

Solving Thermal Measurement Problems Using The TC72 And TC77 Digital Silicon Temperature Sensors

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The circuitry inside the TC72 and TC77 will be analyzed to illustrate the principles that these sensors use to accurately measure temperature. In addition, application guidelines will be provided that can maximize the accuracy of the temperature measurement.

INTRODUCTION

The TC72 and TC77 are CMOS silicon temperature sensors that provide an accurate digital temperature measurement to solve thermal measurement problems. Data is converted from an internal diode temperature-sensing element to a digital format that can be directly interfaced to a microcontroller, as shown in Figure 1. The TC72 and TC77 sensors offer many system-level advantages, including the integration of the sensor and signal conditioning circuitry in a small Integrated Circuit (IC) package.

The main distinguishing feature of the TC72 is its One-shot Operating mode, which performs a single temperature measurement and then goes into power-saving Shutdown mode. The One-shot mode makes the TC72 sensor a good choice for power-critical, portable applications. The main feature of the TC77 sensor is its excellent temperature accuracy specification of 1°C from +25°C to +65°C (max.), making this device an excellent choice for precision temperature-sensing applications.

SILICON IC SENSOR FUNDAMENTALS

Temperature Measurement Diode

IC sensors measure temperature by monitoring the voltage across a diode. The TC72 and TC77 use a bipolar temperature-sensing diode that is built from the substrate of a CMOS IC process. The bipolar diode is created from a PNP transistor that is formed by combining the appropriate P and N junctions, as shown in Figure 2. This method of creating the bipolar substrate diode is also used by the band gap voltage reference circuit that is used in almost every analog and digital IC.

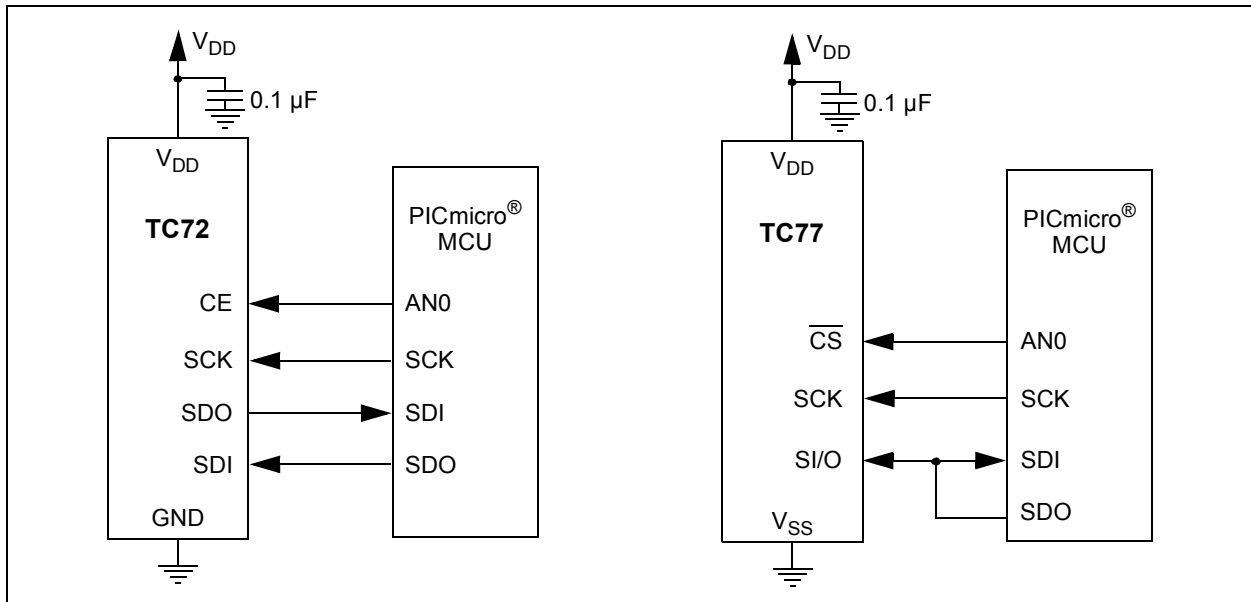


FIGURE 1: Typical Applications of the TC72 and TC77 Temperature Sensors.

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A bipolar diode is used for the temperature measurement because its electrical characteristics are better than a MOSFET diode. The current and voltage relationship of a MOSFET diode is dependent on the

threshold voltage, which is process-dependent. Since it is difficult to obtain an accurate sensor with a MOSFET diode, most silicon sensors use the substrate bipolar diode as the temperature-sensing element.

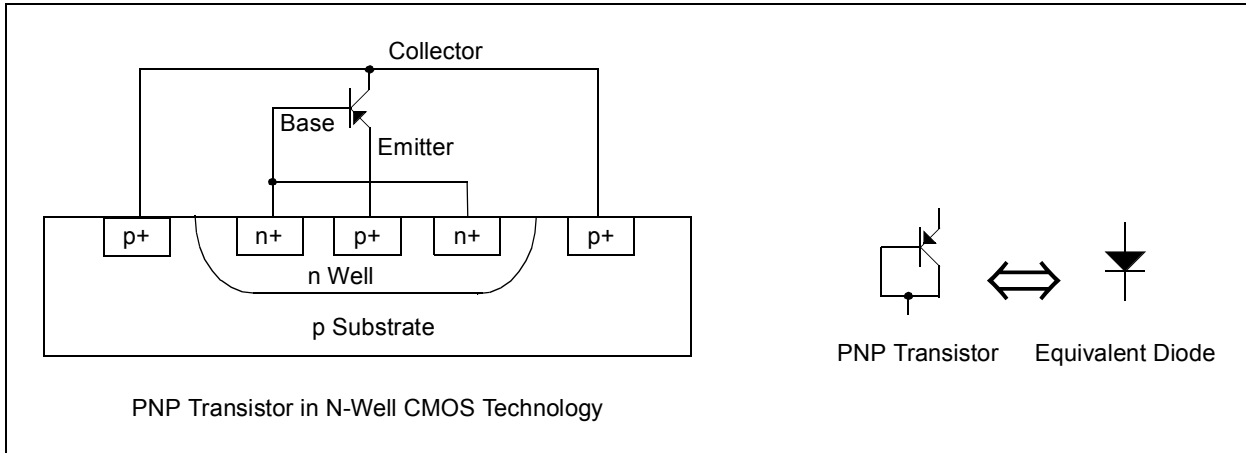


FIGURE 2: Temperature-Sensing Substrate Diode.

Fundamental Diode Equations

The voltage and current equations for a diode are listed in Figure 3. These equations show that a diode has a voltage that is proportional to temperature and the constants k and q . However, the process-dependant constants of η and I_S are also in the equation. IC temperature sensors solve the process-dependent issue with a voltage proportional to temperature (V_{PTAT}) voltage generator circuit, which is similar to a band gap voltage reference.

The non-ideality constant (η) for a silicon diode varies from 0.95 to 1.05. However, η will be assumed to be equal to one. The assumption of η not being equal to one produces a temperature gain and offset error. This error is minimized in the sensor's calibration procedure.

The I_S variable must be eliminated because I_S varies with temperature and also from wafer to wafer. The I_S variable in the diode's voltage equation can be eliminated by two different methods. The first method eliminates I_S using two different current sources and a single diode, while the second method uses a single current source and two different diodes.

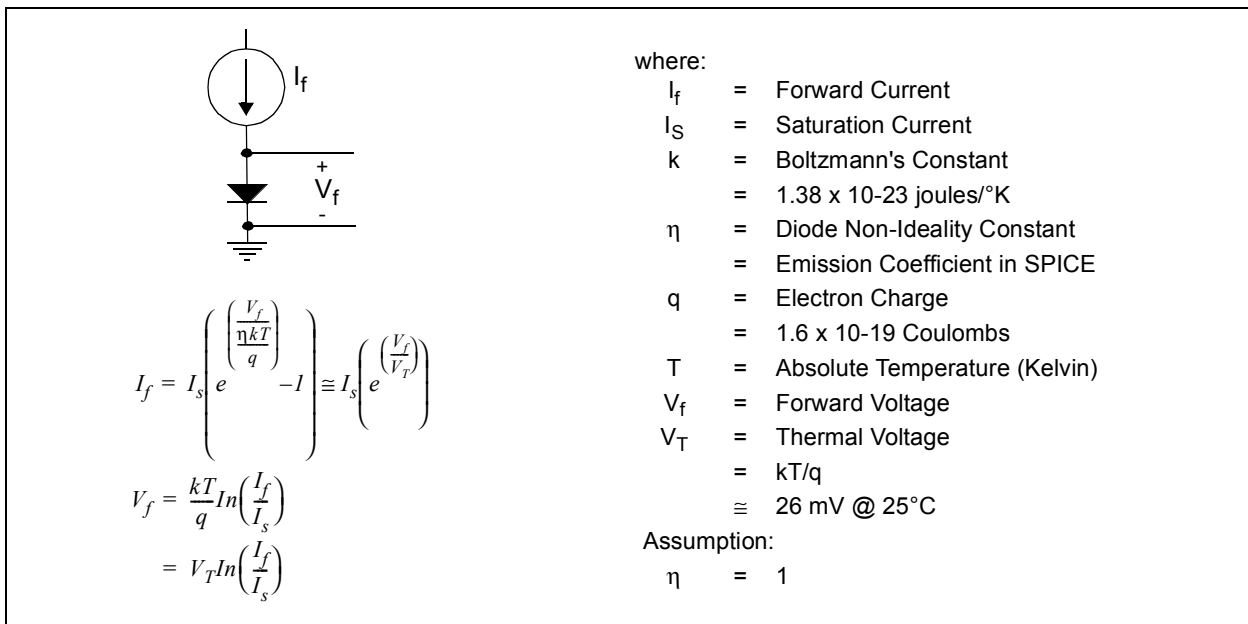


FIGURE 3: Fundamental Diode Equations.

Creating A Voltage Proportional To Temperature

The TC72 and TC77 use the two current sources with a single diode method to eliminate I_S . Figure 4 provides a simplified schematic of the circuit that measures the voltage resulting from multiplexing two current sources across a diode. The equations illustrate that the I_S variable is cancelled by either subtracting the voltages or equivalently by calculating the ratio of the logarithmic equations.

The two current, one diode method is used to eliminate I_S because it is relatively easy to build current sources that are a ratio of each other. In practice, the two currents are chosen to have a ratio of ten, which produces a voltage with a temperature coefficient of approximately $200 \mu\text{V}/^\circ\text{C}$. The ΔV_{EB} equation is important because it contains three constants (k , q and N) and the temperature variable T . This equation establishes a voltage that is proportional to a constant multiplied by temperature, while eliminating the process-dependent variable, I_S .

Voltage ΔV_{EB} is also referred to as V_{PTAT} , or the voltage which is proportional to absolute temperature. Figure 5 shows a graphical representation of the V_{PTAT} voltage,

which is linear with a slope, or temperature coefficient, equal to approximately $200 \mu\text{V}/^\circ\text{C}$ with $N = 10$. The absolute value of the current source is not in the temperature equation. It is only important that the ratio (N) of the two current sources track each other over temperature. Note that it has been assumed that ΔV_{EB} is only a function of the current and thermal voltage V_T ($V_T = kT/q$). While the complete equation for ΔV_{EB} is more complex, this complication can be neglected as a second order effect.

An alternative method to eliminate the I_S term in the diode's voltage equation is accomplished by measuring the voltage of two different diodes created from a single current source, as shown in Figure 6. This method to eliminate the process variable I_S is used because the magnitude of the currents can be controlled by the dimensions of a transistor. The current ratio circuit can be created by using a parallel circuit of N transistors identical to the first. Reference [4] provides further details on the current ratio circuit shown in Figure 6. The total current is shared equally between the transistors and the voltage $V_{EB(N)}$ is established. A second method to implement this circuit is to scale the emitter area of the transistors.

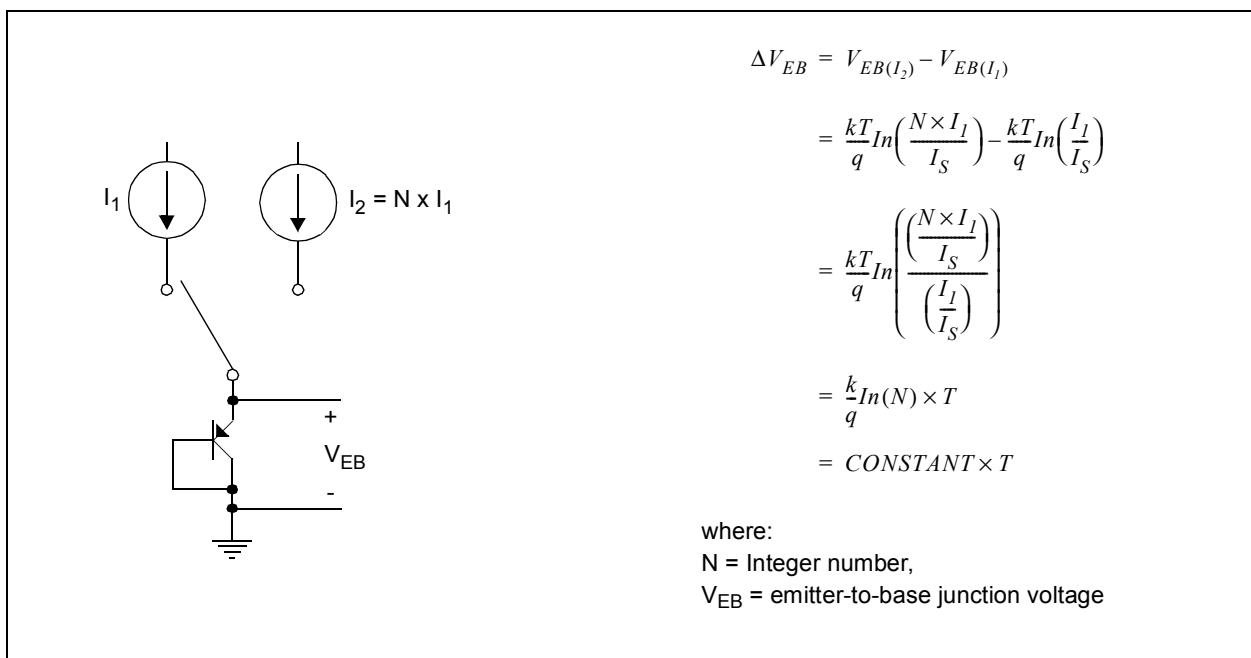


FIGURE 4: Creating a Voltage Proportional to Temperature with Two Current Sources and One Diode.

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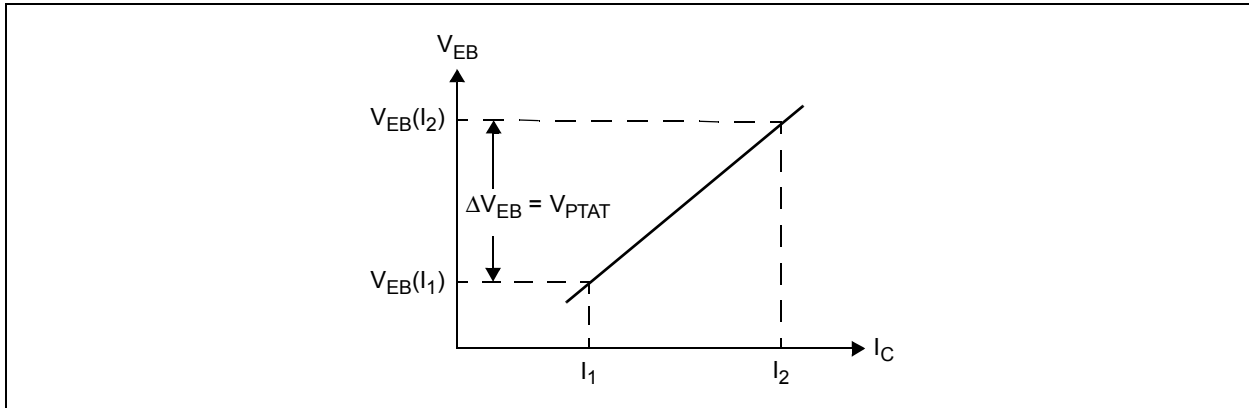


FIGURE 5: Graphical Representation of the V_{PTAT} Voltage Created with Two Current Sources and One Diode.

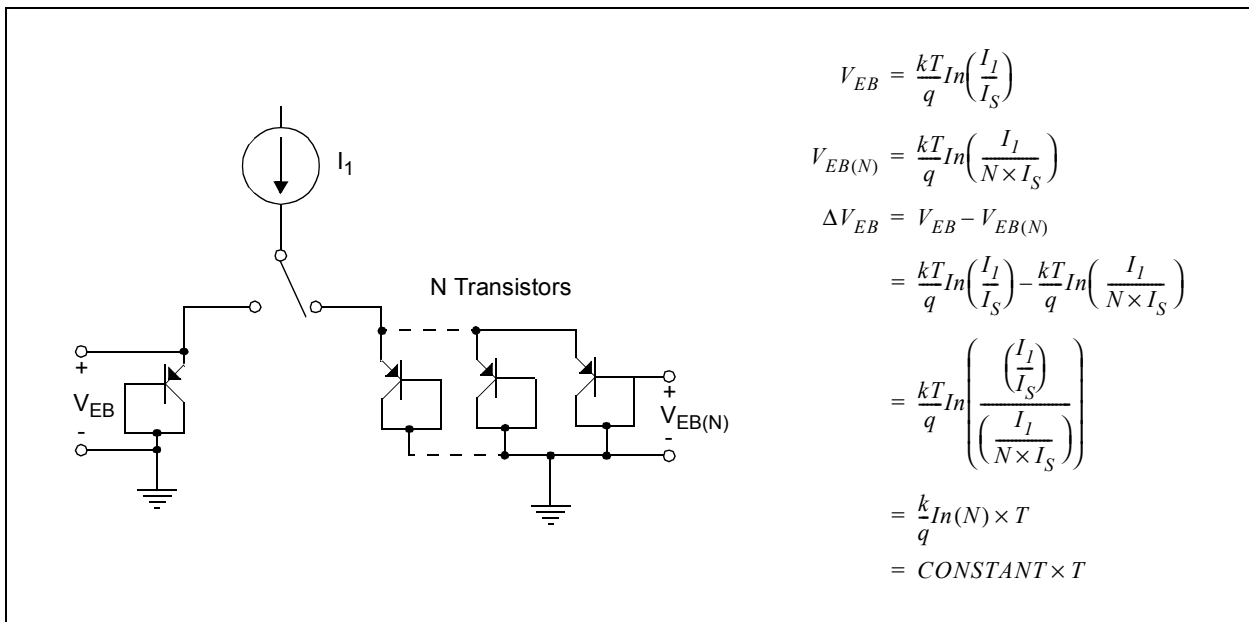


FIGURE 6: Creating a Voltage Proportional to Temperature with One Current Source and Two Diodes.

TC72 AND TC77 BUILDING BLOCKS

Figure 7 provides simplified block diagrams of the TC72 and TC77. Details of the temperature building blocks will be analyzed to demonstrate how a silicon sensor accurately measures temperature. In addition, the review of the circuitry inside the temperature sensor will provide an understanding of the advantages and disadvantages of silicon sensors as compared to other temperature sensor technologies.

The TC72 and TC77 sensors offer many system-level advantages, including the integration of the sensor and the signal conditioning circuitry. Advancements in CMOS IC fabrication processes has enabled the integration of the temperature sensor, ADC and digital registers on a single chip that is connected to the processor through a serial data bus. The serial I/O communication interface to a microcontroller allows the user the ability to select either the Continuous Temperature Conversion, One-shot or the power-saving Shutdown operating mode, in addition to reading the temperature and manufacturer ID registers.

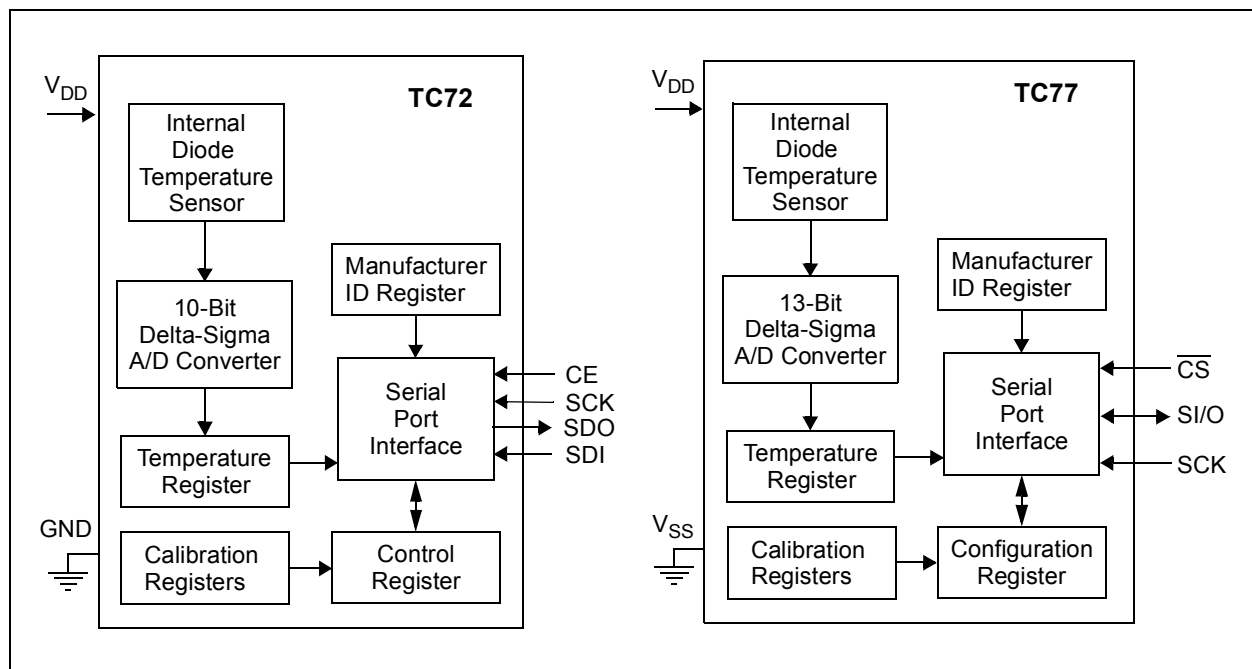


FIGURE 7: TC72 and TC77 Simplified Block Diagrams.

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Internal Diode Temperature Sensor

BAND GAP VOLTAGE REFERENCE

A band gap voltage reference circuit is used to create a reference voltage that is stable over temperature. The term band gap refers to the theoretical voltage of a silicon junction at 0°K. Band gap circuits achieve temperature independence by canceling the negative temperature coefficient of a PNP transistor's emitter-to-base diode voltage (V_{EB}) with the positive temperature

coefficient of the voltage created from a V_{PTAT} circuit, as shown in Figure 8. The voltage V_{EB} has a temperature coefficient of $-2.2 \text{ mV}/^\circ\text{C}$, while the V_{PTAT} voltage has a temperature coefficient of $+0.085 \text{ mV}/^\circ\text{C}$. Next, V_{PTAT} is amplified by K so that the temperature coefficient is scaled to $+2.2 \text{ mV}/^\circ\text{C}$. When V_{EB} is added to the scaled V_{PTAT} signal, the two temperature coefficients cancel and an output voltage results that is independent of temperature.

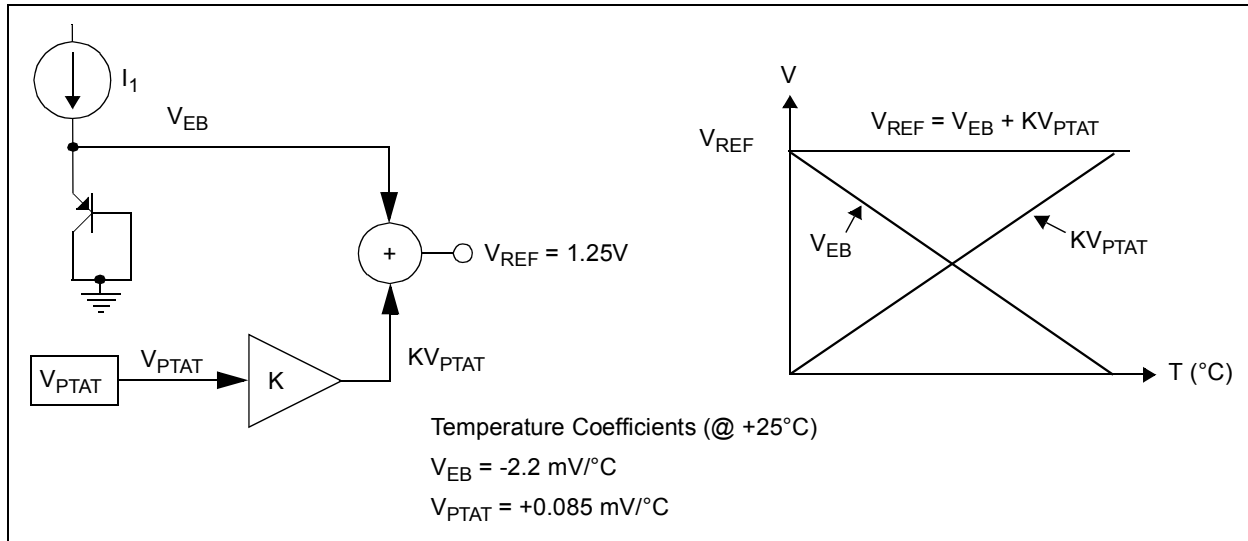


FIGURE 8: Band Gap Voltage Reference Concept.

A simplified schematic of a band gap circuit is shown in Figure 9. This circuit is based on the principle that the magnitude of currents I_1 and I_2 are proportional to the size of the emitter area (AE) of the transistors. A 1.250V reference voltage (V_{REF}) will be produced if the

emitter area ratio is equal to eight ($n = 8$) and the resistor ratio is set to ten ($p = 10$). References [1] and [3] provide further details on the band gap voltage reference circuit.

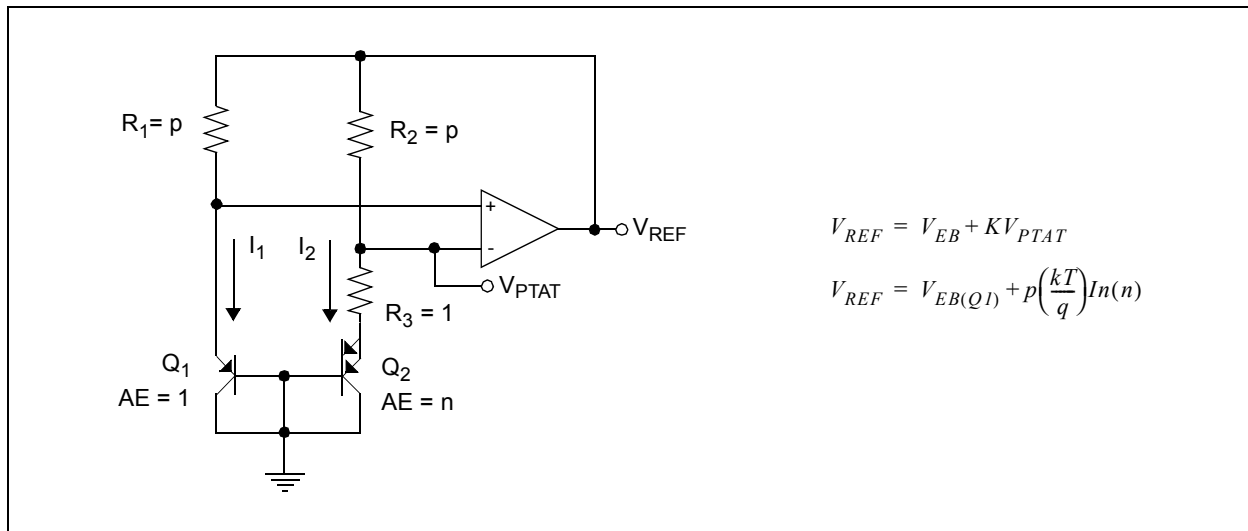


FIGURE 9: Band Gap Voltage Reference Building Block.

Delta-Sigma Converter

FUNDAMENTALS

The TC72 and TC77 use a Delta-Sigma ($\Delta\Sigma$) analog-to-digital converter (ADC). $\Delta\Sigma$ ADCs are used in the majority of digital temperature sensors because they are easy to integrate, offer a high bit resolution and have low power consumption. The TC72 has a 10-bit ADC with a typical conversion time of 150 ms, while the TC77 has a 13-bit ADC with a typical conversion time of 300 ms.

A block diagram of the architecture of the $\Delta\Sigma$ ADC is given in Figure 10. The first part of the ADC is a difference amplifier, followed by an integrator amplifier. The difference amplifier is used to buffer the analog input signal and to complete the feedback loop from the DAC. The integrator is used to provide gain and functions as a high-pass filter that will minimize the quantization noise. Next, the comparator converts the

input signal to a high-frequency digital signal by functioning as a 1-bit ADC where the output is a digital pulse stream that is representative of the average value of the input signal. The comparator then drives a 1-bit DAC, which is essentially a switch that provides a reference signal to the difference amplifier.

The basic principle of the $\Delta\Sigma$ ADC is to digitize an analog signal with a very low resolution 1-bit ADC at a very high sampling rate. This over-sampling technique effectively increases the resolution of the ADC. The output of the $\Delta\Sigma$ ADC is a 1-bit data stream that is converted by a counter or accumulator circuit to a digital count, which is representative of the measured temperature. The counter circuit provides the digital filtering function to restore an output stream of either ones or zeroes which is representative of the input data. The filtering is accomplished by counting the number of pulses in a fixed time window.

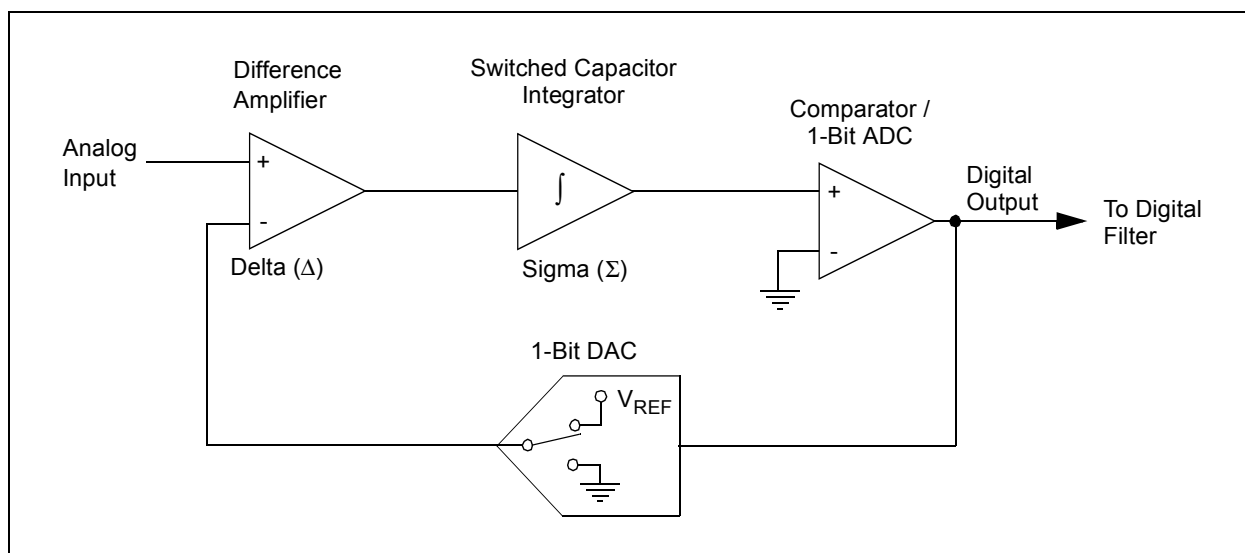


FIGURE 10: Simplified Delta-Sigma ADC Block Diagram.

SWITCHED CAPACITOR AMPLIFIER

The switched capacitor amplifier provides gain in the $\Delta\Sigma$ ADC. The V_{PTAT} signal created from the V_{PTAT} voltage generator circuit is amplified with the switched capacitor integrator to increase the magnitude of the temperature coefficient. Switched capacitor amplifiers feature low noise and offset voltages that are needed to accurately amplify the V_{PTAT} voltage of $200 \mu\text{V}/^\circ\text{C}$ to a voltage of approximately of $2 \text{ mV}/^\circ\text{C}$.

A switched capacitor amplifier is based on the principle that a capacitor can be used to create an equivalent resistance in a switching circuit, as shown in Figure 11. Amplifier circuits can be built using capacitors in place of resistors and have the advantage of an inherent “auto-zeroing” feature that minimizes the input offset

voltage error of the amplifier. The analog switches are built by using both a N-channel and P-channel MOSFET in parallel.

Switched capacitor amplifiers are also used because it is relatively easy to build capacitors that are equal to a ratio of each other in an IC process. Also, the effective magnitude of the capacitance can be accurately controlled using a time multiplexed scheme. For example, a 2 nF capacitor that is switched into the circuit with a 50% duty cycle is equivalent to a 1 nF capacitor.

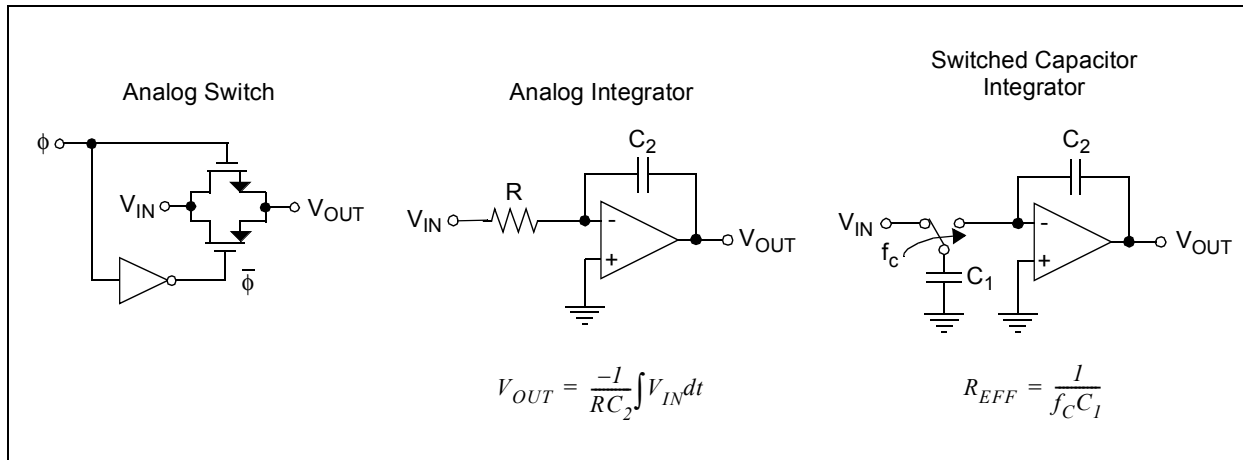


FIGURE 11: Switching Capacitor Circuits.

A switched capacitor, V_{PTAT} amplifier is shown in Figure 12. See reference [3] for additional information. For simplicity, the circuit shown in Figure 12 is single-ended, while the TC72 and TC77 use a differential topology. A differential integrator increases the noise immunity of the amplifier by reducing the common mode noise of the analog ground signal.

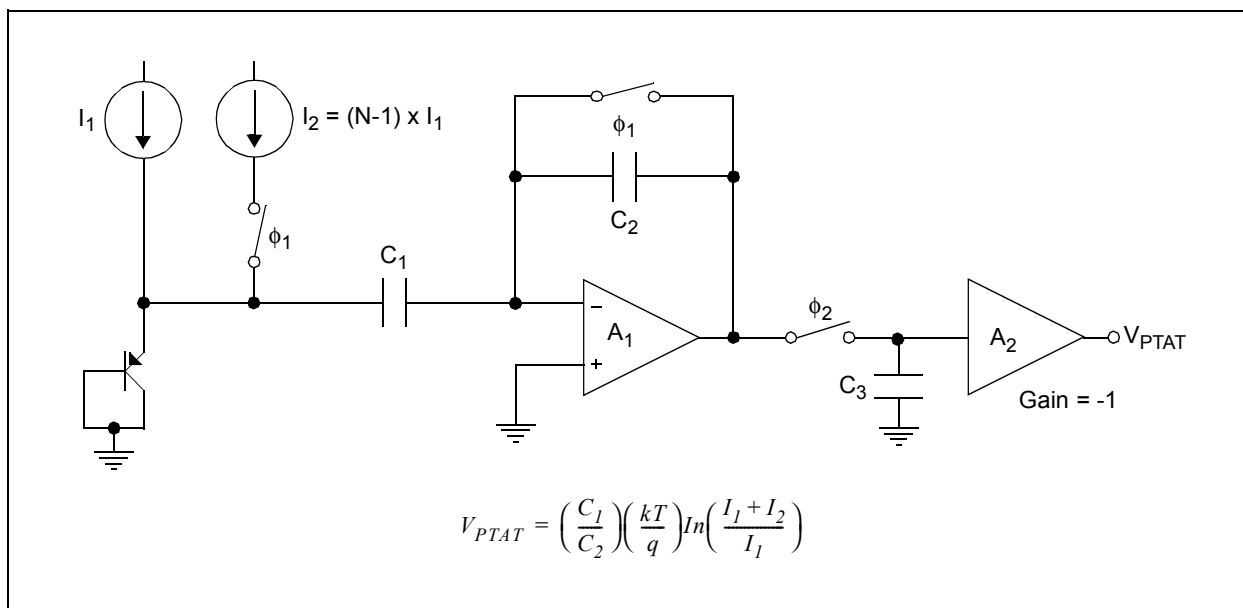


FIGURE 12: Switched Capacitor V_{PTAT} Amplifier.

Digital Registers

The TC72 has four internal 8-bit registers, while the TC77 has three 16-bit registers that are used by a microcontroller for communication. The temperature measurement data is stored in the Temperature Register, while the TC72 Control Register or TC77 Configuration Register is used to select the operating mode of the sensor. The Manufacturer's Identification (ID) register is used to identify the sensor as a Microchip component. Tables 1, 2 and 3 provide the bit definitions of the registers.

The Calibration Register is used to store the adjustments that are determined during the sensor's acceptance test procedure. The Calibration Registers are not accessible by the external microcontroller. The contents of the Calibration Registers are nonvolatile.

OPERATING MODES

The user configured operating modes of the TC72 and TC77 include a Continuous Temperature and a Shutdown mode that are selected via the Control/Configuration Register. In the Continuous Temperature mode, an ADC conversion is performed every 150 ms for the TC72 and every 300 ms for the TC77. If a Temperature Register read operation is requested while an ADC conversion is in progress, the previous completed ADC conversion data will be outputted via the sensor's serial I/O port.

The Shutdown mode is used to minimize the power consumption of the TC72 and TC77 sensors when active temperature monitoring is not required. The Shutdown mode disables the temperature conversion circuitry; however, the serial I/O communication port remains active. The current consumption of the sensor will be less than 1 μ A when the Shutdown mode is activated.

The TC72 offers a One-shot mode, which is useful when only a single temperature recording is required. The One-shot mode performs a single temperature measurement and returns to the power-saving Shutdown mode.

TABLE 1: TC72 DIGITAL REGISTERS

Register	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0	Value at Power-up/Reset
Control	0	0	0	One-shot (OS)	0	1	0	Shutdown (SHDN)	Shutdown mode
LSB Temperature	2^{-1}	2^{-2}	0	0	0	0	0	0	Temp. = 0.00°C
MSB Temperature	Sign	2^6	2^5	2^4	2^3	2^2	2^1	2^0	Temp. = 0°C
Manufacturer ID	0	1	0	1	0	1	0	0	54 hex

TABLE 2: TC72 CONTROL REGISTER TEMPERATURE CONVERSION MODE SELECTION

Operational Mode	Control Register Bit 4 One-shot (OS)	Control Register Bit 0 Shutdown (SHDN)
Continuous Temperature Conversion	0	0
Shutdown	0	1
Continuous Temperature Conversion (One-shot Command is ignored if SHDN = '0')	1	0
One-shot	1	1

TABLE 3: TC77 DIGITAL REGISTERS

Register	Bit 15	Bit 14	Bit 13	Bit 12	Bit 11	Bit 10	Bit 9	Bit 8	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0	Value at Power-up/Reset
Configuration **	C15	C14	C13	C12	C11	C10	C9	C8	C7	C6	C5	C4	C3	C2	C1	C0	Continuous Temperature Conversion mode
Temperature	Sign	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0	2^{-1}	2^{-2}	2^{-3}	2^{-4}	*	x	x	Temp. = -2°C
Manufacturer ID	0	1	0	1	0	1	0	0	0	0	0	0	0	0	x	x	Bit 15 to Bit 8 = 54 hex

* Temperature Bit 2 = 0 during power-up; otherwise, Bit 2 = 1

** C15:C0 = xxxx/xxxx 1111/1111 (Shutdown mode)

C15:C0 = xxxx/xxxx 0000/0000 (Continuous Temperature Conversion mode)

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Temperature Data Format

The TC72's temperature data is represented by a 10-bit two's complement word with a resolution of 0.25°C per bit, as shown in Table 4. The example below is of the Temperature Data Registers bit definition for a temperature of 41.5°C.

Example:

Temperature = 41.5°C
 MSB Temperature Register = 00101001b
 = $2^5 + 2^3 + 2^0$
 = $32 + 8 + 1 = 41$
 LSB Temperature Register = 10000000b
 = 2^{-1}
 = 0.5

TABLE 4: TC72 TEMPERATURE OUTPUT DATA

Temperature	Binary		
	Bit 7	MSB / LSB Bit 0 / Bit 7	Bit 0
+125°C	0111	1101 / 0000	0000
+25°C	0001	1001 / 0000	0000
+0.25°C	0000	0000 / 0100	0000
0°C	0000	0000 / 0000	0000
-0.25°C	1111	1111 / 1100	0000
-25°C	1110	0111 / 0000	0000
-55°C	1100	1001 / 0000	0000

The TC77's temperature data is represented by a 13-bit two's complement digital word, as shown in Table 5. The Least Significant Bit (LSb) is equal to 0.0625°C. Note that the last three bits (Bit 0, 1 and 2) are tri-stated and are represented as a logic '1' in the table. The example below is of the TC77's Temperature Register bit definition for a temperature of 85.125°C.

Example:

Temperature = 85.125°C
 Temperature Register = 00101010 10010111b
 = $2^6 + 2^4 + 2^2 + 2^0 + 2^{-3}$
 = $64 + 16 + 4 + 1 + 0.125$
 = 85.125

TABLE 5: TC77 TEMPERATURE OUTPUT DATA

Temperature	Binary			
	Bit 15			Bit 0
+125°C	0011	1110	1000	0111
+25°C	0000	1100	1000	0111
+0.0625°C	0000	0000	0000	1111
0°C	0000	0000	0000	0111
-0.0625°C	1111	1111	1111	1111
-25°C	1111	0011	1000	0111
-55°C	1110	0100	1000	0111

Serial Port Interface

The TC72 and TC77 are designed to be compatible with the Serial Peripheral Interface™ (SPI™) Serial I/O Specification. This provides a simple communication interface to a variety of microcontrollers.

The TC72's serial interface consists of:

- Chip Enable (CE)
- Serial Clock (SCK)
- Serial Data Input (SDI)
- Serial Data Output (SDO)

The TC77's serial interface consists of:

- Chip Select (\overline{CS})
- Serial Clock (SCK)
- Bidirectional Serial Data (SI/O) signals

Details on the sensor's SPI protocol are given in the TC72 data sheet (DS21743) and TC77 data sheet (DS20092). Note that the SPI configuration defines the voltage level and timing specifications for the I/O signals. However, the register bit definitions and the protocol of the read and write operations are unique for most silicon IC sensors.

Putting the Building Block Circuits Together to Create the TC72 and TC77

The main building blocks of the TC72 and TC77 are the V_{PTAT} generator, band gap voltage reference, Delta-Sigma ADC, Digital Registers and the SPI serial I/O port. Figure 13 shows these building blocks, which along with an oscillator, logic control unit and voltage detector, produce a sensing system that can accurately measure temperature.

The basic temperature measurement is implemented by the V_{PTAT} circuit, which produces the current I_{PTAT} , which is proportional to temperature. The band gap voltage reference produces the reference current, I_{REF} from the reference voltage, which is not sensitive to temperature. Next, the $\Delta\Sigma$ ADC compares the I_{PTAT} and I_{REF} currents to produce a digital output that is representative of the temperature measurement.

Details on the circuitry inside the TC72 and TC77 has been greatly simplified to illustrate the features and application issues of these sensors. The actual circuitry of the sensor is more complex and has been optimized to produce a small, power-efficient sensor. For example, the V_{PTAT} circuit is implemented as part of the $\Delta\Sigma$ ADC circuit.

The TC72 and TC77 sensors use a sophisticated network of switched current circuits and precisely matched capacitors. The timing sequence of the switching networks is controlled by the control unit, which is, essentially, a digital state machine. The voltage detector is used to control the power-up and power-down sequencing of the digital registers.

Please refer to the TC72 data sheet (DS21743) and TC77 data sheet (DS20092) for details on the digital registers and SPI communication protocol.

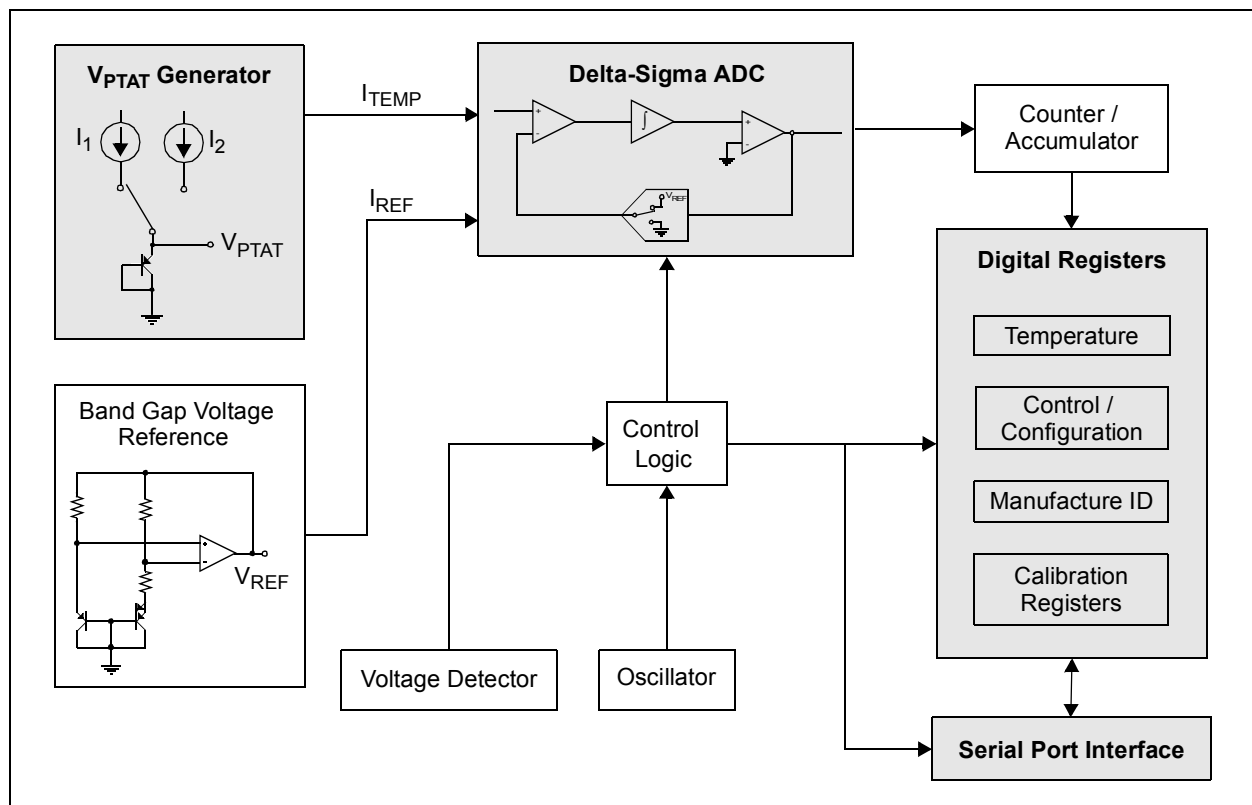


FIGURE 13: Detailed Block Diagram of the TC72 and TC77.

GUIDELINES TO MAXIMIZE TC72 AND TC77 PERFORMANCE

Interpreting the Data Sheet Temperature Accuracy Specification

The accuracy of the TC72 and TC77 sensors is measured by comparing the temperature output of the sensors to the temperature measured by a calibrated platinum RTD sensor. The sensors are placed in a temperature chamber that provides a stable ambient temperature. Figure 14 shows the temperature accuracy graph of the TC77 that was created by measuring a number of sensors and averaging the temperature error.

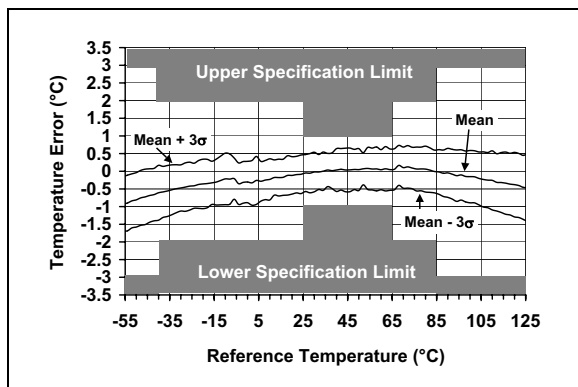


FIGURE 14: *TC77's Temperature Accuracy (TC77-X.XMXX).*

The TC72 data sheet (DS21743) and TC77 data sheet (DS20092) also provide histograms of the temperature accuracy of the sensor. The histogram data shows the variance of the temperature error over a sample of sensors. Figure 15 shows a histogram of the temperature error of the TC77 at +25°C.

The accuracy of the TC72 and TC77 is better than the specification limits listed in the data sheet. However, Microchip can only ensure that the devices will meet the minimum and maximum error limits. The error limits of the TC72 and TC77 data sheets are determined by the accuracy of the sensor and production test equipment. The accuracy plots in the data sheets were determined by qualifying the IC design with laboratory-grade instrumentation. In contrast, the ovens used in the high volume IC fabrication have a much larger temperature variance. Therefore, the data sheet limits have to be set higher to take into account the error of the test equipment.

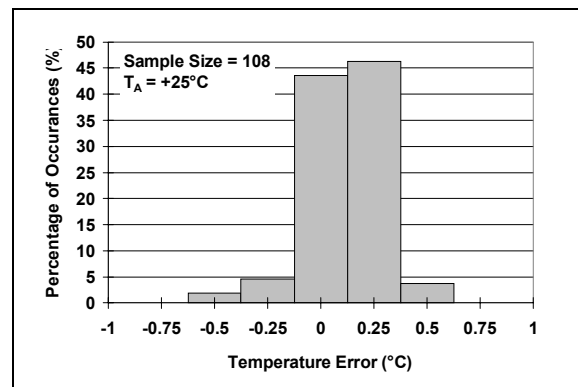


FIGURE 15: *Histogram of TC77's Temperature Accuracy at +25°C (TC77-X.XMXX).*

Temperature Accuracy vs. V_{DD}

The TC72 is specified with a V_{DD} range of 2.65V to 5.5V. However, the temperature accuracy is tested and calibrated at either 2.8V, 3.3V or 5.0V. The TC77 has a supply voltage specification of 2.7V to 5.5V and the temperature accuracy is tested and calibrated at either 3.3V or 5.0V. As V_{DD} varies from the the voltage used during the calibration procedure, the accuracy may be degraded as shown in Figures 16 and 17.

The user should select a TC72 or TC77 sensor that has a calibration voltage that is as close as possible to the system voltage on the PCB to maximize the temperature accuracy of the sensor. Note that the temperature error resulting from using a V_{DD} voltage is different than what was used during the calibration procedure and varies as a function of temperature. In addition, the temperature error versus V_{DD} curve varies slightly from sensor to sensor. Therefore, it is typically not possible to compensate for this error at the microcontroller system level.

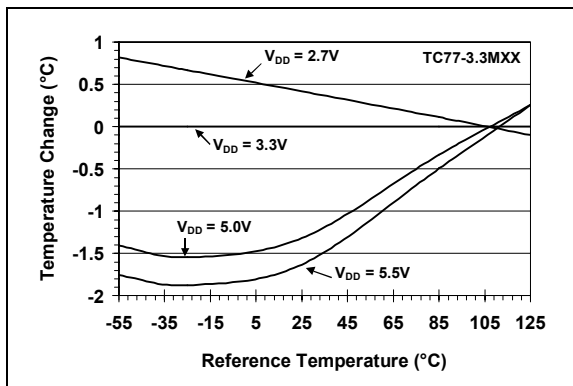


FIGURE 16: TC77's Temperature Accuracy vs. Supply Voltage Plotted at $V_{DD} = 2.7V, 3.3V, 5.0V$ and $5.5V$.

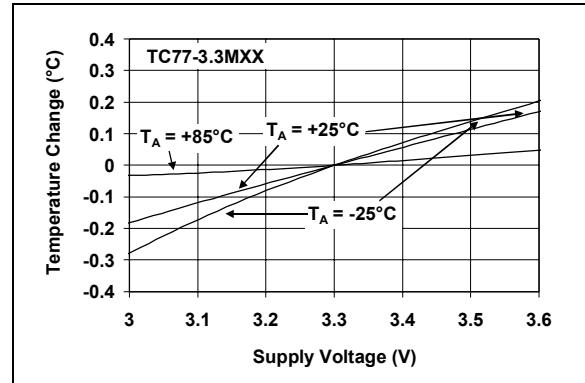


FIGURE 17: TC77's Temperature Accuracy vs. Supply Voltage Plotted at $-25^{\circ}C, +25^{\circ}C$ and $+85^{\circ}C$.

Factory Calibration

The TC72 and TC77 sensors are calibrated during the manufacturing process to maximize the accuracy of the temperature measurement. The calibration procedure can be compared to the $y = mx + b$ representation of a straight line. An adjustment to the sensor is accomplished at the factory to calibrate both the slope (m) or the temperature coefficient and the offset (b) of the sensor. A simplified representation of the sensor calibration procedure is shown in Figure 18. Note that the calibration registers are only accessible during the testing operation and cannot be reconfigured by the user.

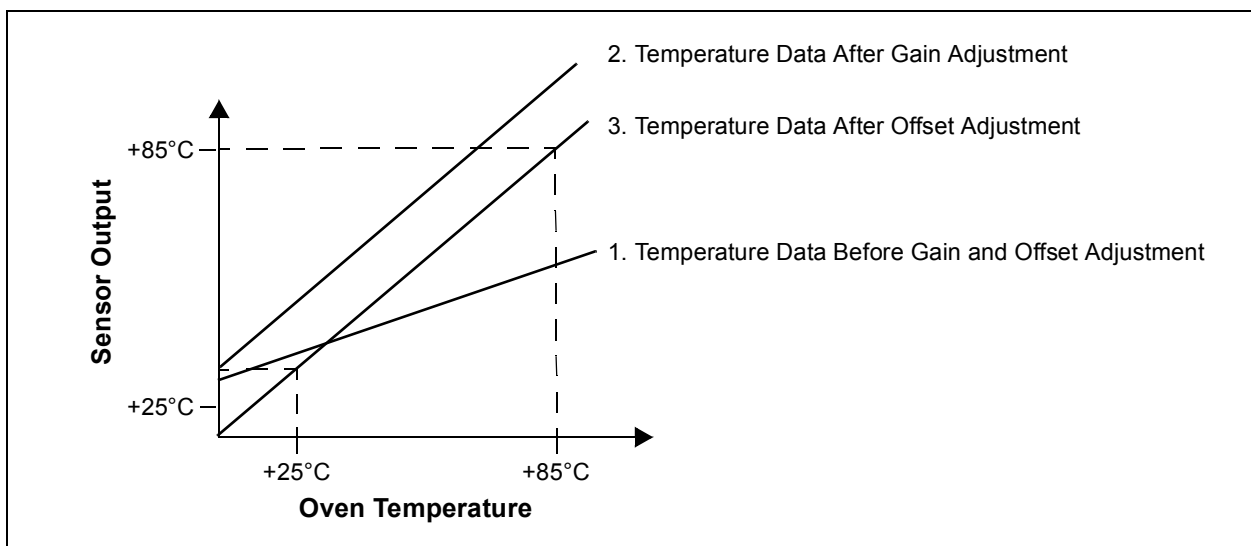


FIGURE 18: Simplified Factory Calibration Procedure.

Optional User Printed Circuit Board (PCB) Level Calibration

While the TC72 and TC77's temperature accuracy is adequate for most applications, the accuracy of the sensor can be improved by measuring the output of the sensor, providing a correction in a microcontroller. Data is provided in reference [2] that shows that the temperature error curve of a silicon IC is very repeatable. Reference [2] uses a second-order, curve-fitting equation to compensate for the offset and curvature of the sensor's error, improving the accuracy of the sensor by a factor of ten. The sensor correction can also be implemented with a simple microcontroller lookup table routine where the correction temperature offsets are stored in nonvolatile memory. Note that the temperature error curve will vary from sensor to sensor. Thus, the optional temperature error adjustment requires a board-level calibration for each sensor.

ADC Resolution

The resolution of the sensor is defined as the temperature reading per bit of the ADC. Although a higher ADC resolution typically produces a more accurate sensor, this may not always be true. The TC72's 10-bit ADC has a resolution of 0.25°C/bit, while the TC77's 13-bit ADC has a resolution of 0.0625°C/bit. Note that the TC72's data is formatted using a range of -128°C to +127°C, while the TC77's data is formatted with a range of -256°C to +255°C. The resolution of the two sensors is calculated below:

$$\begin{aligned} \text{TC72 Resolution} &= (-128^\circ\text{C to } +127^\circ\text{C}) / 2^{10} \\ &= 256 / 2^{10} \\ &= 256 / 1024 \\ &= 0.25^\circ\text{C/bit} \\ \text{TC77 Resolution} &= (-256^\circ\text{C to } +255^\circ\text{C}) / 2^{13} \\ &= 512 / 2^{13} \\ &= 512 / 8192 \\ &= 0.0625^\circ\text{C/bit} \end{aligned}$$

While the temperature accuracy and resolution of a silicon sensor are related, they are two different specifications. Increasing the ADC's number of bits decreases the temperature per bit step size, which reduces the quantization error and effectively averages out some of the uncertainty error inherent in the analog-to-digital conversion. In general, higher bit order ADCs produce a more accurate sensor. However, the conversion time of a $\Delta\Sigma$ is typically doubled for each additional ADC bit.

Noise Immunity

While the TC72 and TC77 sensors do not require any external components, it is recommended that a 0.1 μF to 1 μF decoupling capacitor be provided between the power supply and ground pins. Although the current consumption of the TC72 and TC77 is modest, the sensors contain an on-chip data acquisition system with internal digital switching circuitry. Thus, it is good design practice to use a decoupling capacitor with the sensor. A high-frequency ceramic capacitor should be used and be located as close as possible to the IC power pins in order to provide effective noise protection to the sensor.

The TC72 and TC77's PCB should be designed with the standard layout guidelines used for a low noise circuit. The PCB should provide a ground plane or copper trace as thick as possible at the ground pin. The temperature sensor's main thermal path to the PCB is through the ground connection. Thus, the size of the ground pad should be as large as possible. An IC socket or extender board should not be used with the sensors. The coupling of noise to the serial communication pins can be minimized by keeping the digital traces away from any high-frequency clock or switching power supply signal traces.

Thermal Response Time

Internal diode silicon IC sensors provide an accurate temperature measurement for a steady state or relatively constant temperature. However, their response time to a rapid change in temperature is relatively poor compared to other temperature sensors, such as platinum RTDs and thermistors. For example, IC sensors are an excellent sensor for measuring the temperature of an electronic enclosure, but they would not be a good choice for a flow sensor that requires a thermal response time of a few milliseconds. Applications requiring a fast thermal response time should consider using a remote diode sensor. A remote diode sensor is similar to the internal diode sensor, except that this sensor measures the temperature of a remote diode located outside of the silicon IC sensor. For example, remote diode sensors can be used to measure the temperature of a remote diode located on the die of a Pentium[®] PC microprocessor.

The thermal response time of a silicon temperature sensor is specified by mounting the device on a small PCB, measuring the sensor's output at a nominal temperature such as +25°C and quickly exposing the device to a temperature step such as +125°C. The thermal time constant, defined as the time required for the sensor to reach 63.2% of its final value, is usually specified in either still air or a hot oil bath. The thermal response is also defined by the time required by the sensor to output a stable measurement equal to the final temperature of the step response.

The time required for a silicon sensor to reach the final temperature of the step response is typically 1 to 3 minutes in still air and approximately 5 to 20 seconds in a hot oil bath. Note that the thermal response measurement of a silicon sensor varies by the size of the PCB that the sensor is mounted on and also by the IC's package.

Silicon IC sensors measure temperature by monitoring the voltage of a diode located on the IC die. Figure 19 provides a cross section of the SOT23 package. The TC72 and TC77's die substrate is connected to the PCB's ground plane through a bonding wire and the ground pin of the package. The Ground pin of the IC provides a low-impedance thermal path between the die and the PCB, allowing the sensor to effectively monitor the temperature of the PCB board. The other non-grounded IC pins also provide a good thermal path to the die. However, they are not directly connected to the substrate and have a smaller effect on the die temperature. It is unlikely that a large temperature gradient exists between the package pins, but if this condition exists, an additional error will result in the temperature measurement.

The thermal path between the top of the package to the ambient air and between the bottom of the package and the PCB is not as efficient because the plastic IC housing package functions as a thermal insulator. Thus, the ambient air temperature (assuming that a large temperature gradient exists between the air and PCB) has only a small effect on the temperature measured by the silicon sensor.

Sensor Location

Silicon IC sensors are typically mounted on a PCB and measure the ambient temperature inside an electronic enclosure. The TC72 and TC77 can be used to determine the surface temperature of a hot object, such as a metal heat sink. The sensors can be connected to

the surface by using a thermally-conductive adhesive, such as thermal epoxy. The self-heating error of the sensor is small because of the TC72 and TC77's low power consumption. Therefore, the die temperature will accurately track the surface temperature.

Silicon sensors provide a "non-contact" temperature measurement by being in close proximity to a "hot object", such as the MOSFETs used in a switching power supply circuit. The location of the silicon IC sensor on the PCB can be critical, especially if large temperature gradients exist. A silicon sensor measures temperature by monitoring the voltage of a diode located on the IC die. Thus, the sensor should be located as close as possible to the external heat source.

Note that it is difficult to develop a correlation that could be used to adjust the temperature reading of the sensor, which is in the vicinity of, but not in direct contact with, the hot object that requires an accurate temperature measurement. The accumulation of the thermal resistances between the sensor and heat source, in addition to factors such as the air-flow velocity, will produce a temperature measurement with too much uncertainty to accurately model. Remote diode sensors and thermistors offer the advantage that they are available in a variety of packages, including parts that can be mounted directly on a hot object, such as a heatsink.

The TC72 and TC77 can also be located inside a probe for applications such as a liquid temperature measurement. The sensors can be mounted on a small PCB, which is then placed inside a sealed tube that is dipped into the liquid. The temperature sensor and PCB can be insulated against moisture by using a protective coating, such as Humiseal.

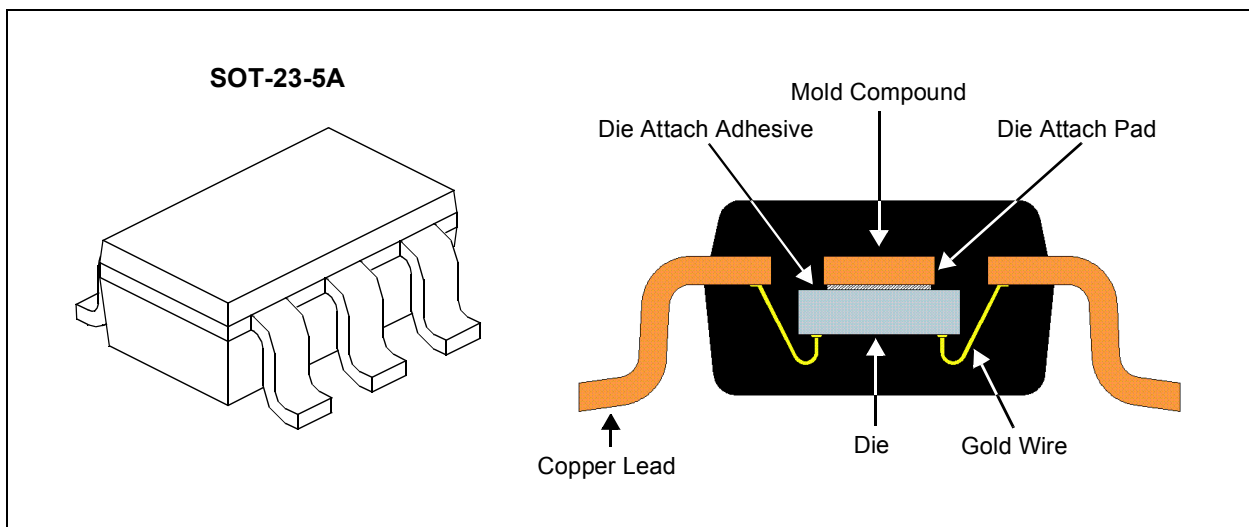


FIGURE 19: Cross section of the TC77's 5-Pin SOT23 Package.

Power-Up and Power-Down

The TC72 and TC77 devices contain a voltage detector circuit that determines when a power-up or power-down condition has occurred. A supply voltage lower than 1.6V (typ.) is considered a power-down state for the TC72 and TC77. The internal voltage detector ensures that the sensor is held in a reset condition until the voltage reaches a high enough level to ensure the proper operation of the sensor. Also, the voltage detector resets the digital registers to the power-up values when a power-down or brown-out condition is detected.

The TC72 and TC77's minimum supply voltage is specified at 2.65V and 2.7V, respectively. However, the voltage supply should match the V_{DD} used in the calibration procedure in order to accurately measure temperature. The operation of the sensor cannot be ensured for a steady-state voltage below the minimum specified V_{DD} voltage.

Self-Heating Errors

The supply current for the TC72 and TC77 is less than 250 μ A (typ.); therefore, the self-heating error is less than 0.2°C. The rise in the die temperature (T_j) due to the power consumption of the TC77's SOT-23 5-pin package operating at 3.3V in the Continuous Temperature Conversion operating mode is shown below:

$$\begin{aligned}\Delta T_j &= P_{\text{Dissipation}} \times \theta_{JA} \\ &= (3.3V \times 250\mu A) \times 230^\circ\text{C/W} \\ &= 0.19^\circ\text{C}\end{aligned}$$

Where:

θ_{JA} is the package junction-to-air thermal resistance provided in the data sheet.

A potential for self-heating errors can exist if the SPI communication lines are heavily loaded. A temperature accuracy error will result from self-heating if the SPI communication pins sink/source the maximum current specified for the sensor. The output loading of the SPI signals should be minimized to maximize the accuracy of the temperature measurement.

CONCLUSION

The TC72 and TC77 are CMOS silicon temperature sensors that provide an accurate digital temperature measurement to solve thermal management problems. The TC72 and TC77 sensors offer many system-level advantages, including the integration of the sensor and the signal-conditioning circuitry in a small IC package. This provides for easy system integration and minimizes the required PCB space, component count and design time.

The TC72 is a good sensor for power-critical portable applications. The TC72's One-shot Operating mode performs a single temperature measurement and then goes to the power-saving Shutdown mode. The TC77 offers a 1°C accuracy from +25°C to +65°C, making this device an excellent choice for precision temperature sensing applications.

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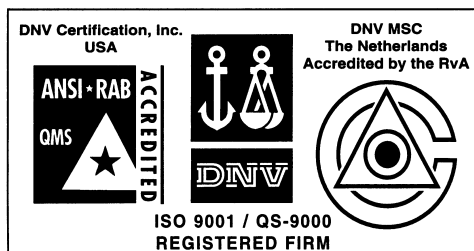
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