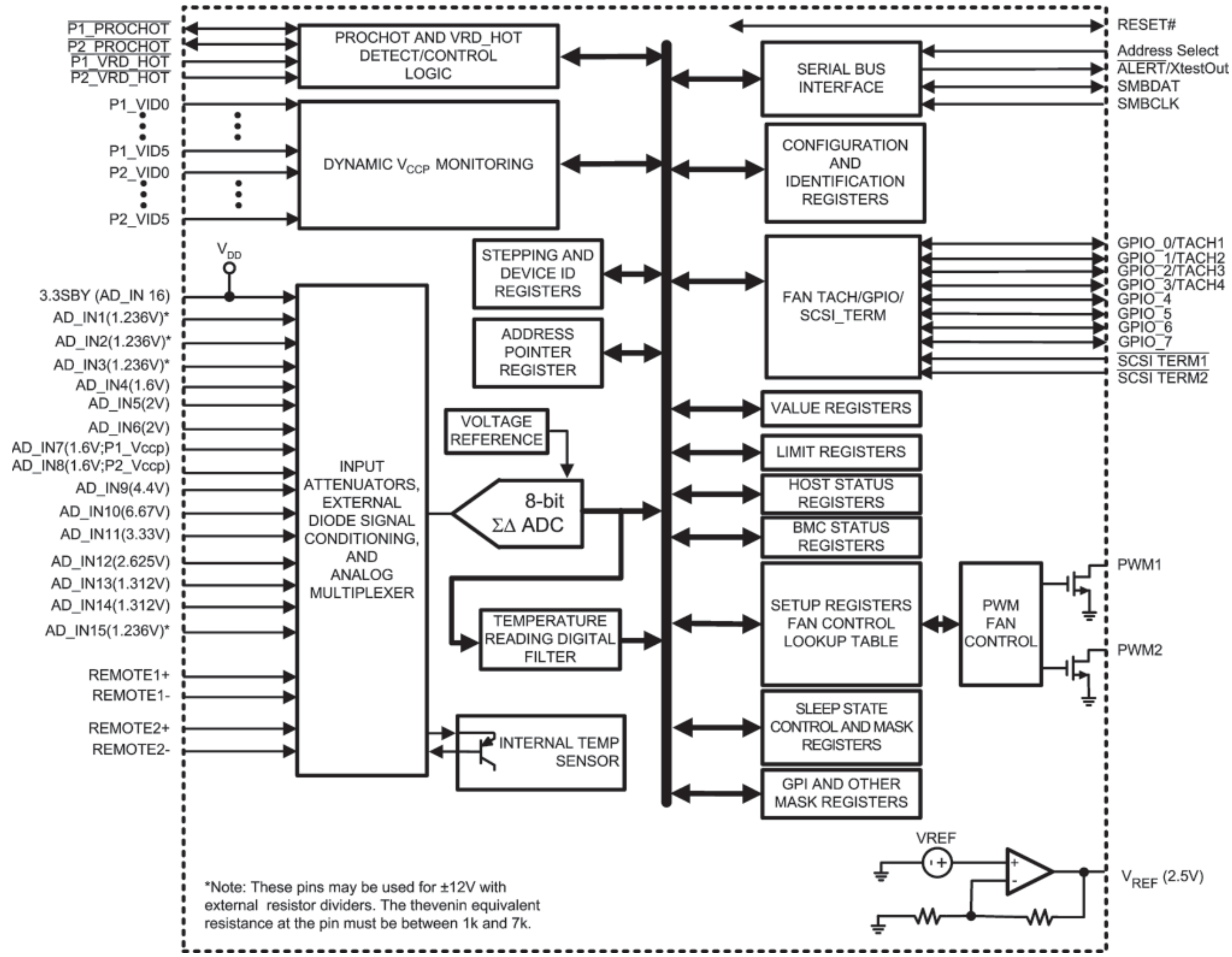


Figure 2-34. LM93 Block Diagram

LM96194 and LM94 TruTherm Hardware Monitors with Integrated Proportional Integral (PI) Loop Fan Control

The LM96194 and LM94 devices are hardware monitors with a 2-wire digital interface compatible with SMBus 2.0. The LM96194 and LM94 devices are designed to monitor workstation and server motherboards, respectively, with a minimum number of external components. Using a ΔΣ ADC, these monitors measure the temperature of their own die as well as four external devices such as processor thermal diodes or a diode-connected transistors. All four remote temperature channels support TruTherm technology that enables precise temperature measurements of processors on deep sub-micron geometries. The advanced fan-control algorithm can set the fan speed with two PWM outputs based on up to six temperature zones. The fan-control algorithm includes multiple programmable lookup tables and dual PI control loops. The PI control loops support the processor T_CONTROL-based fan control for acoustically-quiet system solutions. The LM96194 and LM94 monitors include digital filters that can be invoked to smooth temperature readings for better control of fan speed. They have four tachometer inputs with smart-tachometer-mode support to measure fan speed. Limit and status registers for all measured values are included. The LM94 includes two sets of dynamic V_{CCP} monitors, PROCHOT measurements, and VID monitors for VRD10/11, whereas the LM96194 monitor includes one set of each. Also, the LM94 monitor has a voltage reference output pin.

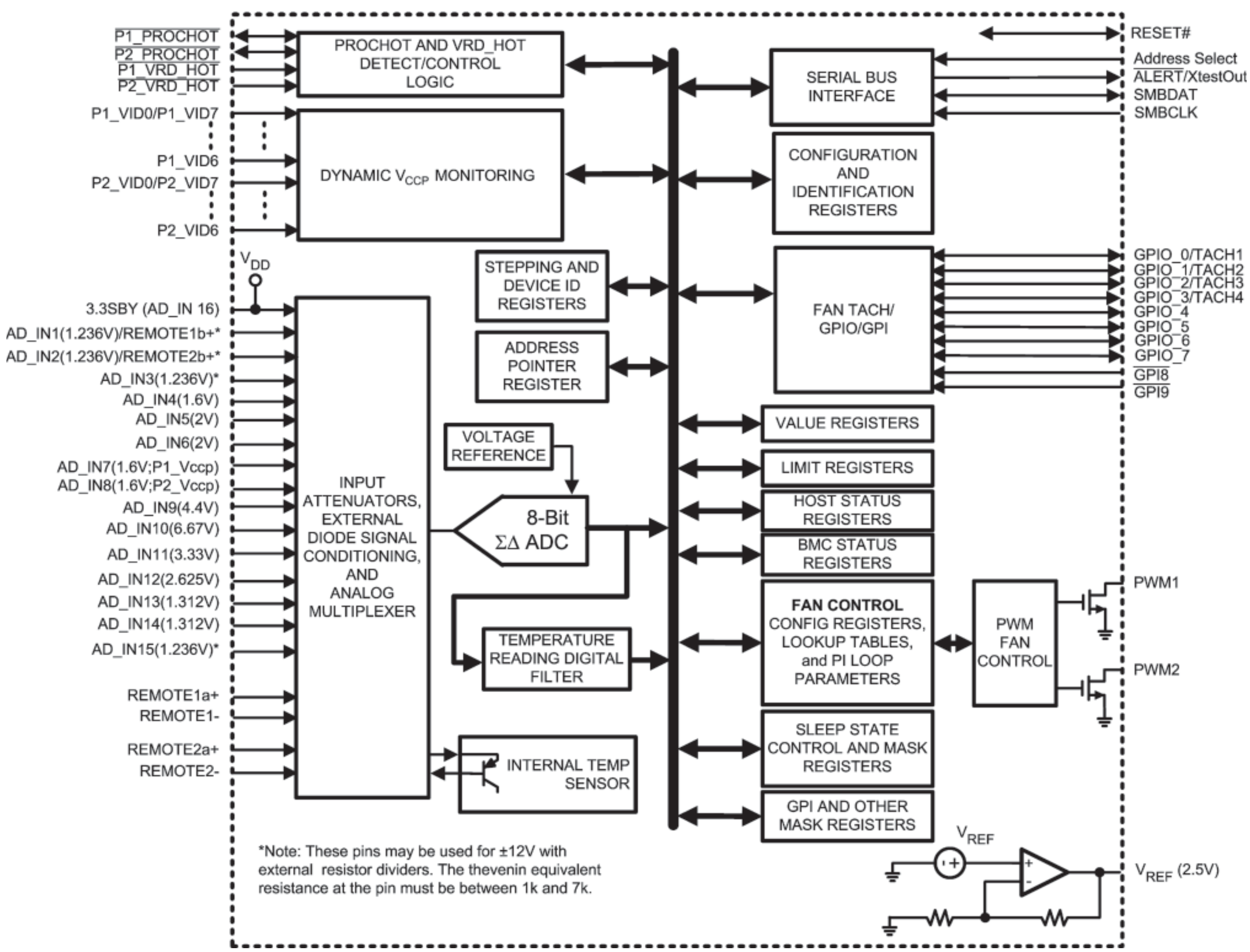


Figure 2-35. LM94 Block Diagram

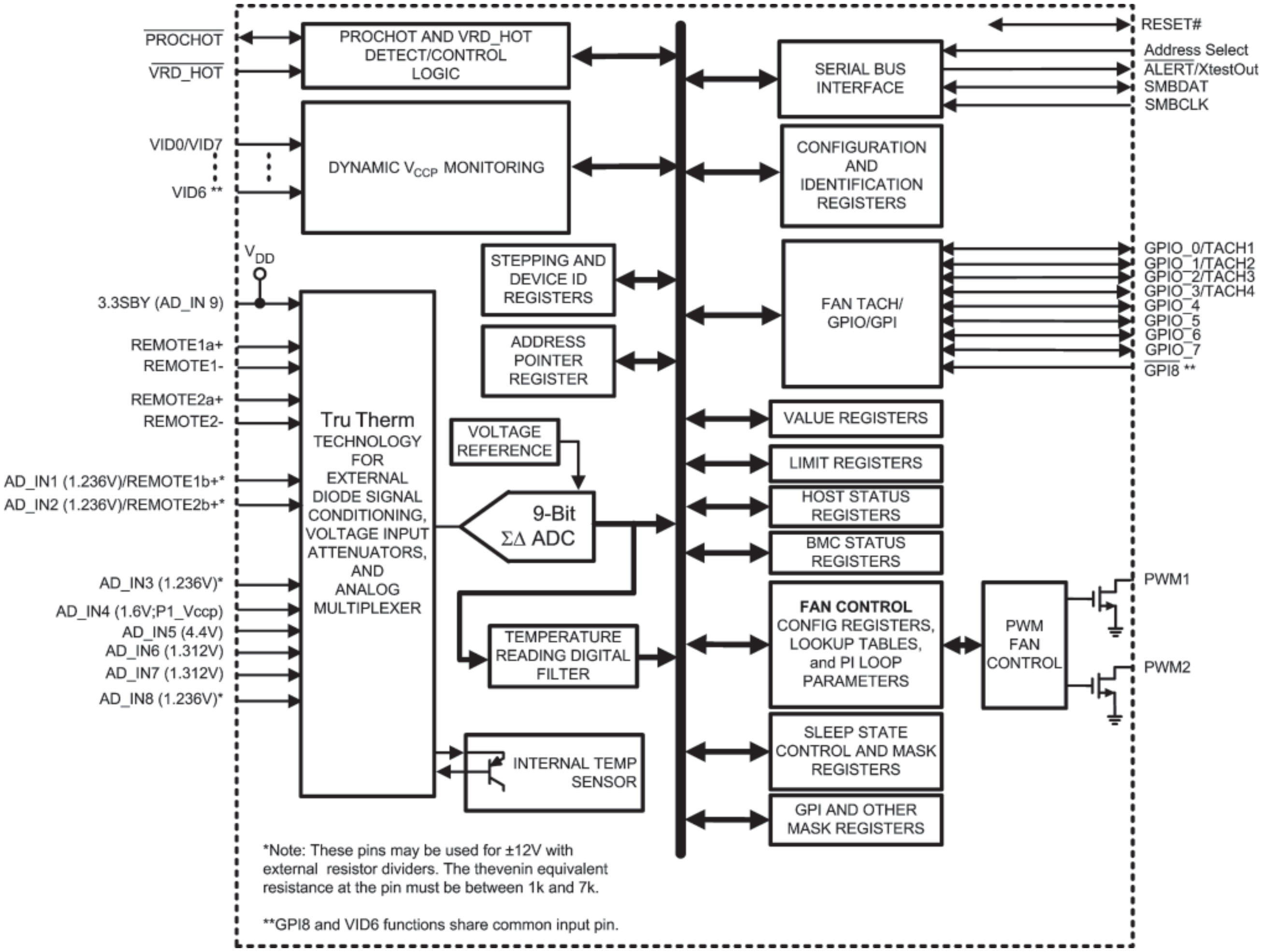


Figure 2-36. LM96194 Block Diagram

The following application hints apply to most of National's temperature-sensor ICs. For hints that are specific to a particular sensor, please refer to that sensor's datasheet.

3.1 Sensor Location for Accurate Measurements

A temperature sensor produces an output, whether analog or digital, that depends on the temperature of the sensor. Heat is conducted to the sensing element through the sensor's package and its metal leads. In general, a sensor in a metal package (such as a LM35 sensor in a TO-46) will have a dominant thermal path through the package. For sensors in plastic packages like the TO-92, SO-8, SC-70, and SOT-23, the leads provide the dominant thermal path. Therefore, a board-mounted IC sensor will do a fine job of measuring the temperature of the circuit board, especially the traces to which the leads are soldered. If the board's temperature is very close to the ambient air temperature; that is, if the board has no significant heat generators mounted on it, the sensor's temperature will also be very near that of the ambient air.

In order to measure the temperature of something other than the circuit board, the sensor and its leads must be at the same temperature as the object being measured. This usually involves making a good mechanical and thermal contact, for example, by attaching the sensor (and its leads) to the object being measured with thermally-conductive epoxy. If electrical connections can be made directly from the sensor's leads to the object being measured, soldering the leads of an IC sensor to the object will give a good thermal connection. If the ambient air temperature is the same as that of the surface being measured, the sensor will be within a fraction of a degree of the surface temperature. If the air temperature is much higher or lower than the surface temperature, the temperature of the sensor die will be at an intermediate temperature between the surface temperature and the air temperature. A sensor in a plastic package (a TO-92 or SC-70, for example) will indicate a temperature very close to that of its leads and will be very close to the circuit board's temperature, with air temperature having a less significant effect. A sensor in a metal package (like a TO-46) will usually be influenced more by air temperature. The influence of air temperature can be further increased by gluing or clamping a heat sink to the metal package.

If liquid temperature is to be measured and that liquid is electrically conductive, a sensor can be mounted inside a sealed-end metal tube. It can then be dipped into a bath or screwed into a threaded hole in a tank. Temperature sensors and any accompanying wiring and circuits must be kept insulated and dry to avoid leakage and corrosion. This is especially true for IC temperature sensors if the circuit may operate at cold temperatures where condensation can occur. Printed-circuit coatings and varnishes such as Humiseal and epoxy paints or dips are often used to ensure that moisture cannot corrode the sensor or its connections. There are some oils available that do not require electronic devices to be protected as they are not electrically conductive or corrosive.

So where should the sensor be placed in a given application? Following are three examples:

Example 1. Audio Power Amplifier

It is often desirable to measure temperature in an audio power amplifier to protect the electronics from overheating, either by activating a cooling fan or shutting down the system. Even an IC amplifier that contains internal circuitry to shut down the amplifier in the event of overheating (National's Overture® series amplifiers, for example) can benefit from additional temperature sensing. By activating a cooling fan when the temperature gets high, the system can produce more output power for longer periods of time, but still avoids having the fan, and producing noise when output levels are low.

Audio amplifiers that dissipate more than a few watts virtually always have their power devices (either discrete transistors or an entire monolithic amplifier) bolted to a heat sink. The heat sink's temperature depends on ambient temperature, the power device's case temperature and power dissipation, and the thermal resistance from the case to the heat sink. Similarly, the power device's case temperature depends on the device's power dissipation and the thermal resistance from the silicon to the case. The heat sink's temperature is therefore not equal to the "junction temperature", but it is dependent on it and related to it.

A practical way to monitor the power device's temperature is to mount the sensor on the heat sink. The sensor's temperature will be lower than that of the power device's die, but if the correlation between heat sink temperature and die temperature is understood, the sensor's output will still be useful.

Figure 3-1 shows an example of a monolithic power amplifier bolted to a heat sink. Next to the amplifier is a temperature-sensor IC in a TO-46 metal-can package. The sensor package is in a hole drilled into the heat sink; the sensor is cemented to the heat sink with heat-conducting epoxy. Heat is conducted from the heat sink through the sensor's case, and from the circuit board through the sensor's leads. Depending on the amplifier, the heat sink, the printed-circuit-board layout, and the sensor, the best indication of the amplifier's temperature may be obtained through the metal package or through the sensor's leads.

The amplifier IC's leads will normally be within a few degrees of the temperature of the heat sink near the amplifier. If the amplifier is soldered directly to the printed circuit board, and if the leads are short, the circuit board traces at the amplifier's leads will be quite close to the heat sink temperature — sometimes higher, sometimes lower, depending on the thermal characteristics of the system. Therefore, if the sensor can be soldered to a point very close to the amplifier's leads, a good correlation with heat sink temperature will be achieved. This is especially good news if a temperature sensor is in a plastic package, since thermal conduction for such a device is through the leads. The sensor should be located as close as possible to the amplifier's leads. If the amplifier has a ground pin, the sensor's ground pin should be placed right next to that of the amplifier and the other sensor leads should be kept at the same temperature as the amplifier's leads.

If the heat sink is mounted to the backside of the printed circuit board, the sensor can be mounted on the top of the board, as close as practical to the power device(s). This will provide good correlation between measured temperature and heat sink temperature.

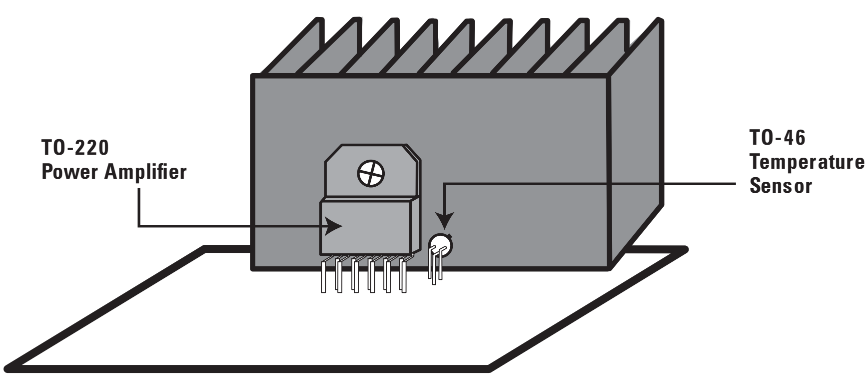


Figure 3-1. TO-220 Power Amplifier and TO-46 Sensor Mounted on Heat Sink. Excellent Results Can Also be Obtained by Locating the Sensor on the Circuit Board Very Close to the Amplifier IC's Leads.

Example 2. Processors

High-performance processors, (such as CPUs, GPUs, ASICs, and FPGAs) consume significant power and can get hot enough to suffer catastrophic damage due to excessive temperature. To enhance system reliability, it is often desirable to monitor processor temperature and activate a cooling fan, slow down the system clock, or shut the system down completely if the processor gets too hot.

As with power amplifiers, there are several potential mounting sites for the sensor. Most highly-integrated devices that have power concerns also have integrated thermal diodes that can be used to measure their junction temperature. This simplifies the physical connection of the sensor, as it is already available on the device being measured. National makes several devices called remote-diode temperature sensors that can sense the junction temperature of these "processors". Since not all "processors" have an integrated thermal diode, external mounting sites need to be identified. One such site is in a hole drilled into the center of the microprocessor's heat sink, shown as location "a" in ***Figure 3-2***. The heat sink which can be clipped to the processor or attached with epoxy generally sits on top of the processor. The advantage of this location is that the sensor's temperature will be within a few degrees of the microprocessor's case temperature in a typical assembly. A disadvantage is that relatively long leads will be required to return the processor's output to the circuit board. Another disadvantage is that if the heat-sink-to-microprocessor thermal connection degrades (either because of bad epoxy or because a clip-on heat sink gets "bumped" and is no longer in intimate contact with the processor), the sensor-to-microprocessor connection will probably also be disrupted, which means that the sensor will be at a lower-than-normal temperature while the processor temperature is rising to a potentially damaging level.

Another potential location is in the cavity beneath a socketed processor (***Figure 3-2***, location "b"). An advantage of this site is that, since the sensor is attached to the circuit board using conventional surface-mounting techniques, assembly is straightforward. Another advantage is that the sensor is isolated from air flow and will not be influenced excessively by changes in ambient temperature, fan speed, or direction of cooling air flow. Also, if the heat sink becomes detached from the microprocessor, the sensor will indicate an increase in microprocessor temperature. A disadvantage is that the thermal contact between the sensor and the processor is not as good as in the previous example, which can result in temperature differences between the sensor and the microprocessor case of 5°C to 10°C. This is only a minor disadvantage however, and this approach is the most practical one in many systems.

It is also possible to mount the sensor on the circuit board next to the microprocessor's socket (location "c"). This is another technique that is compatible with large-volume manufacturing, but the correlation between sensor temperature and processor temperature is much weaker; the microprocessor case can be as much as 20°C warmer than the sensor.

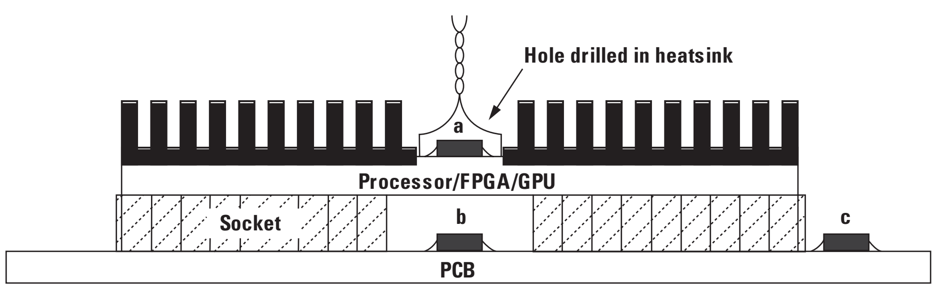


Figure 3-2. Three Potential Sensor Locations for High-Performance Processor Monitoring

Finally in some lower-cost systems, the microprocessor may be soldered to the motherboard, with the heat sink mounted on the opposite side of the motherboard, as shown in ***Figure 3-3***. In these systems, the sensor can be soldered to the board at the edge of the heat sink. Since the microprocessor is in close contact with the motherboard, the sensor's temperature will be closer to that of the microprocessor than for a socketed microprocessor.

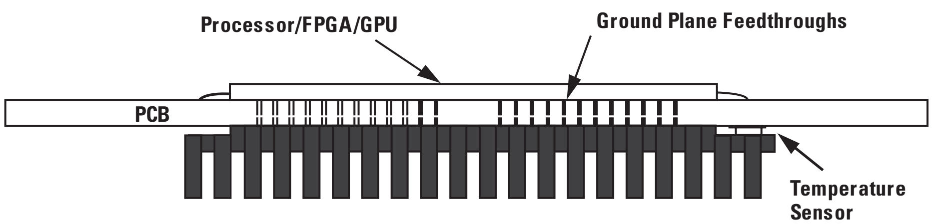


Figure 3-3. Sensor Mounted Near Edge of Soldered Processor

Remote-diode temperature sensors can also be used to measure the actual junction temperature of the "processor" through the use of a thermal diode/transistor that is integrated on the processor. See **Sections 2.5** and **3.6** on remote-diode temperature sensing for further details.

Example 3. Measuring Air Temperature

Because the sensor's leads are often the dominant thermal path, a board-mounted sensor will usually do an excellent job of measuring board temperature. But what if the goal is to measure air temperature? If the board is at the same temperature as the air, this will be accomplished easily.

If the board and the air are at different temperatures, things get more complicated. The sensor can be isolated from the board using long leads. If the sensor is in a metal can, a clip-on heat sink can bring the sensor's temperature close to ambient. If the sensor is in a plastic package, it may need to be mounted on a small "sub-board", which can then be thermally isolated from the main board with long leads as shown in ***Figure 3-4***.

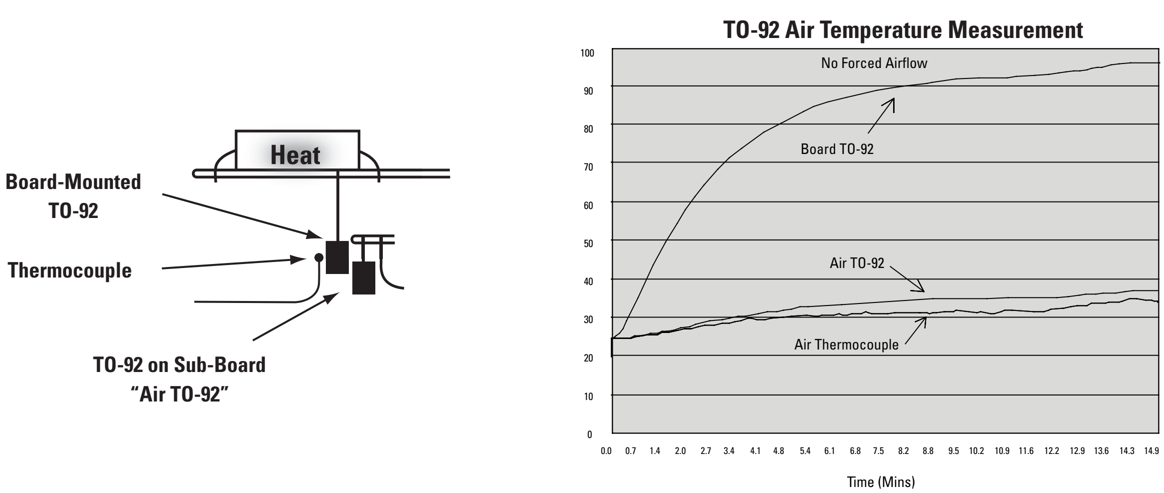


Figure 3-4. Effects of PCB Heat When Trying to Measure Air Temperature

3.2 Mapping Temperature to Output Voltage or Current

The earliest analog-output temperature sensors developed by National generated output signals that were proportional to absolute temperature (K). The LM135 series of sensors has a nominal output voltage equal to 10 mV/K, while the LM134 series (a current-output device) produces a current proportional to absolute temperature. The scaling factor is determined by an external resistor.

Because the Celsius and Fahrenheit scales are more convenient in many applications, three of National's sensors have output voltages proportional to one of those scales. The LM35 and LM45 sensors produce nominal output voltages equal to 10 mV/°C, while the LM34 sensor produces a nominal output equal to 10 mV/°F.

While the Celsius and Fahrenheit sensors have more convenient temperature-to-voltage mapping than the absolute temperature sensors, they are somewhat less convenient to use when temperatures are below 0°C or 0°F. To measure "negative" temperatures with these devices, either a negative power supply must be provided as in ***Figure 3-5***, or the sensor above ground must be biased and the voltage differential between its output and "ground" pins should be reviewed as in ***Figure 3-5***.

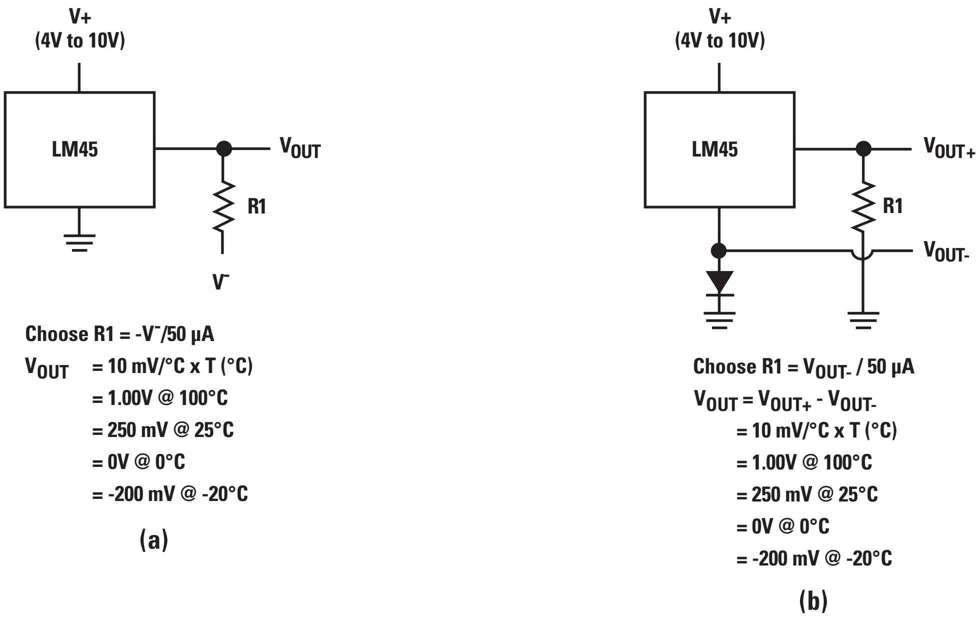


Figure 3-5. Two ways to measure negative temperatures with single-supply sensors.
(a) If a negative supply voltage is available, use a pull-down resistor to allow the sensor's output to go below ground.
(b) Alternatively, bias the "ground" pin using a diode, a voltage reference, or other voltage source.
The differential output voltage will be negative for negative temperatures.

The LM50 and LM60 sensors use an alternative approach. These devices have a built-in positive-offset voltage that allows them to produce output voltages corresponding to negative temperatures when operating on a single positive supply. The LM50 sensor has a 10 mV/°C scale factor, but the output voltage is 500 mV at 0°C. The device is specified for temperatures as low as -40°C (100 mV). The LM60's scale factor is 6.25 mV/°C, and its output voltage is 424 mV at 0°C. The LM60 sensor also is specified for temperatures as low as -40°C (174 mV).

3.3 Driving Capacitive Loads *(These hints apply to analog-output sensors)*

National's temperature-sensor ICs are micro-power circuits, and like most micro-power circuits, they generally have a limited ability to drive heavy capacitive loads. The LM94022 sensor can drive 1100 pF without requiring a series resistor on the output (***Figure 3-6***). The LM34 and LM35 sensors, can drive 50 pF without special precautions, while the LM45 sensor can handle 500 pF. If heavier capacitive loads are anticipated, it is easy to isolate or decouple the load with a resistor; as seen in ***Figure 3-7a***. It should be noted that the series resistor will attenuate the output signal unless the load resistance is very high. If this is a problem, the tolerance to capacitive loading can be improved without increasing output resistance by using a series R-C damper from output to ground as shown in ***Figure 3-7b.***

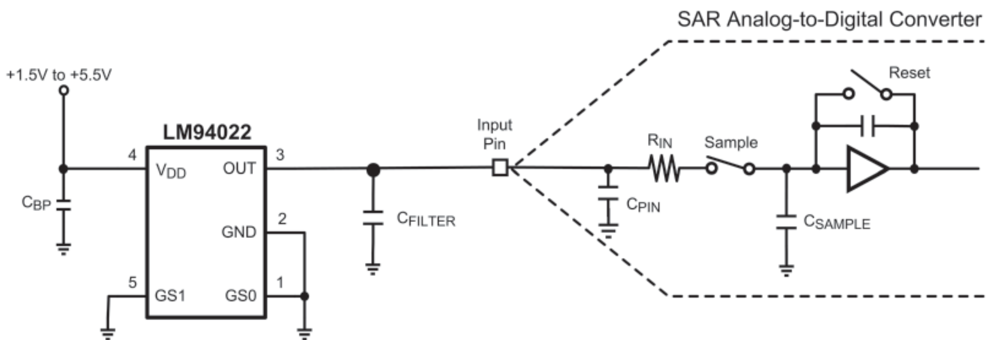


Figure 3-6. The LM94022 sensor can drive 1100 pF of load capacitance without requiring an external series resistor, reducing component count and board space. This is ideal for driving the filter capacitor that is often located at the input to an analog-to-digital converter. Greater capacitance can be driven, if necessary, with the addition of a series resistor.

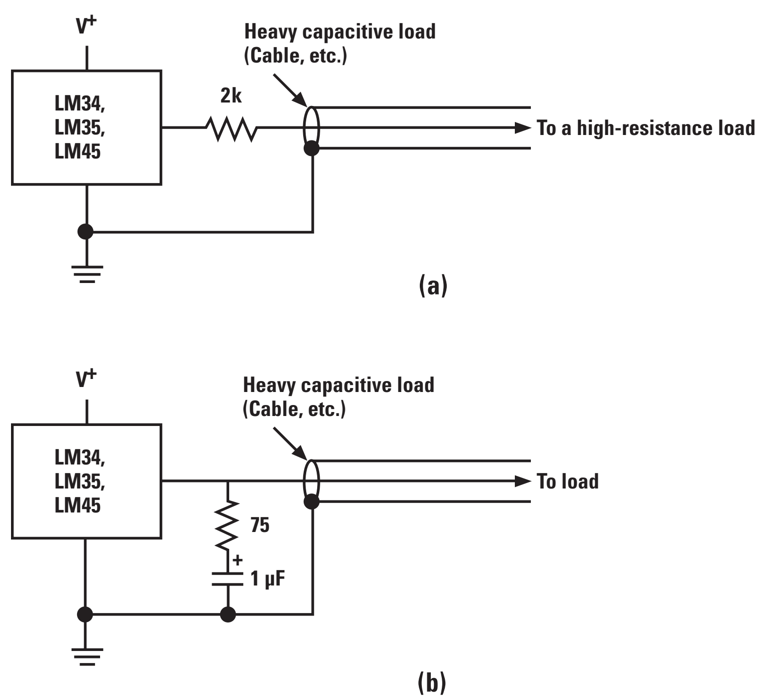


Figure 3-7. Capacitive drive options. The LM34, LM35, and LM45 sensors can drive large external capacitance if isolated from the load capacitance with a resistor as in (a), or compensated with an R-C network as in (b).

The LM50 and LM60 sensors have internal isolation resistances and can drive any value of capacitance with no stability problems. The load impedance should be sufficiently high to avoid attenuation of the output signal.

3.4 Analog Sensor Noise Filtering

Any analog circuit connected to wires in a hostile environment can have its performance adversely affected by intense electromagnetic sources such as relays, radio transmitters, motors with arcing brushes, or SCR transients, as its wiring can act as a receiving antenna and its internal junctions can act as rectifiers. In such cases, a 0.1 µF bypass capacitor from the power supply pin to ground will help reduce power supply noise. Output filtering can be added as well. Sensors like the LM50 and LM60 sensors can drive filter capacitors directly; a 1 µF to 4.7 µF output capacitor generally works well although the overall response time will increase. When using sensors that should not directly drive large capacitive loads, the filter capacitor can be isolated with a resistor as shown in ***Figure 3-7***, or the R-C damper can be used as in ***Figure 3-7*** to provide filtering. Typical damper component values are 75Ω in series with 0.2 µF to 1 µF.

3.5 Performance Comparison of Thermistor to Analog IC Sensors

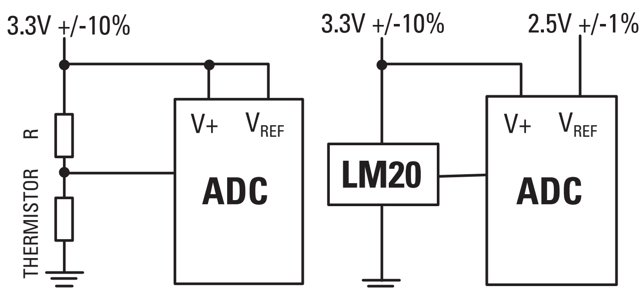


Figure 3-8. Connecting a Thermistor or an LM20 Sensor to an ADC

Thermistors, when biased ratiometrically (as shown in ***Figure 3-8***), have the advantage of not requiring an accurate or stable voltage reference in the system. In ratiometric operation, the error introduced by the reference is cancelled out. If ratiometric operation is not possible, for instance when the ADC reference voltage is in an ASIC and is not pinned out, using ICs like the LM20 will result in better total system accuracy. Devices like the LM20 draw only 10 mA of current, while the current drawn by the thermistor circuit depend on the value of R.

National analyzed a specific thermistor, the Murata NTH5G10P/16P33B103F. This thermistor has an accuracy of 1% at 25°C. The evaluation used ADCs with various resolutions to examine the overall accuracy which depends on the resolution of the ADC, the ADC's errors (gain, offset, and nonlinearity or total unadjusted error, TUE), and the resolution of the compensation table. Since the power dissipation is dependent upon R, signal level can be affected drastically.

Shown in ***Figure 3-9***, is an output plot of the voltage applied at the ADC input for the thermistor circuit shown in ***Figure 3-8***. Note that the ADC input voltage decreases logarithmically with increasing temperature. The 97.6k resistor optimizes the power dissipation in the thermistor. It allows the thermistor to operate at a power level not exceeding its maximum power rating while maintaining specified accuracy.

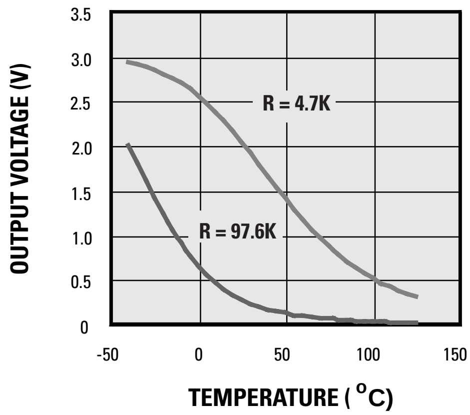


Figure 3-9. Thermistor Output Voltage vs Temperature for Different Values of R

Lowering the value of R will decrease the temperature range over which the thermistor's transfer function is linear. With a 4.7k bias resistor, the slope at higher temperature increases, thus providing more resolution at the cost of greater power consumption.

The plot shown in ***Figure 3-10***, compares the overall system accuracy when using a thermistor with an 8-bit ADC and R = 100k, a thermistor with a 10-bit ADC and R = 33k, or an LM20 device with an 8-bit ADC. The quantization error and ADC Total Unadjusted Error (combination of offset, gain, and linearity errors) was considered to determine the overall system accuracy. The green lines show the min/max system performance of the LM20 device super-imposed over the blue min/max performance of the thermistor. As can be seen, overall system accuracy for the LM20 sensor remains constant over temperature. At temperatures above 60° C, the LM20 sensor is far superior when compared to the performance of the thermistor and 8-bit ADC.

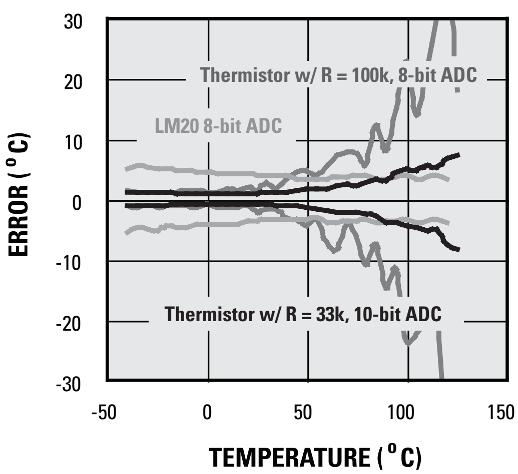


Figure 3-10. ADC Resolution Effect on System Accuracy

Increasing the ADC resolution and decreasing the value of R in the thermistor circuit decreases the overall system error but increases cost (10-bit ADC) and power dissipation. Improving the accuracy of the voltage reference will bring the LM20 system accuracy closer to that of the specifications found on the LM20 datasheet of ±2.5°C at +130°C and -55°C, and ±1.5°C at +30°C. Since the output slope of the LM20 is negative, the gain error introduced by the reference voltage plays less of a role in the overall accuracy as the temperature increases (thus the slight negative slope of the LM20 performance.) Optimum cost, power consumption, and performance can be obtained when using an integrated analog sensor such as the LM20 over a thermistor.

3.6 Remote-Diode Temperature Sensing

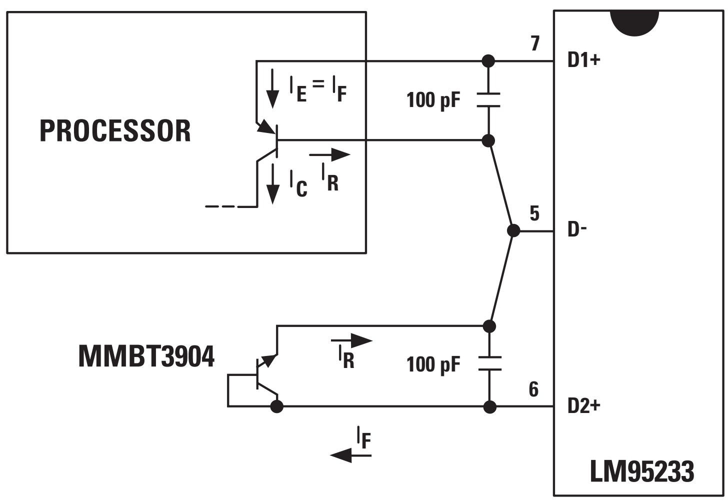


Figure 3-11. RDTS Application

Sensor location is critical in obtaining an accurate measurement of the temperature required. As mentioned in the **Sensor Mounting** section, many highly-integrated computational devices such as CPUs, GPUs, and FPGAs have integrated thermal diodes to enable easy measurement of their junction temperature. These thermal diodes are in reality a bipolar junction transistor (BJT). Remote-diode temperature sensors (RDTS) also enable a cost-effective alternative for measuring multiple temperature locations or zones with just the addition of a simple BJT such as an MMBT3904. This section will describe traditional and TruTherm® BJT/Transistor beta-compensation methods used in measuring the remote-diode temperature of microprocessors in deep sub-micron processes. Following is a list of articles, papers, and web seminars that are available from National Semiconductor that further describe these methods and the associated challenges:

- TruTherm BJT/Transistor Beta-Compensation Technology Presentation: national.com/appinfo/tempsensors/files/national_trutherm_presentation.pdf
- Multiple Remote-Diode Temperature Sensing: national.com/appinfo/tempsensors/files/MultipleRDTS.pdf
- Thermal Management for Traditional RDTS Processor Systems (2002 online seminar): national.com/onlineseminar/2002/thermal/thermal.html
- Remote Diodes Yield Accurate Temperature Measurements http://www.edn.com/article/CA307863.html

The following sections describe the remote-diode temperature-sensing method and can be found in most of National's RDTS datasheets.

Traditional Diode Non-Ideality and Series Resistance

BJT-thermal-diode characteristics are dependent on process geometry and other process variables. Each RDTS device therefore is targeted most commonly to a specific thermal diode. Two of the thermal diode characteristics that are affected are series resistance and non-ideality. Therefore each RDTS is targeted for a specific series resistance and ideality. A review of how remote-diode temperature sensors work is a good place to begin.

When a transistor is connected as a diode, the following relationship holds for variables V_{BE}, T, and I_F:

(1)

$$I_F = I_S \times \left[e^{\left(\frac{V_{BE}}{\eta \times V_t}\right)} - 1 \right]$$

where:

$$V_t = \frac{kT}{q}$$

- q = 1.6 × 10^{-19} Coulombs (the electron charge),
- T = Absolute temperature in Kelvin,
- k = 1.38 × 10^{-23} joules/K (Boltzmann's constant),
- η is the non-ideality factor of the process on which the diode is manufactured,
- I_S = Saturation current; process dependent,
- I_F = Forward current through the base-emitter junction,
- V_{BE} = Base-emitter-voltage drop

In the active region, the -1 term is negligible and may be eliminated, yielding the following equation:

(2)

$$I_F = I_S \times \left[e^{\left(\frac{V_{BE}}{\eta \times V_t}\right)} \right]$$

In ***Equation 2***, η and I_S are dependent upon the process that was used in the fabrication of the particular diode. By forcing two currents with a very controlled ratio(I_{F2} / I_{F1}) and measuring the resulting voltage difference, it is possible to eliminate the I_S term. Solving for the forward voltage difference yields the relationship:

(3)

$$\Delta V_{BE} = \eta \times \left(\frac{kT}{q}\right) \times \ln\left(\frac{I_{F2}}{I_{F1}}\right)$$

Solving ***Equation 3*** for temperature yields:

(4)

$$T = \frac{q \times \Delta V_{BE}}{\eta \times k \times \ln\left(\frac{I_{F2}}{I_{F1}}\right)}$$

Equation 4 holds true when a diode-connected transistor such as the MMBT3904 is used. When this "diode" equation is applied to an integrated device, such as the transistor found on a processor, with its collector tied to GND (as shown in ***Figure 3-11***), it will appear to yield a wide non-ideality spread. This wide non-ideality spread is not due to true process variation but due to the fact that ***Equation 4*** is an approximation.

TruTherm BJT/Transistor Beta-Compensation Technology

TruTherm BJT/Transistor beta-compensation technology uses the transistor equation (***Equation 5***) which is a more accurate representation of the topology of the thermal diode found on an FPGA or processor.

(5)

$$T = \frac{q \times \Delta V_{BE}}{\eta \times k \times \ln\left(\frac{I_{C2}}{I_{C1}}\right)}$$

Equation 5 is a better approximation of the textbook Ebbers-Moll model and does not make any assumptions such as the one made by ***Equation 4***. ***Equation 4*** simplifies the RDTS circuitry by concluding that the collector-current ratio will match the emitter-current ratio in all cases. In sub-micron geometry processes this is not the case as variation in beta truly affects the collector-current ratio and the assumption made by traditional RDTS no longer holds true. TruTherm BJT/Transistor beta compensation should only be enabled when measuring the temperature of a transistor integrated as shown in the processor of ***Figure 3-11***, because ***Equation 5*** only applies to this topology.

For free information on Ebbers-Moll and other theoretical transistor information, visit:
http://en.wikipedia.org/wiki/Bipolar_junction_transistor

The following curves show a real example of the improvement in accuracy that can be obtained by using TruTherm BJT/Transistor beta-compensation technology.

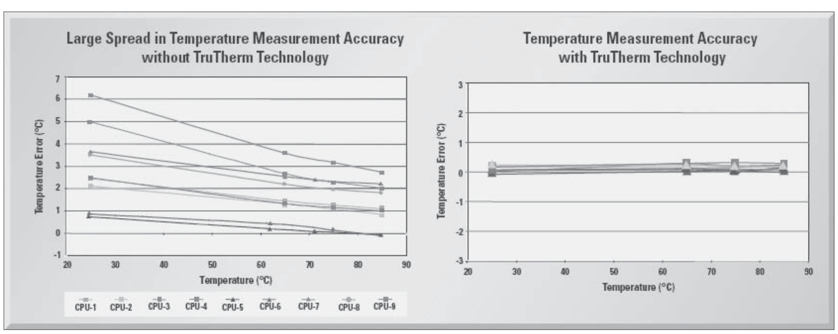


Figure 3-12. Comparison of remote diode temperature measurement accuracy with and without TruTherm technology.

Calculating Total System Accuracy

When calculating the total system accuracy, the total voltage drop that the RDTS device sees needs to be taken into account. The voltage seen by the RDTS also includes the voltage drop across the series resistance (R_S) caused by the forward current (I_F), as discussed previously. Variation in non-ideality factor, η, depends on the diode that is used for measurement. The effects of series resistance and variation in η on total system accuracy will be discussed in this section.

V_{BE} is proportional to both η and T, therefore the variations in η cannot be distinguished from variations in temperature. Since the non-ideality factor is not controlled by the temperature sensor, it will directly add to the inaccuracy of the sensor. For an Intel processor on 65 nm process, Intel specifies a +4.06%/-0.897% variation in η from part to part when the processor diode is measured by a circuit that assumes the diode equation, ***Equation 4***, as true. For example, assume a temperature sensor has an accuracy specification of ±1.0°C at a temperature of 80°C (353 Kelvin) and the processor diode has a non-ideality variation of +1.19%/-0.27%. The resulting system accuracy of the processor temperature being sensed will be:

TACC = + ***1.0°C*** + ***(+4.06% of 353 K)*** = ***+15.3°C***

and

TACC = - ***1.0°C*** + ***(-0.89% of 353 K)*** = ***-4.1°C***

TruTherm technology uses the transistor equation, ***Equation 4***, resulting in a non-ideality spread that reflects the process variation which is very small. The transistor equation non-ideality spread is ±0.39% for the Intel processor on 65 nm process. The resulting accuracy when using TruTherm technology improves to:

TACC = ±***0.75°C*** + ***(±0.39% of 353 K)*** = ± ***2.16°C***

Another error term is that due to the series resistance of the thermal diode and PCB traces. The thermal diode series resistance is specified on most processor datasheets. For Intel processors in 65 nm process, this is specified at 4.52Ω typical. It is beneficial to perform a calculation for a specific part because each part is targeted for a specific diode and thus, a specific series resistance. The LM95233 device accommodates the typical series resistance of an Intel processor on 65 nm process. The error that is not accounted for is the spread of the processor's series resistance; that is, 2.79Ω to 6.24Ω or ±1.73Ω. The equation to calculate the temperature error due to additional series resistance (T_E) for the LM95233 device is simply:

(6)

$$T_E = \left(0.62\frac{°C}{\Omega}\right) \times R_{Series}$$

Solving ***Equation 6*** for R_{Series} equal to ±1.73Ω results in the additional error due to the spread in the series resistance of ±1.07°C. The spread in error cannot be canceled out, as it is a processor part-to-part variation and would require measuring each individual thermal-diode device. This is quite difficult and impractical in a large-volume production environment. ***Equation 6*** can also be used to calculate the additional error caused by series resistance on the printed circuit board. Since the variation of the PCB series resistance is minimal, the bulk of the error term is always positive and can be cancelled out simply by subtracting it from the output readings of the LM95233 device.

Each RDTS device datasheet should be consulted for the proper series resistance equation, and the processor datasheets for ideality and series resistance values.

Compensating for Different Non-Ideality and Series Resistance

In order to compensate for the errors introduced by non-ideality, the temperature sensor is calibrated for a particular processor. National's temperature sensors are always calibrated to the typical non-ideality and series resistance of a given processor type. Newer RDTS devices from National are targeted for two thermal diodes. For example the LM95233 device is calibrated for two non-ideality factors and series resistance values thus supporting the MMBT3904 transistor and Intel processors on 65 nm process without the requirement for additional trims.

For most accurate measurements, TruTherm BJT/Transistor beta-compensation mode should be turned on when measuring the Intel processor on a 65 nm process to minimize the error introduced by the false non-ideality spread (see ***Figures 3-11*** and ***3-12*** on diode ideality and series resistance). When a temperature sensor calibrated for a particular processor type is used with a different processor type, additional errors are introduced. Temperature errors associated with non-ideality of different processor types may be reduced in a specific temperature range of concern through the use of software calibration. Most RDTS devices include a register that allows the user to compensate for this additional error by adjusting the offset of the transfer function. Typical non-ideality specification differences cause a gain variation of the transfer function, therefore the center of the temperature range of interest should be the target temperature for calibration purposes. The following equation can be used to calculate the temperature correction factor (T_{CF}) required to compensate for a target non-ideality differing from that supported by the RDTS device.

(7)

$$T_{CF} = \left(\frac{\eta_S - \eta_{PROCESSOR}}{\eta_S} \right) \times \left(T_{CR} + 273K \right)$$

where

- η_S = RDTS device target non-ideality for accuracy specification,
- $\eta_{PROCESSOR}$ = Processor thermal diode typical non-ideality specification,
- T_{CR} = center of the temperature range of interest in °C.

The correction factor should be directly added to the temperature reading produced by the RDTS device. For example when using the LM95233 device with the 3904 mode selected, to measure an AMD Athlon processor with a typical non-ideality of 1.008 for a temperature range of 60 °C to 100 °C, the correction factor would calculate to:

(8)

$$T_{CF} = \left(\frac{1.003 - 1.008}{1.003} \right) \times \left(80 + 273 \right) = -1.75°C$$

Therefore, -1.75°C should be subtracted from the temperature readings of the LM95233 device to compensate for the differing typical non-ideality target. And -1.75°C should be programmed in the LM95233 devices's offset compensation register.

PCB Layout For Minimizing Noise

The method used in measuring requires sensing 250 µV/1°C signal levels. In a noisy environment, such as a processor motherboard, layout considerations are critical. Noise induced on traces running between the remote-diode temperature sensor and the RDTS device can cause temperature-conversion errors. The following guidelines should be followed:

1. The RDTS device power pin (V_{DD}) should be bypassed as recommended on the datasheet. This is usually a 0.1 µF capacitor in parallel with 100 pF. The 100 pF capacitor should be placed as close as possible to the power supply pin. A bulk capacitance of approximately 10 µF needs to be in the near vicinity of the RDTS device. In general, noise on the power supply pin should be kept below 150 mV_{P-P}.
2. A diode-bypass capacitor is recommended to filter high-frequency noise but may not be necessary. If it is used, the traces to the diode-bypass capacitor should be matched. The filter capacitors should be placed close to the RDTS device pins. The RDTS device datasheet can be consulted for the value of the capacitor; it is usually 100 pF or 2.2 nF.
3. Ideally, the RDTS device should be placed within 10 cm of the thermal diode pins with the traces being as direct, short, and identical as possible. As discussed in **Section 3.6**, Calculating Total System Accuracy, trace resistance of 1Ω can cause as much as 0.62°C of error for some RDTS devices. This error can be compensated by using simple software offset compensation or the offset compensation register(s) in the RDTS device.
4. Diode traces should be surrounded by a GND guard ring to either side, above and below if possible. This GND guard should not be between the D+ and D- lines. In the event that noise does couple to the diode lines, it would be ideal if it is coupled common mode; that is, equally to the D+ and D- lines.
5. Routing diode traces in close proximity to power supply switching or filtering inductors should be avoided.
6. Running diode traces close to or parallel to high-speed digital and bus lines should be avoided. Diode traces should be kept at least 2 cm apart from the high-speed digital traces.
7. If it is necessary to cross high-speed digital traces, the diode traces and the high-speed digital traces should cross at a 90 degree angle.
8. The ideal place to connect the RDTS device's GND pin is as close as possible to the device GND associated with the sense diode.
9. Leakage current between D+ and GND and between D+ and D- should be kept to a minimum. Leakage current values as small as 13 nA can cause as much as 0.2°C of error in the diode temperature reading. Keeping the printed circuit board as clean as possible will minimize leakage current.

3.7 Digital Interface Noise Considerations

Noise coupling into the digital interface lines of the RDTS device can also cause havoc in a system. Noise coupling into the digital lines greater than 400 mV_{P-P} (typical hysteresis) or undershoot less than 500 mV below GND, may prevent successful SMBus communication with any digital sensor or hardware monitor. SMBus no acknowledge is the most common symptom, causing unnecessary traffic on the bus. Although the SMBus maximum frequency of communication is rather low (100 kHz max), care still needs to be taken to ensure proper termination within a system with multiple parts on the bus and long PCB traces. An RC low-pass filter with a 3 dB corner frequency of about 40 MHz is included in most National devices. Additional resistance can be added in series with the SMBDAT and SMBCLK lines to help further filter noise and ringing. Noise coupling can be minimized by keeping digital traces out of the switching power supply areas as well as ensuring that digital lines containing high-speed data communication cross at a right angle to the SMBDAT and SMBCLK lines.

4.1 Personal Computers

Recent generations of personal computers dissipate a lot of power, which means they tend to run hot. The microprocessor, memory, and the hard disk drive are notable hot spots. Cooling fans help to keep heat under control, but if a fan fails or if ventilation paths become blocked by dust or desk clutter, the temperature inside a computer's case can get high enough to dramatically reduce the life of the internal components. Notebook computers are even more difficult.

High-performance personal computers, notebooks, and servers use monolithic temperature sensors on their motherboards to monitor system temperatures so that system failure is averted or for fan-speed control to minimize acoustical noise. Typical locations for the sensors are near (and sometimes under) the microprocessor, inside the hard disk drive, or on the processor itself through the use of a thermal diode. In an Intel-based computer, when the sensor detects excessive temperature, the system can reduce its clock frequency to minimize power dissipation. Fast temperature rise inside a desktop unit or server can indicate fan failure and a well designed system can notify the user that the unit requires servicing. If the temperature continues to rise, the system can shut itself off. Inaccurate temperature measurement can force the fan to run at a higher RPM than necessary thus making the system have more acoustic noise.

Temperature sensors range from simple trip point sensors such as the LM56 device, to digital sensors with remote diodes for sensing processor-junction temperature for cost-effective multipoint sensing. In addition, there is another family of devices called hardware monitors that builds upon the remote-diode temperature sensors. Hardware monitors include DAC or PWM outputs for fan-speed control, RPM tachometer inputs, power supply monitor, chassis intrusion detection, and many other processor-related digital signal monitors. These devices have found a home mainly in desktop and server systems.

Simple Fan Controller

The circuit in ***Figure 4-1*** senses system temperature and turns a cooling fan on when the sensor's temperature exceeds a preselected value. The LM56 thermostat IC senses temperature and compares its sensor output voltage to the voltages at its V_{T1} and V_{T2} pins, which are set using three external resistors. The 1.25V system voltage reference is internal. As shown, V_{T1} will go low and the fan will turn on when the sensor's temperature exceeds 50°C. If the sensor's temperature rises above 70°C, V_{T2} will go low. This output can be used to slow the system clock (to reduce processor power) or drive an interrupt that causes the microprocessor to initiate a shutdown procedure. If the second output is not needed, the 9.09k resistor can be replaced with a short, and the 2.67k resistor with an 11.8k resistor. V_{T1} will still go low at T=50°C, but V_{T2} will remain inactive.

Typically, the LM56 thermostat will be located on the circuit board as close as possible to the microprocessor so that its temperature will be near that of the processor. This circuit is designed for a 12V fan. An alternative approach with a p-channel MOSFET and a 5V fan is shown in ***Figure 4-2.***

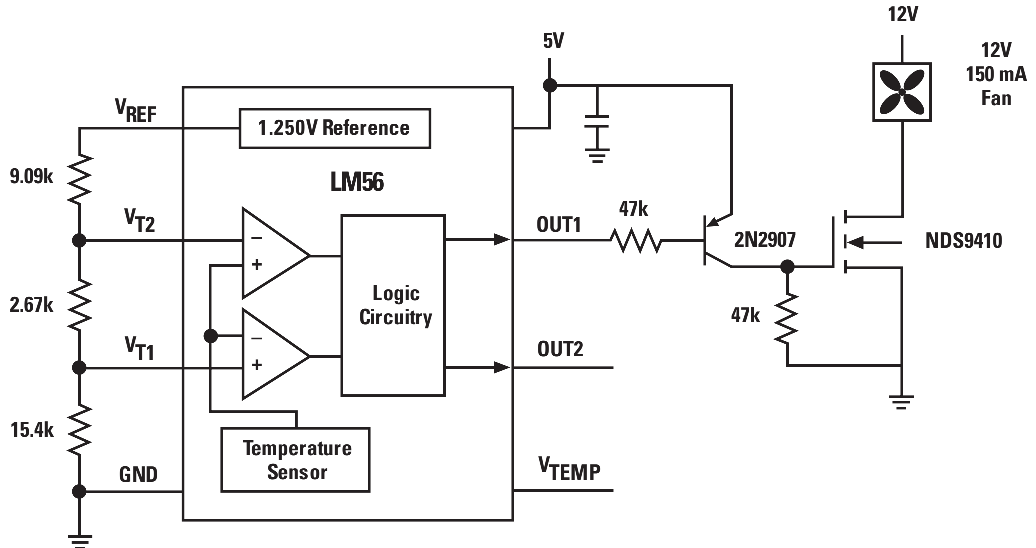


Figure 4-1. This circuit turns on a 12V cooling fan when the LM56 thermostat's temperature exceeds 50°C. OUT2 goes low when the temperture reached 70°C. The comparator outputs are open collector, so OUT2 will need a pull-up resistor if it is to drive a logic input.

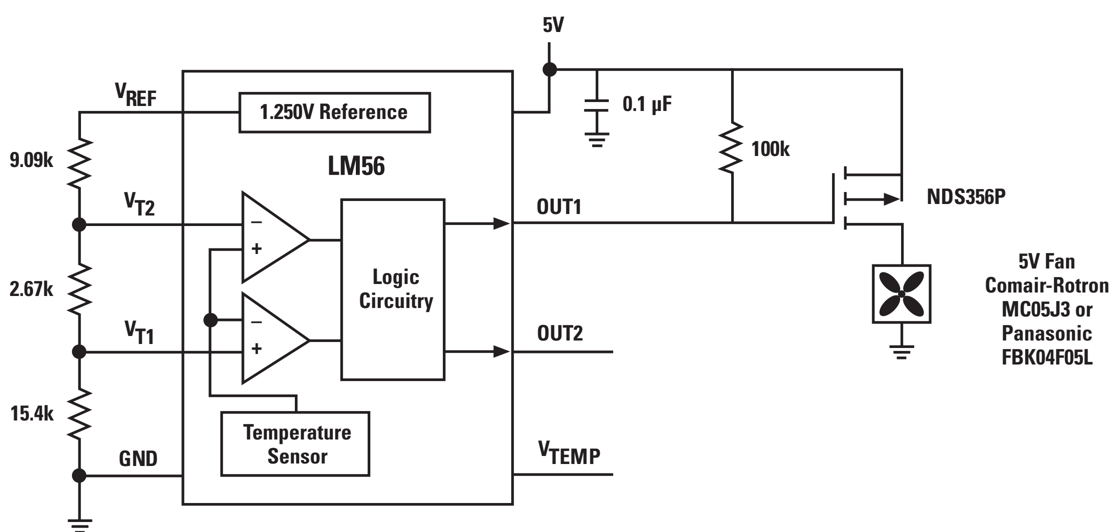


Figure 4-2. This Circuit Performs the Same Function as the Circuit in 4-1, but it is designed for a 5V Cooling Fan

Low/High Fan Controllers

The circuit in ***Figure 4-3*** again uses the LM56 thermostat, but in this case the fan is always on. When the circuit board's temperature is low, the fan runs at a relatively slow speed. When the temperature exceeds 50°C, the fan speed increases to its maximum value. As with the circuits in ***Figures 4-1 and 4-2***, OUT2 is a second logic-level output that indicates that the LM56 thermostat's temperature is greater than 70°C. Again, if this second logic output is not needed, the V_{REF} and V_{T2} pins can be connected together and the two resistors can be replaced by a single resistor whose value is equal to the sum of their resistances.

Another variation on this approach uses a MOSFET to turn the fan on at the lower temperature threshold, and the fan's speed control input to increase the fan's speed when the second threshold is exceeded.

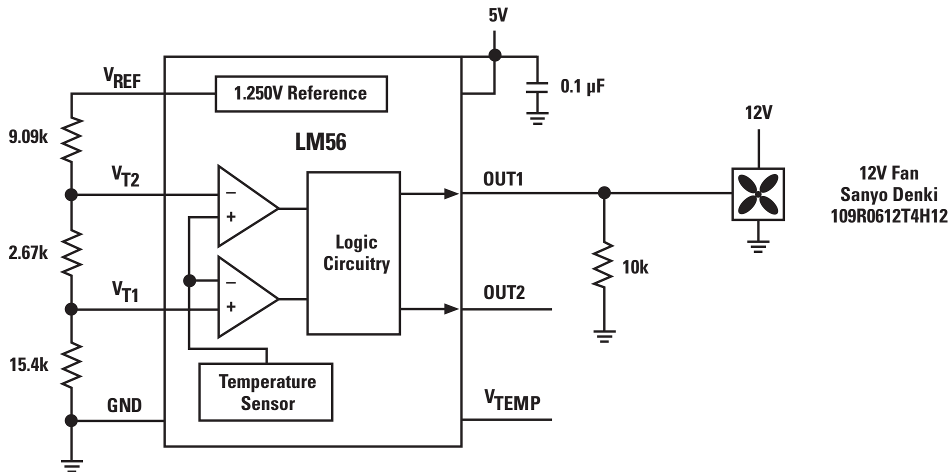


Figure 4-3. Some fans can be controlled without adding a power device to the system. This circuit controls a fan's speed by taking a "third lead" low when temperature is high. This increases the fan's speed to provide additional cooling.

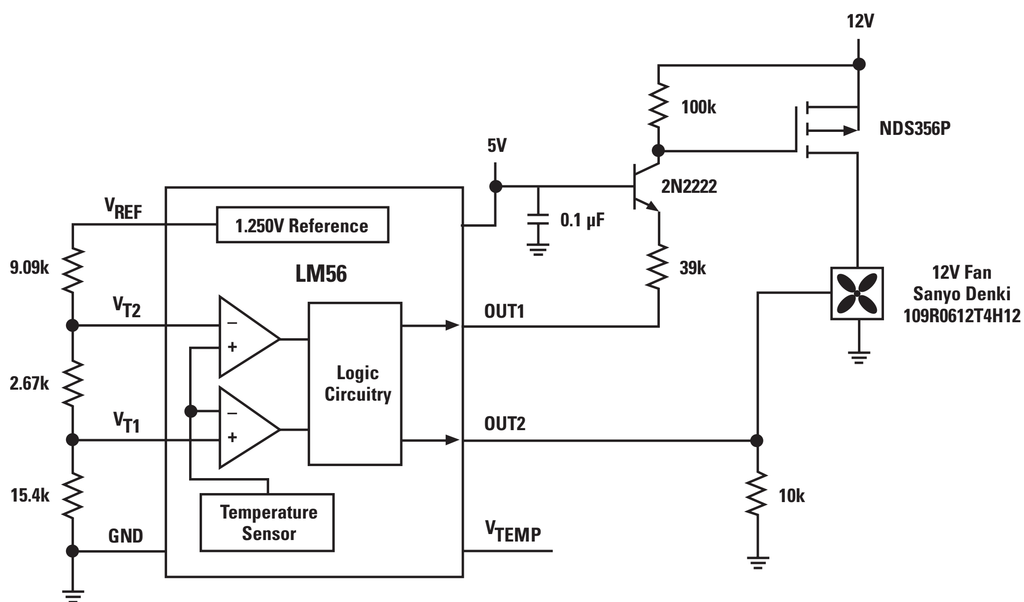


Figure 4-4. By combining the two approaches shown in the previous circuits, a fan controller can be built that turns the fan on at one temperature, then increases its speed if temperature rises above a second threshold.

Desktop Temperature Monitor

Temperature sensors with digital I/O are ideally suited to motherboard applications. The LM95231 device shown here communicates with the host via the SMBus, which is a 2-wire communications protocol. The LM95231 sensor has an internal temperature sensor, remote-diode inputs, and delta-sigma ADC, which continuously converts the device's internal temperature and external remote-diode temperatures into data. The LM95234 sensor includes TruTherm® BJT/Transistor beta-compensation technology for sensing sub-micron geometry processor thermal diodes. See **Section 3.6** on remote-diode temperature sensors for more details. This data can be read at any time over the SMBus interface. Shown in ***Figure 4-5*** is a desktop system in which three thermal zones are being measured. The digital data is used by the thermal management controller to control the system fans.

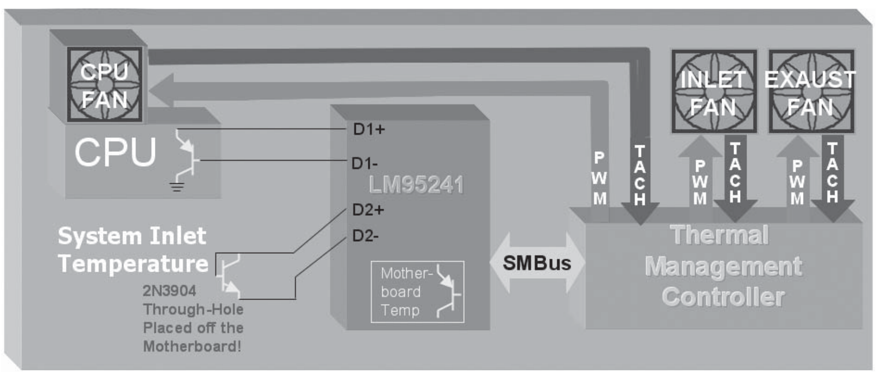
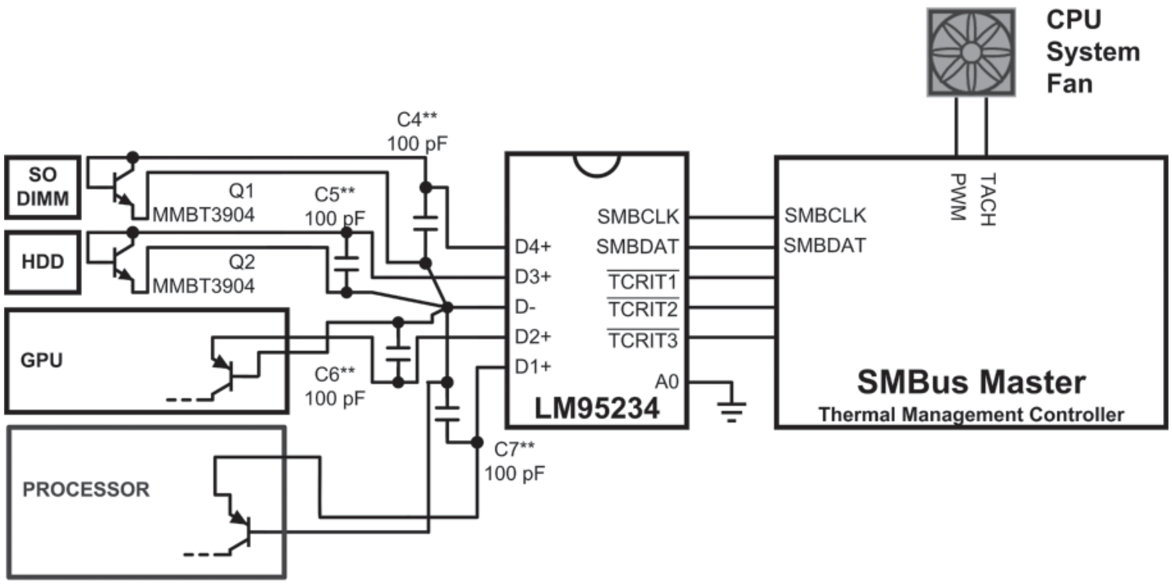


Figure 4-5. Digital Thermal Monitor in a Desktop System

Notebook Temperature Monitor

The multipoint RDTS LM95234 directly senses its own temperature and the temperature of four external PN junctions or diodes. One is dedicated to the CPU of choice. The other three can be dedicated to another part of the system that may have an overheating issue such as the GPU. The LM95234 temperature sensor supports I²C Bus and SMBus interfaces. It has user-programmable limits and WATCHDOG capability with critical temperature (T_CRIT) alarm outputs for system-power-supply shutdown or thermal-management-controller interrupt. The LM95234 sensor includes TruTherm BJT/Transistor beta-compensation technology for sensing sub-micron geometry processor thermal diodes. Please refer to **Section 3.6** on remote-diode temperature sensors for more details.



* Note, place close to LM95234 pins.
** Note, optional - place close to LM95234 pins.

Figure 4-6. Notebook Thermal Monitor

Workstation System Hardware Monitor with Integrated LUT and PI Fan Control

In the system shown in ***Figure 4-7***, an LM96194 hardware monitor is used not only to monitor several thermal zones with remote diodes but also to monitor other critical system signals or power sources. The LM96194 device has dynamic VID V_{CCP} monitoring that supports the VRD 11 specification. VID signals from the CPU are routed to the CPU power-supply voltage regulator (V_{CCP}) and to the LM96194 monitor. The VID signals define the regulator output voltage. The LM96194 device monitors these signals as well as the V_{CCP} power and determines if the voltage is within a preprogrammed window of the target defined by the VID signals. The LM96194 device is also monitoring other system power-supply voltages and includes scaling resistors for some power-supply voltages such as 5V. The LM96194 monitor includes eight GPIOs, four of which can be redirected to monitor fan-tachometer outputs. The LM96194 monitor includes two fan-control methods lookup table (LUT) and proportional integral (PI) fan control that can drive up to two PWM outputs. The LM96194 device can also monitor processor system signals such as PROCHOT, VRD_HOT, ThermTrip, and IERR.

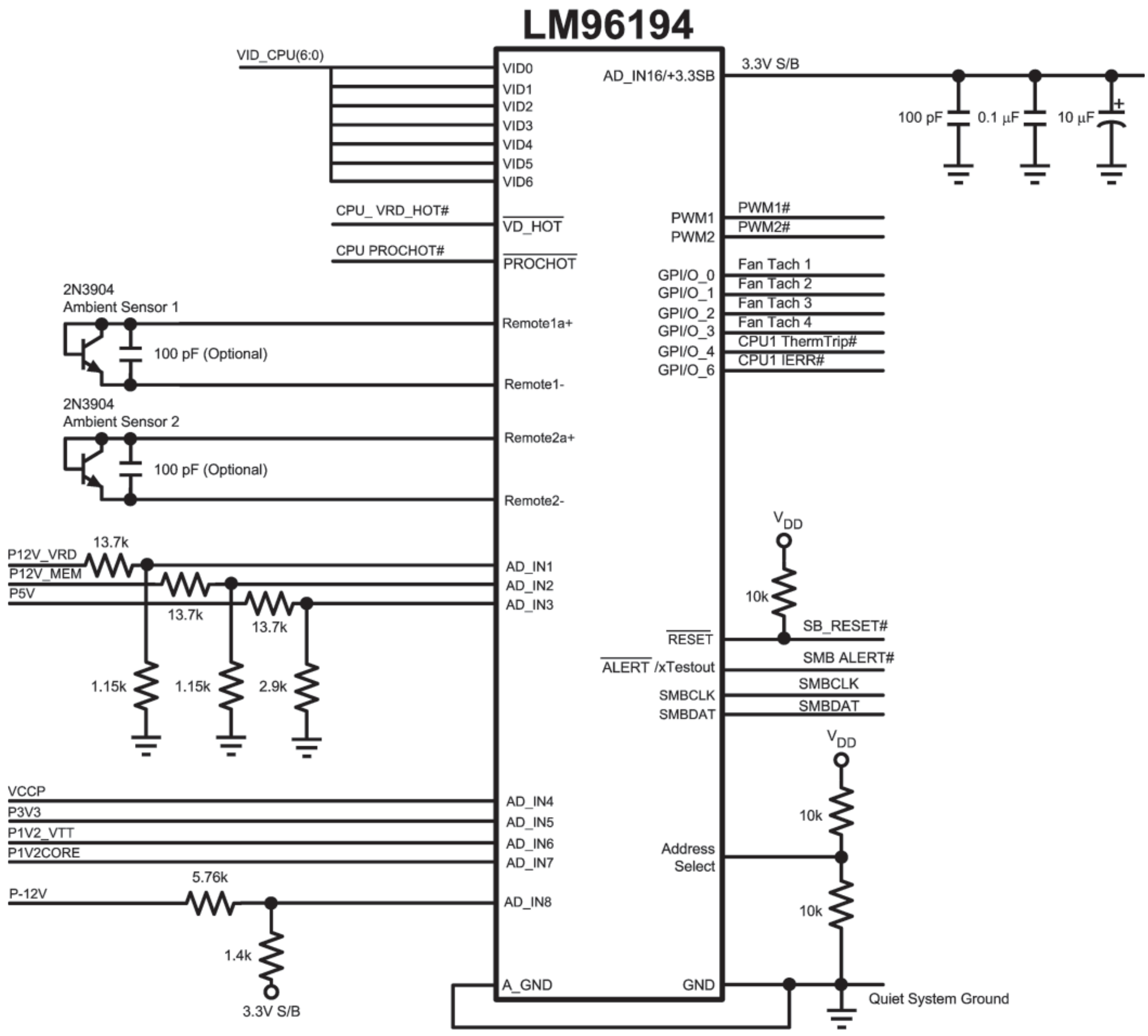


Figure 4-7. LM96194 Workstation System Hardware Monitor

4.2 Optically-Interfacing Digital Temperature Sensors

A digital-output temperature sensor can be coupled through the isolated I²C interface shown in ***Figure 4-8***. Electrically isolating the sensor allows operation in situations exposed to high common-mode voltages, or could be useful in breaking ground loops. Note that the SCL/SMBCLK (clock) line is not bi-directional. Shown in ***Figure 4-8***, the LM75 sensor is a slave and its SCL pin is an input only.

The OS optocoupler is optional and needed only if it is desired to monitor the OS or provide an isolated supply voltage, either a DC-DC converter or a battery. The LM75 sensor will operate from 3V to 5V, and typically requires 250 µA, while IC1 and IC3 require 7 mA to 10 mA each (the LEDs require about 700 µA, but only when active), for a total current drain of about 30 mA.

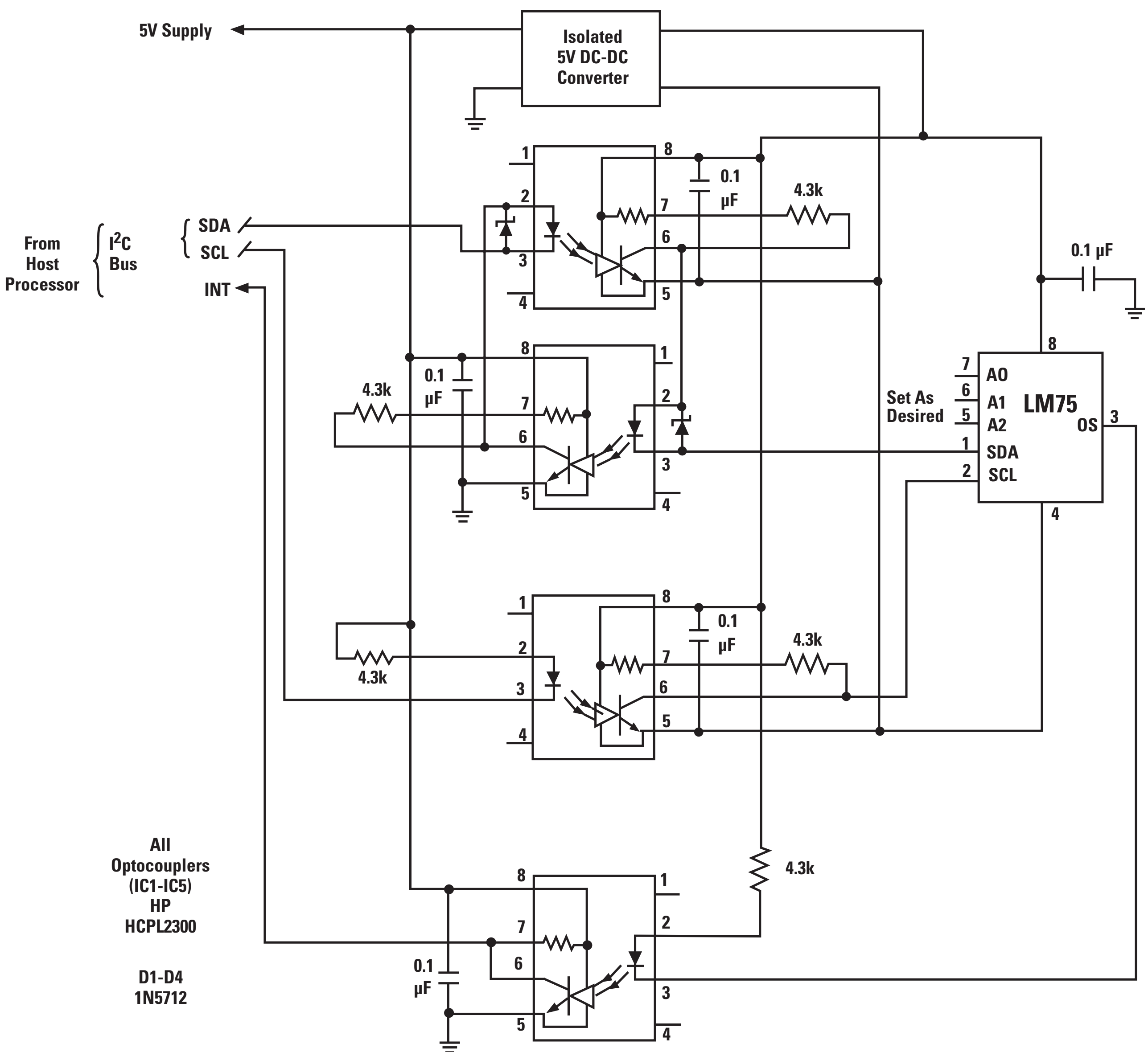


Figure 4-8. Isolated LM75 I²C Bus Interface

4.3 Low-Power Systems

Low-Voltage, Low-Power Temperature Sensor with "Shutdown"

Battery-operated portable equipment such as cordless and wireless telephones must operate from very low supply voltages and draw minimal current from the supply in order to maximize battery life. The circuit shown in ***Figure 4-9*** is an LM94022 temperature sensor, which has been optimized for portable applications operating from as little as 1.5V. In battery-powered systems, however, even the LM94022 sensor's low 9 µA maximum supply current can hasten the battery discharge if the device is operating full time. Therefore, the LM94022 sensor is shown here being powered by a CMOS logic gate, which means that the LM94022 sensor's supply connection serves as the "shutdown" pin. Because temperature changes slowly, and can be measured quickly, the LM94022 device can be powered up for a small percentage of total operating time, such as one second every two minutes, providing "quick" response to changes in temperature, but using less than 75 pA of average current.

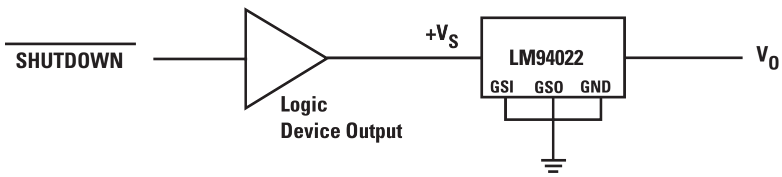


Figure 4-9. 1.5V Temperature Sensor operating from Logic Gate

In many battery-operated portable devices, a microcontroller is available that has ADC inputs. The LM26LV temperature sensor is a prime candidate for such a system with a power supply range of 1.6V to 5.5V and a maximum quiescent current of 16 µA. Temperature can be used to calibrate other circuitry via the microcontroller ADC while at the same time the LM26LV device provides an OVERTEMP output that activates when the LM26LV temperature exceeds a factory-preprogrammed limit. This limit can be set by National during production testing to any value between 0°C and 150°C. The OVERTEMP output is shown in ***Figure 4-10*** going to the microcontroller to enable quick thermal warning. The OVERTEMP output can just as easily be routed to the shutdown pin of a regulator, thereby turning off system circuitry and avoiding catastrophic damage.

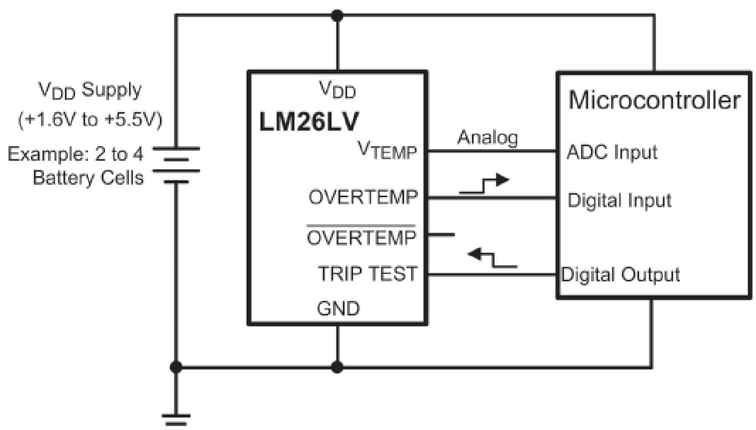


Figure 4-10. The LM26LV sensor connects directly to the analog and digital interface of a microcontroller or processor. The microcontroller reads temperature by sampling the analog V_{TEMP} signal with an ADC. The over-temperature alert is monitored by a digital input. A digital output can drive the TRIP TEST pin in order to verify functionality of the LM26LV sensor.

Battery Management

Battery-charging circuits range in complexity from simple voltage sources with current-limiting resistors to sophisticated systems based on “smart batteries” that include microcontrollers, temperature sensors, ADCs, and non-volatile memory to store optimum charging data and usage history. The charge status of a battery is measured using terminal voltage and tracking the charge flowing in and out of the cells. Fast chargers for NiCad and NiMH batteries also often rely on cell temperature to help determine when to terminate charging.

In NiCad batteries, charging is an endothermic process, so a NiCad battery pack will either remain at the same temperature or cool slightly during charging. When the battery becomes overcharged, its temperature will begin to rise relatively quickly, indicating that the charging current should be turned off (see ***Figure 4-11a***). Charging is an exothermic process in NiMH batteries, so temperature increases slowly during the entire charge cycle. In either kind of nickel-based battery, both voltage and temperature are often monitored to avoid damage from overcharging. However, in NiMH batteries the change in cell voltage is much slower than in NiCad batteries, so temperature becomes the primary indicator of overcharging.

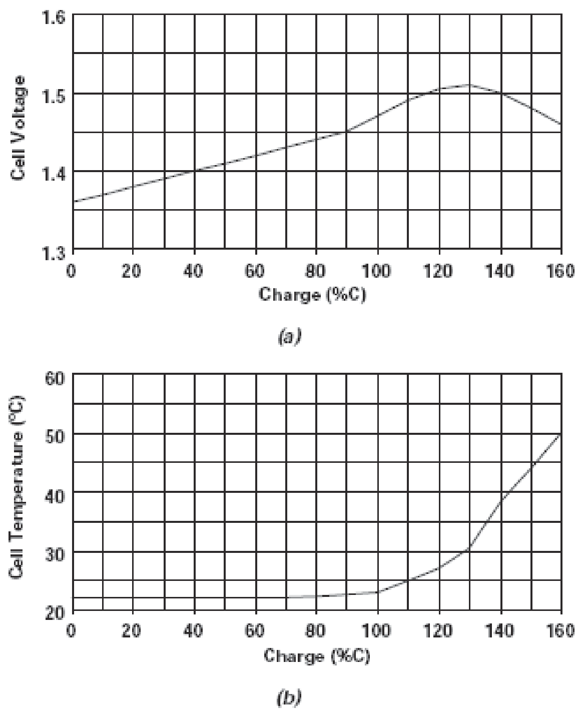


Figure 4-11. Typical NiCad fast-charging curves. Both cell voltage and cell temperature provide indication of overcharging.

“No Power”-Battery Temperature Monitors

Figure 4-12 shows a temperature sensor housed in a battery pack for charge control and safety enhancement. The LM234 sensor produces an output current that is proportional to absolute temperature (1 µA/K). This current can be converted to a voltage by connecting the LM234 sensor’s output to an external resistor, which is located in the host system, or in the battery charger, as shown here. With a 10 kΩ resistor, V_{TEMP} is 10 mV/K. By using an external FET to break the current path, current drain by the sensor drops to zero when temperature is not being monitored. Sensor current drain also drops to zero when the battery is unplugged from the charger, or when it is plugged into a charger that has no AC power, thus preventing accidental battery discharge.

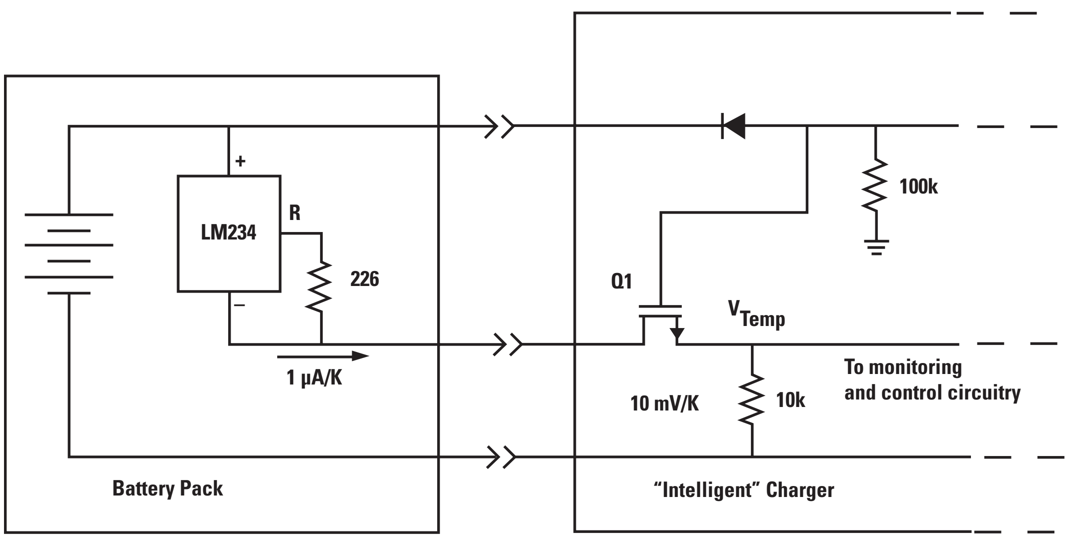


Figure 4-12. This battery-pack temperature sensor uses no power unless Q1 (located either in the charger, as shown here, or in the “load system”) is turned on. This helps prevent accidental battery discharge.

4.4 Audio Power Amplifier Heat-Sink Temperature Detector and Fan Controller

Figure 4-13 shows an over-temperature detector for power devices. In this example, an audio power amplifier IC is bolted to a heat sink and an LM35 Celsius temperature sensor is either glued to the heat sink near the power amplifier, or mounted on the printed circuit board on the opposite side from the heat sink (if the heat sink is mounted flat against one side of the printed circuit board). The comparator’s output goes low if the heat sink temperature rises above a threshold set by R1, R2, and the voltage reference. This fault-detection output from the comparator now can be used to turn on a cooling fan. R3 and R4 provide hysteresis to prevent the fan from rapidly cycling on and off. The circuit as shown is designed to turn the fan on when the heat sink temperature exceeds about 80°C, and to turn the fan off when the heat sink temperature falls below about 60°C.

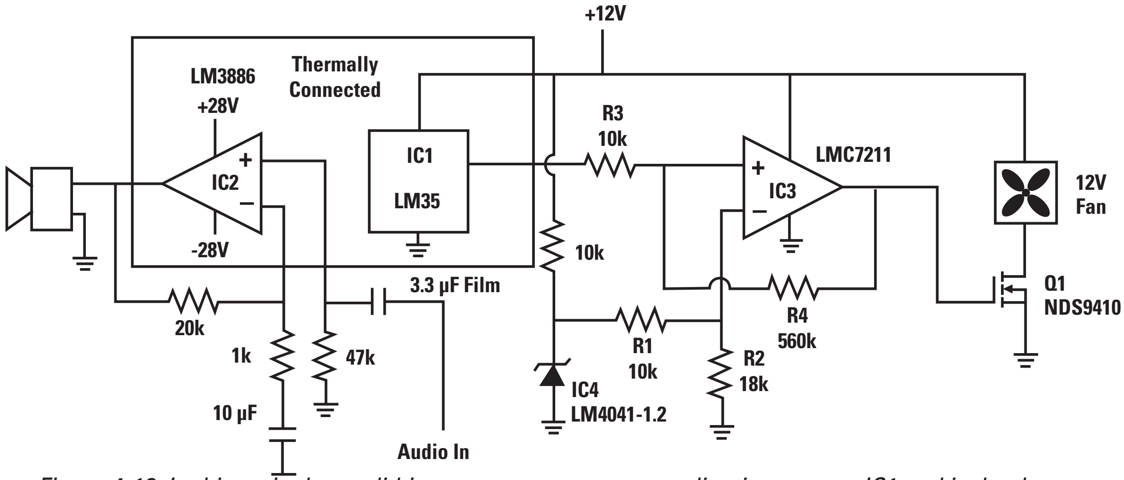


Figure 4-13. In this typical monolithic-temperature-sensor application, sensor IC1 and its leads are attached to 60W audio power amplifier IC2's heat sink. When the heat sink's temperature rises above the 60°C threshold temperature, comparator IC3's output goes high, turning on the cooling fan.

A similar circuit is shown in ***Figure 4-14***. In this circuit, the sensor, voltage reference, and comparator are replaced by the LM56 sensor. The fan turns on at about 80°C, and the LM56 sensor's built-in 5°C hysteresis causes the fan to turn off again when the sensor's temperature drops below about 75°C.

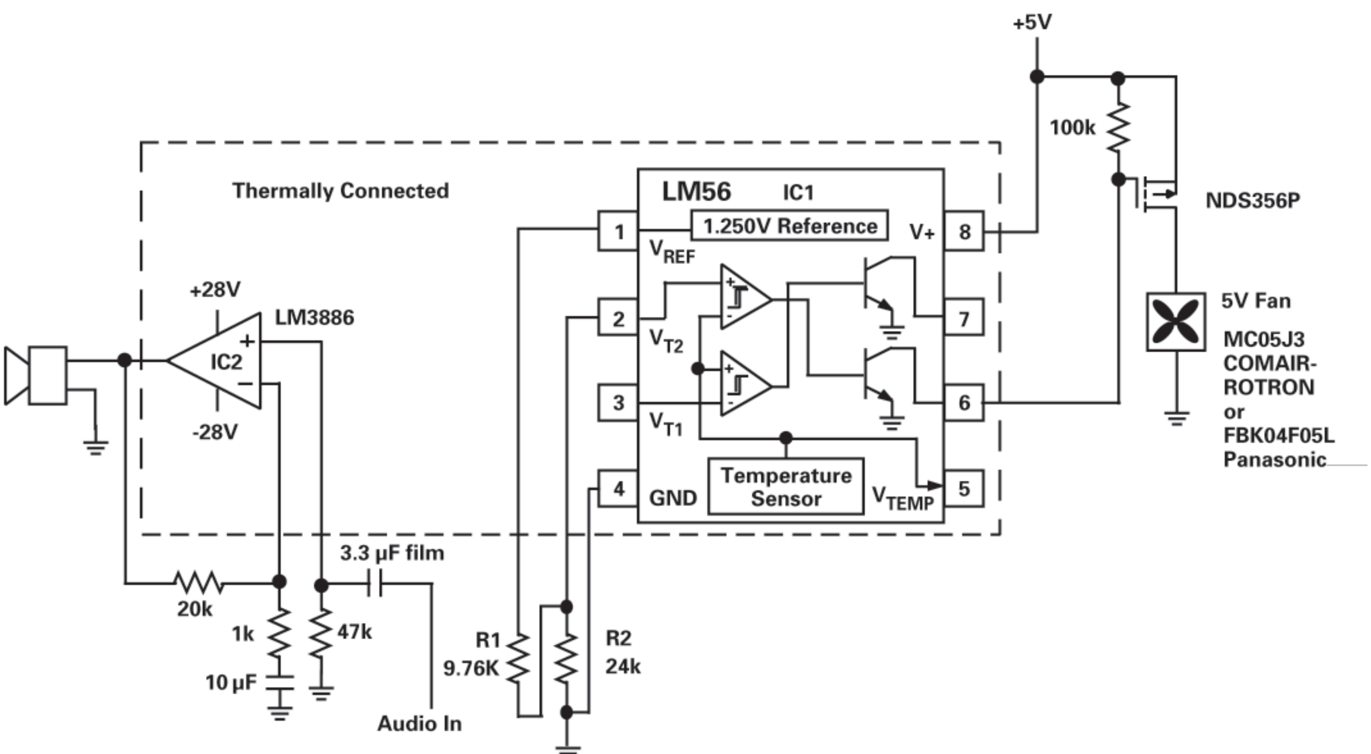


Figure 4-14. This circuit's function is similar to that of the circuit above, except that the sensor, comparator, and voltage reference are integrated within the LM56 sensor. In this circuit, the fan turns on at 80°C and off at 75°C.

4.5 Other Applications

2-Wire Temperature Sensor

When sensing temperature in a remote location, it is desirable to minimize the number of wires between the sensor and the main circuit board. A three-terminal sensor needs three wires for power, ground, and output signal; going to two wires means that power and signal must coexist on the same wires. A two-terminal sensor like the LM334 or LM335 can be used, but these devices produce an output signal that is proportional to absolute temperature, which can be inconvenient. If an output signal proportional to °C and no more than two wires is required, the circuit in ***Figure 4-15*** may be a good solution. The sensor's output voltage is DC, and power is transmitted as an AC signal.

The AC power source for the sensor is a sine-wave oscillator (A1 and A2) coupled to the 2-wire line through blocking capacitor C6. At the LM45 sensor, D1, D2, C1, and C3 comprise a half-wave voltage-doubler rectifier that provides power for the sensor. R2 isolates the sensor's output from the load capacitance, and L1 couples the output signal to the line. L1 and C2 protect the sensor's output from the AC on the 2-wire line.

At the output end of the line, R3, L2, and C4 form a low-pass filter to remove AC from the output signal. C5 prevents DC current from flowing in R3, which would attenuate the temperature signal. The output should drive a high-impedance load (preferably 100 kΩ or greater).

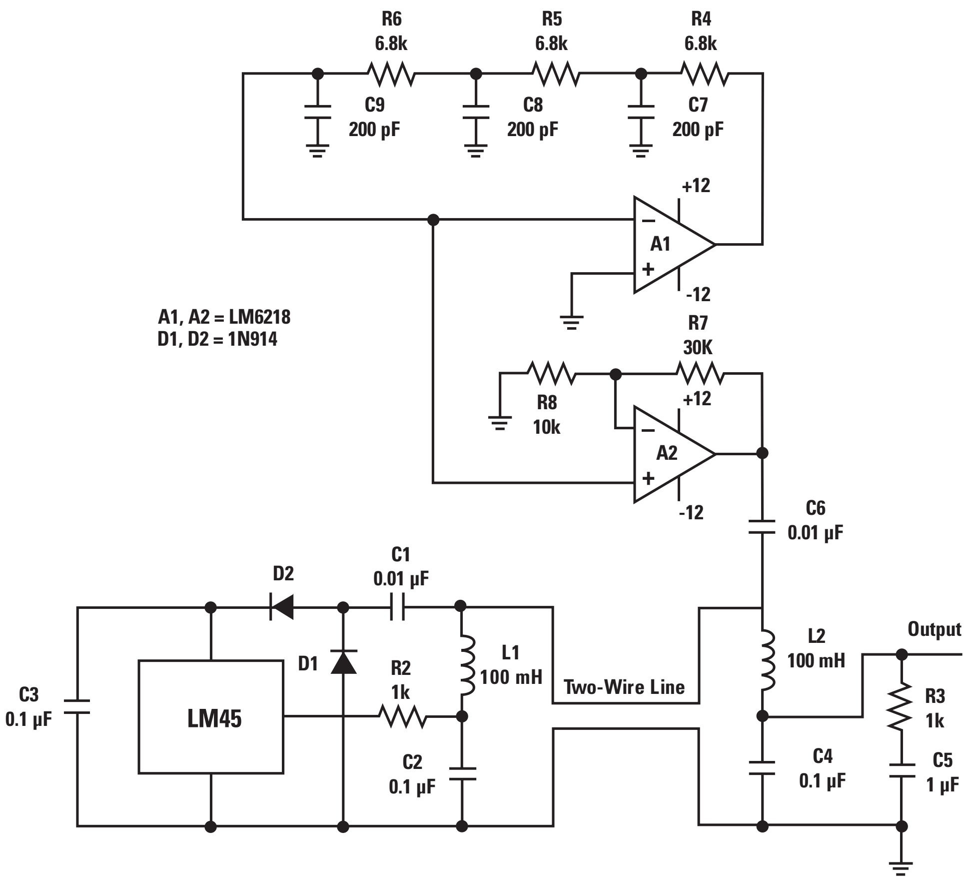


Figure 4-15. This 2-Wire Remote Temperature Sensor Transmits the DC Output of the Sensor Without Reducing Its Accuracy

4-to-20 mA Current Transmitter (0°C to 100°C)

This circuit uses an LM45 or LM35 temperature sensor to develop a 4-to-20 mA current. The temperature sensor's output drive is augmented by a PNP to drive a 62.5Ω load; this provides the 160 μA/°C transfer-function slope required to develop a 4-to-20 mA output current for a 0°C to 100°C temperature range. The LM317 voltage regulator and its load resistors draw about 2.8 mA from the supply. The remaining 1.2 mA is obtained by adjusting the 50Ω potentiometer to develop an offset voltage on the temperature sensor's ground pin.

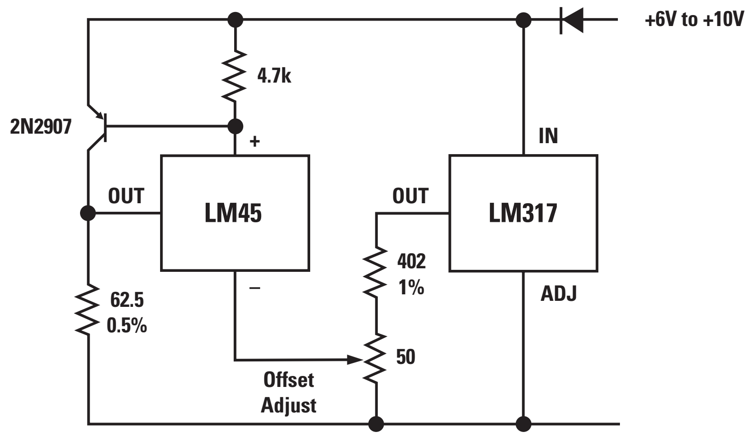


Figure 4-16. 4-to-20 mA Current-Transmitter Temperature Sensor

Multi-Channel Temperature-to-Digital Converter

This circuit implements a low-cost system for measuring temperature at several points within a system and converting the temperature readings to digital form. Remote-diode temperature sensors shine as a more cost-effective solution to this type of application. Shown in ***Figure 4-17*** is an LM95214 device with four remote-diode channels connected to MMBT3904 transistors. The LM95214 device has an address pin allowing up to three of these devices to be placed on a single SMBus line, thus up to 12 thermal zones can be sensed easily.

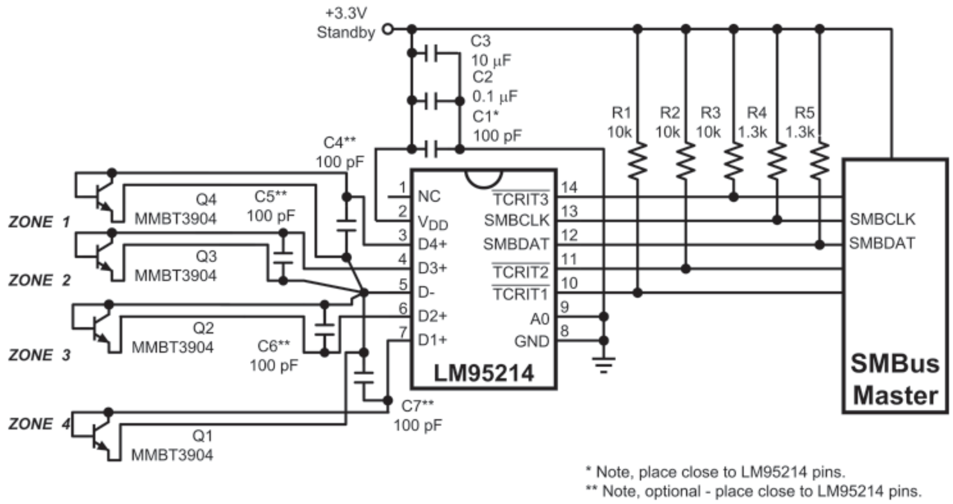


Figure 4-17. 4-Channel Remote-Diode Temperature-to-Digital Converter

Oven Temperature Controllers

The circuit in ***Figure 4-18*** operates on a single +5V supply and controls the temperature of an oven. As shown, the circuit keeps the oven temperature at 75°C, which is ideal for most types of quartz crystals.

The inverting input of amplifier A1 (1/2 of an LM392 amplifier/comparator dual) comes from the LM335 temperature sensor, which should be in good thermal contact with the heater, and the non-inverting input is the output of a voltage divider from the LM4040-4.1 voltage reference. With the divider components shown, the non-inverting input is at 3.48V, which is equal to the LM335 sensor's output at 75°C. The amplifier has a gain of 100 to the difference between the measured temperature and the setpoint.

The output of A1 modulates the duty cycle of the oscillator built around comparator C1. When the oven is cold, the output of A1 is high, which charges the capacitor and forces C1's output low. This turns on Q1 and delivers full DC power to the heater. As the oven temperature approaches the setpoint, A1's output goes lower, and adjusts the oscillator's duty cycle to servo the oven temperature near the setpoint.

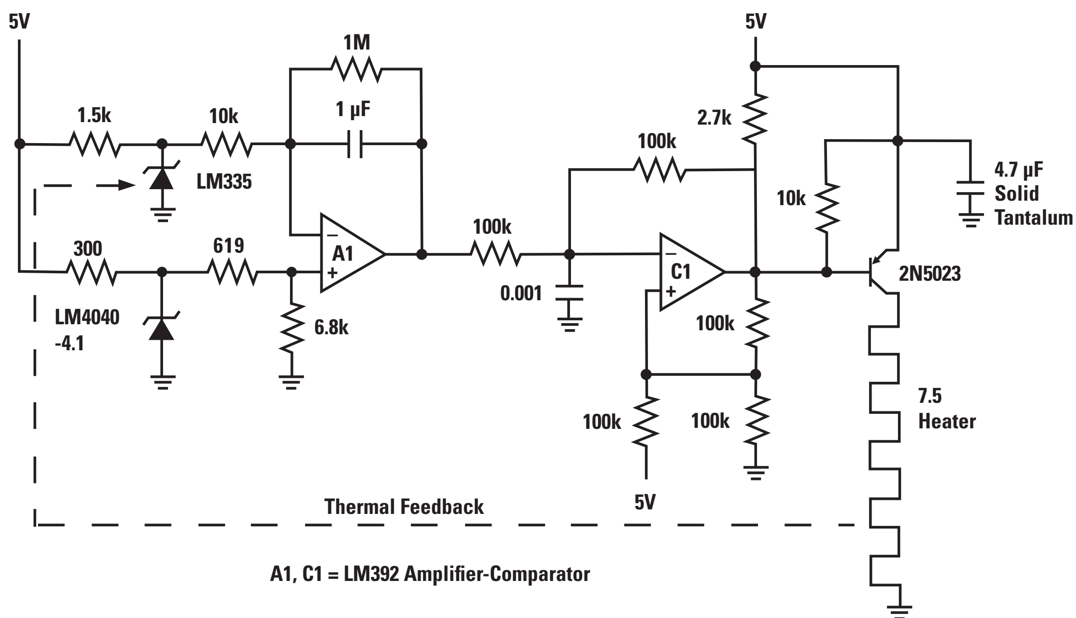


Figure 4-18. Oven Controller

Isolated Temperature-to-Frequency Converter

A simple way to transmit analog information across an isolation barrier is to first convert the analog signal into a frequency. The frequency can then be counted easily on the other side of the isolation barrier by a microcontroller. ***Figure 4-19*** shows a simple way of implementing this. The LM45 sensor's analog output, which is proportional to temperature, drives the input of an LM231 device configured as a V-F converter. Over the temperature range of 2.5°C to 85°C, the LM45 device produces output voltages from 25 mV to 0.85V, which causes the LM231 device to develop output frequencies from 25 Hz to 850 Hz.

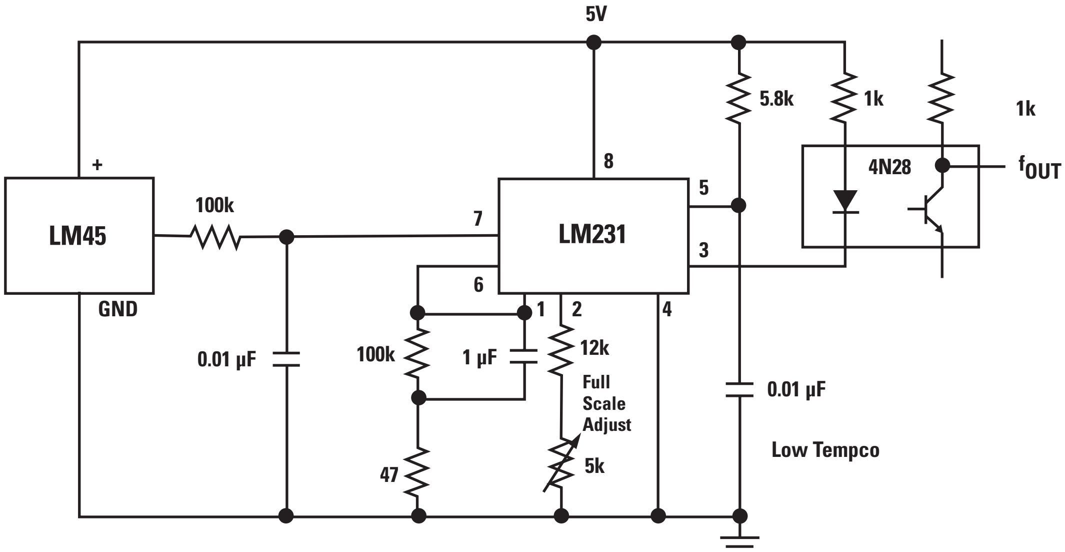


Figure 4-19. Isolated Temperature-to-Frequency Converter

Acronyms

ADC	*Analog-to-Digital Converter*
ALERT	*SMBus signal to bus master that an event occurred that has been flagged for attention*
ASIC	*Application-Specific Integrated Circuit*
CMOS	*Complementary Metal-Oxide Semiconductor*
DAC	*Digital-to-Analog Converter*
FPGA	*Field-Programmable Gate Array*
GPD	*General-Purpose Default*
GPIO	*General-Purpose Input/Output*
HVAC	*Heating, Ventilating, and Air-Conditioning*
I^2C	*Inter-Integrated Circuit (bus)*
LCD	*Liquid Crystal Display*
LLP	*Leadless Leadframe Package*
LSB	*Least Significant Byte*
LUT	*Look-Up Table*
MOSFET	*Metal-Oxide Semiconductor Field-Effect Transistor*
MP	*Multi-Processor*
MSB	*Most Significant Byte*
PI	*Proportional Integral*
PNP	*Plug and Play*
POR	*Power-On Reset*
PRT	*Platinum Resistive Thermometer*
PWM	*Pulse-Width Modulation*
RDTS	*Remote-Diode Temperature Sensor*
RTD	*Resistance Temperature Detector*
SCL	*I^2C-Interface Clock Signal*
SMBus	*System Management Bus*
SMBCLK	*SMBus-Interface Clock Signal*
SMBDAT	*SMBus-Interface Data Signal*
VID	*Voltage Identification (pins on microprocessor)*
VRD	*Voltage Regulator Down – regulates V_{CCP} voltage for a CPU*

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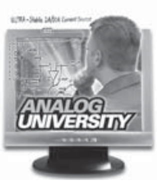

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