AN981

Interfacing a MCP9700 Analog Output Temperature Sensor to a PICmicro® Microcontroller

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INTRODUCTION

Analog output silicon temperature sensors offer an easy-to-use alternative to traditional temperature sensors, such as thermistors. The MCP9700 offers many system-level advantages, including the integration of the temperature sensor and signal-conditioning circuitry on a single chip. Analog output sensors are especially suited for embedded systems due to their linear output. This application note will discuss system integration, firmware implementation and PCB layout techniques for using the MCP9700 in an embedded system.

The firmware required to interface the MCP9700 to a microcontroller will be demonstrated using the PICkit™ 1 Flash Starter Kit. The PICkit 1 Flash Starter Kit is a low-cost development kit with an easy-to-use interface for programming Microchip's 8-pin and 14-pin Flash family of microcontrollers.

The MCP9700 demonstration is designed to measure and display temperature in Binary-Coded Decimal (BCD) with the PICkit 1 Flash Starter Kit's LEDs. Temperature data is converted from the internal thermal sensing element and made available as an analog output voltage. Gerber files for the PCB, source code and hex file (to program a PIC16F676) are included in the companion zip file, 00059R1.zip.

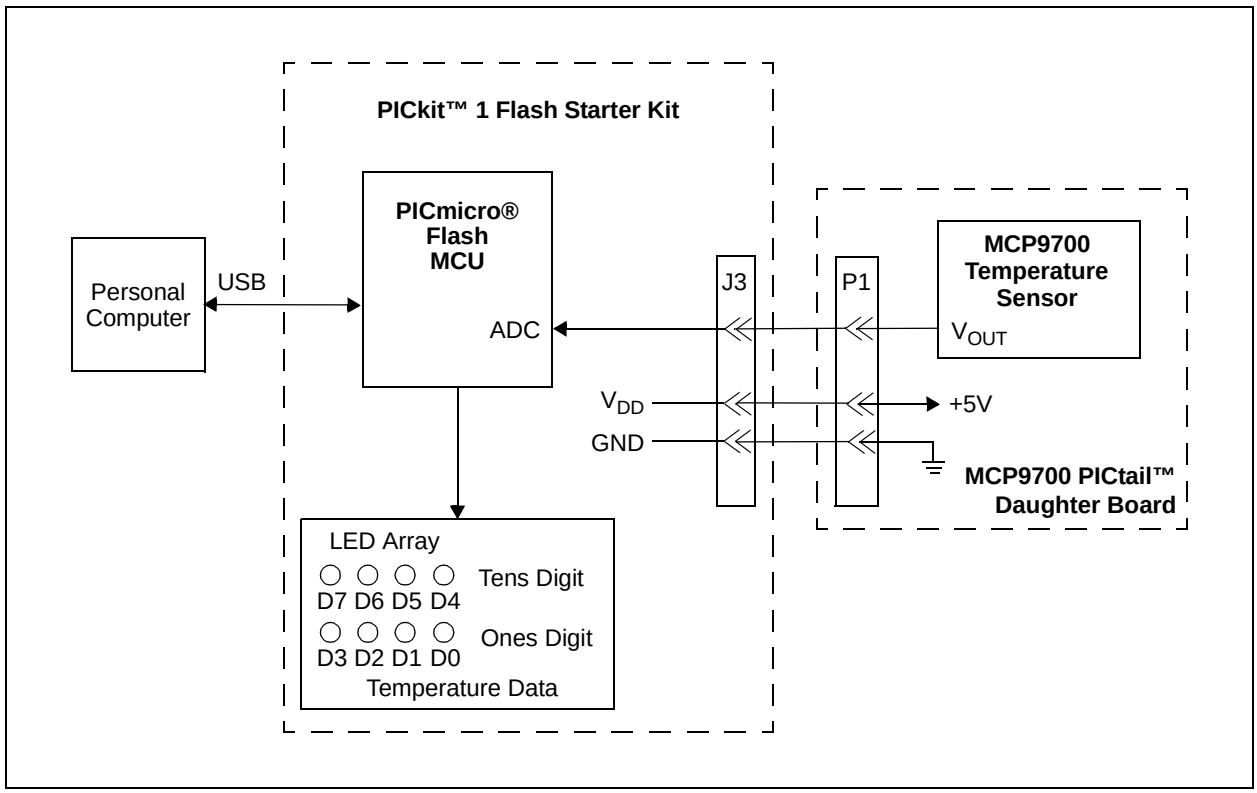

FIGURE 1: *Block Diagram of the MCP9700 Thermal Sensor Demonstration.*

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MCP9700 APPLICATION GUIDELINES

Interfacing the MCP9700 to an Analog-to-Digital Converter (ADC)

A simplified schematic of a typical ADC system is shown in Figure 2. The temperature sensor's output pin is driven by an op amp that has an output impedance (R_{OUT}). The input of the ADC consists of a simple sample-and-hold circuit. A switch is used to connect the signal source with a sampling capacitor, while the ADC measures the C_{SAMPLE} capacitor's voltage in order to determine the temperature. The R_{OUT} and R_{SWITCH} resistances, as well as the C_{SAMPLE} capacitor, form a time constant that must be less than the sampling rate (T_{SAMPLE}) of the ADC as shown.

An external capacitor in the range of 1 nF to 100 nF can be added to the output pin to provide additional filtering and to form an anti-aliasing filter for the ADC. This capacitor may impact the time response of the sensor, so the designer must allow time for the capacitor to charge sufficiently between ADC conversions. Also, the sensor amplifier may oscillate if the filter capacitor is too large. A small resistor of approximately 10 to 100Ω can be added between the output pin of the sensor and C_{FILTER} to isolate the sensor's amplifier from the capacitive load. The output impedance of the sensor (R_{OUT}) varies as a function of frequency. Thus, a series resistor should be added to the effective R_{OUT} resistance if C_{FILTER} is intended to serve as the ADC's anti-aliasing filter.

The output impedance of the MCP9700 is less than 1Ω because the sensor-gain operational amplifier (op amp) functions as a voltage buffer. The negative feedback results in an output impedance that is equal to the impedance of the op amp, divided by the open-loop gain of the amplifier. The open-loop gain of the op amp is relatively large which, in turn, forces the output impedance to be small.

The MCP9700 is built with a CMOS process. The relatively small size and current consumption of the transistors allow the design to incorporate a buffered output. In contrast, bipolar analog output sensors typically do not incorporate an op amp buffer. The resulting output impedance of these devices ranges from 200 to 2000Ω.

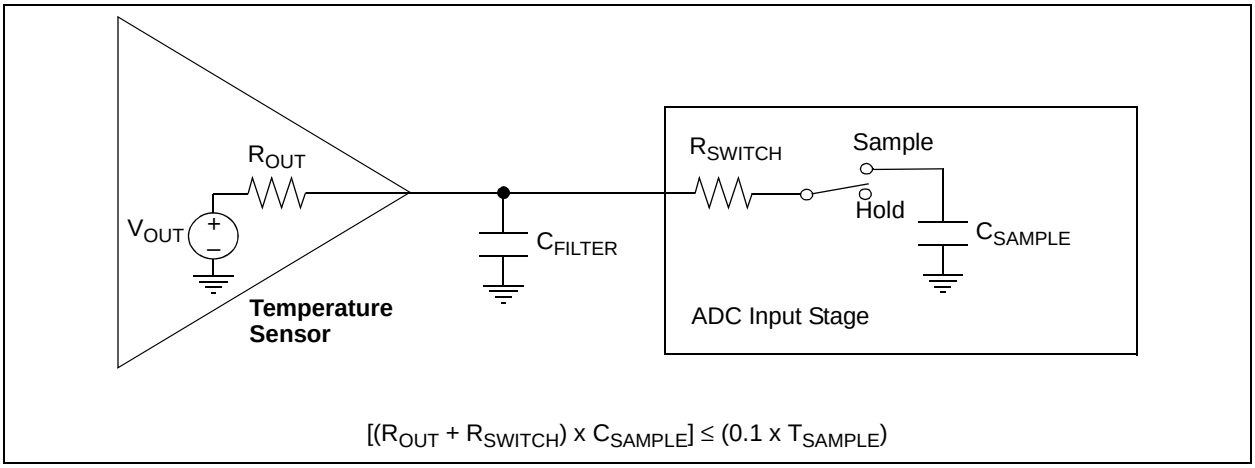

FIGURE 2: *Interfacing an Analog Output Temperature Sensor to an ADC.*

PCB Layout Recommendations

The MCP9700 provides an accurate temperature measurement for a steady-state temperature by monitoring the voltage of a diode located on the IC die. Since silicon sensors provide a "non-contact" temperature measurement, the location of the sensor is important. The substrate of the die is grounded and connected to the PCB's ground plane via a bonding wire and the lead of the package.

Silicon sensors provide a measurement of the temperature of the PCB's ground plane. 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. 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. Therefore, the ambient air temperature has only a small effect on the measurement.

It is recommended that a decoupling capacitor of 0.1 µF to 1 µF be provided between the power supply and ground pins to provide effective noise protection to the sensor. In high-noise applications, connect the power supply voltage to the V_{DD} pin using a 200Ω resistor with a 1 µF decoupling capacitor. A ceramic capacitor is recommended, with the capacitor being located as close as possible to the MCP9700's V_{DD} and ground pins.

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MCP9700 PICtail™ Daughter board

The MCP9700 PICtail™ daughter board is plugged into the PICkit 1 Flash Starter kit via expansion header J3. Figure 3 shows a picture of the MCP9700 PICtail daughter board plugged into the PICkit 1 Flash Starter Kit. For more information on the PICkit 1 Flash Starter Kit, refer to the "PICkit™ 1 Flash Starter Kit User's Guide" (DS40051).

The MCP9700 PICtail daughter board consists of a MCP9700 temperature sensor and a bypass capacitor. The bypass capacitor C_1 is used to provide noise immunity on the +5 VDC power supply. Figure 4 shows a schematic of the board, while Figure 5 provides a layout drawing of the PCB.

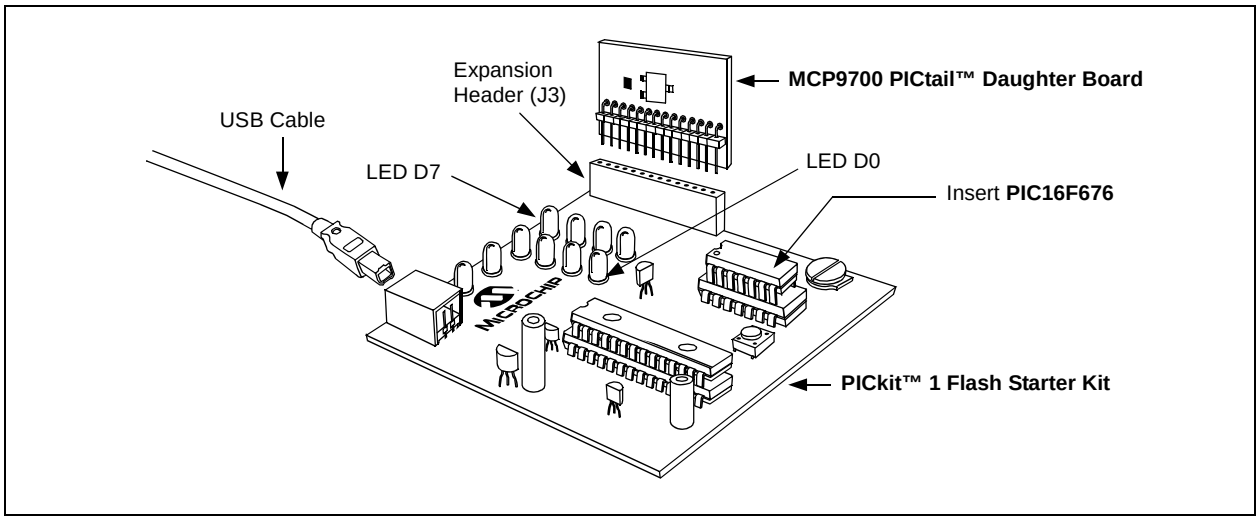

FIGURE 3: *MCP9700 PICtail™ Daughter Board and PICkit™ 1 Flash Starter Kit.*

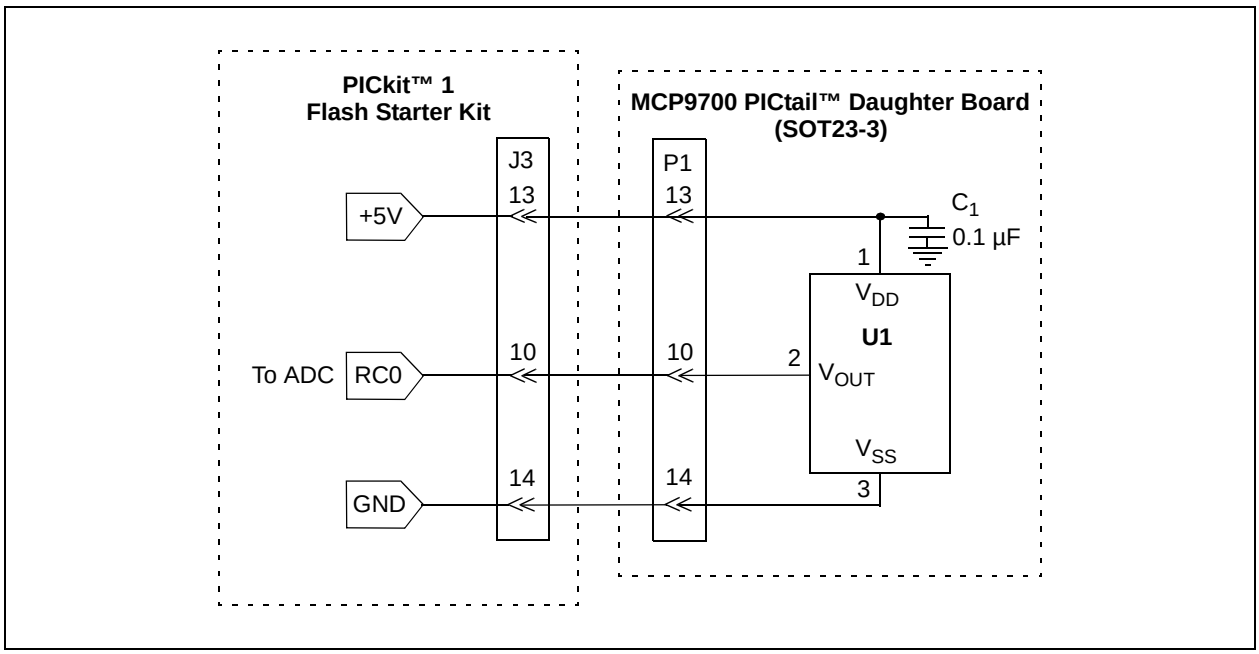

FIGURE 4: *MCP9700 PICtail™ Daughter Board Schematic.*

STAND-ALONE OPERATION

The MCP9700 PICtail daughter board can be used as a stand-alone evaluation board. Power can be applied to the V_{DD} and ground test points. The analog output voltage of the sensor can be monitored by connecting an oscilloscope or voltage meter to the V_{OUT} test point. The MCP9700 requires an operating voltage of 2.5V to 5.5V.

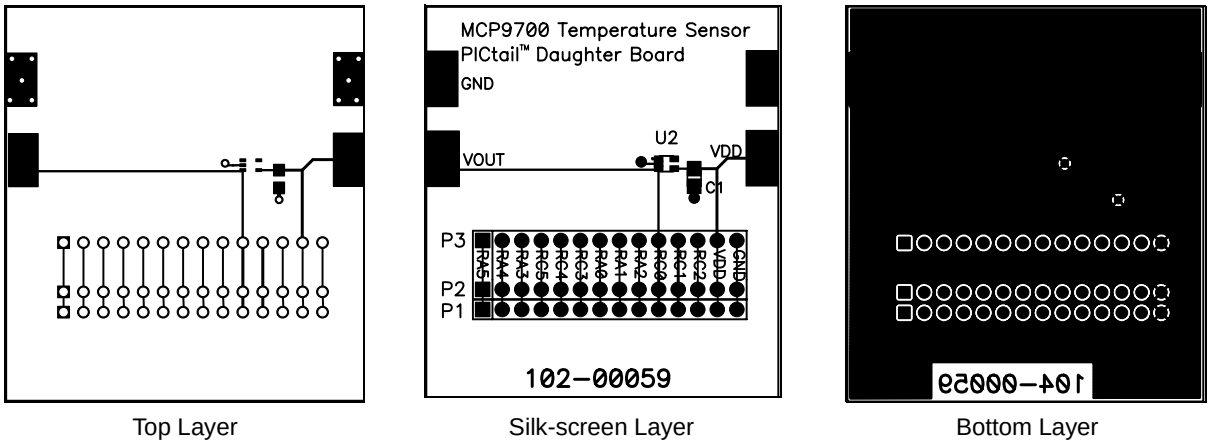

FIGURE 5: *MCP9700 PICtail™ Daughter Board PCB Layout.*

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MCP9700 Interface Software

A flow diagram for the PICtail firmware is given in Figure 6A. The analog output voltage of the MCP9700 sensor is read by the PICmicro® MCU's ADC. The ADC value is converted to degrees Celsius via a voltage-to-temperature conversion routine.

The MCP9700 provides a temperature measurement in Celsius. A provision in the software is provided to display the temperature in either Fahrenheit or Celsius by testing the status of the PICkit 1 SW1 push button switch. If SW1 is not pressed, the temperature value is converted to Celsius. Otherwise, if the push button is pressed, the data is displayed in Fahrenheit. Finally, the temperature value is loaded into the LEDREG variable to be displayed on the LEDs by the DISPLAY subroutine.

Fully documented source code, as well as a hex file ready to program into a PIC16F676, is available in the companion zip file, 00059R1.zip.

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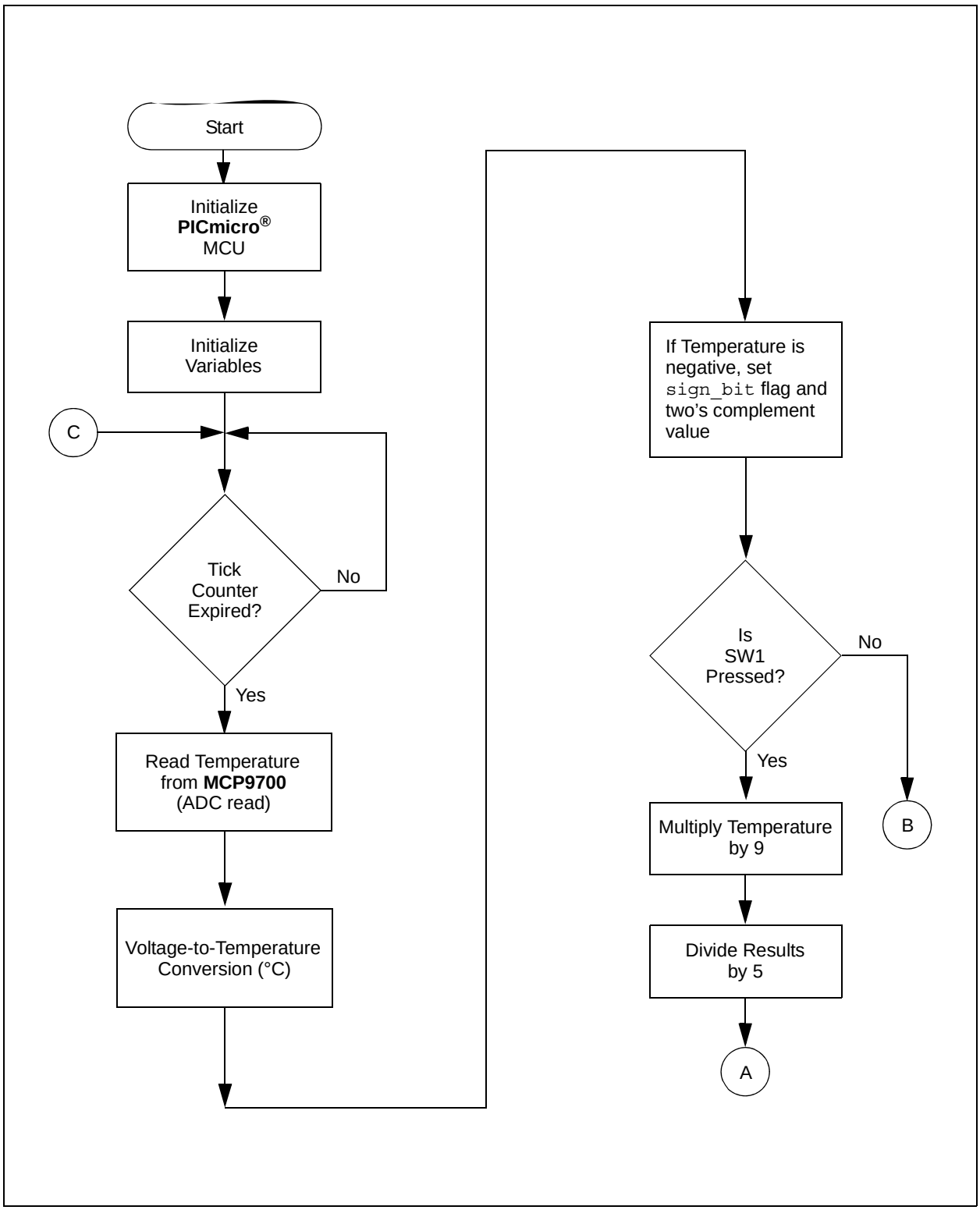

FIGURE 6A: *MCP9700 PICtail™ Daughter Board Program Flow Diagram.*

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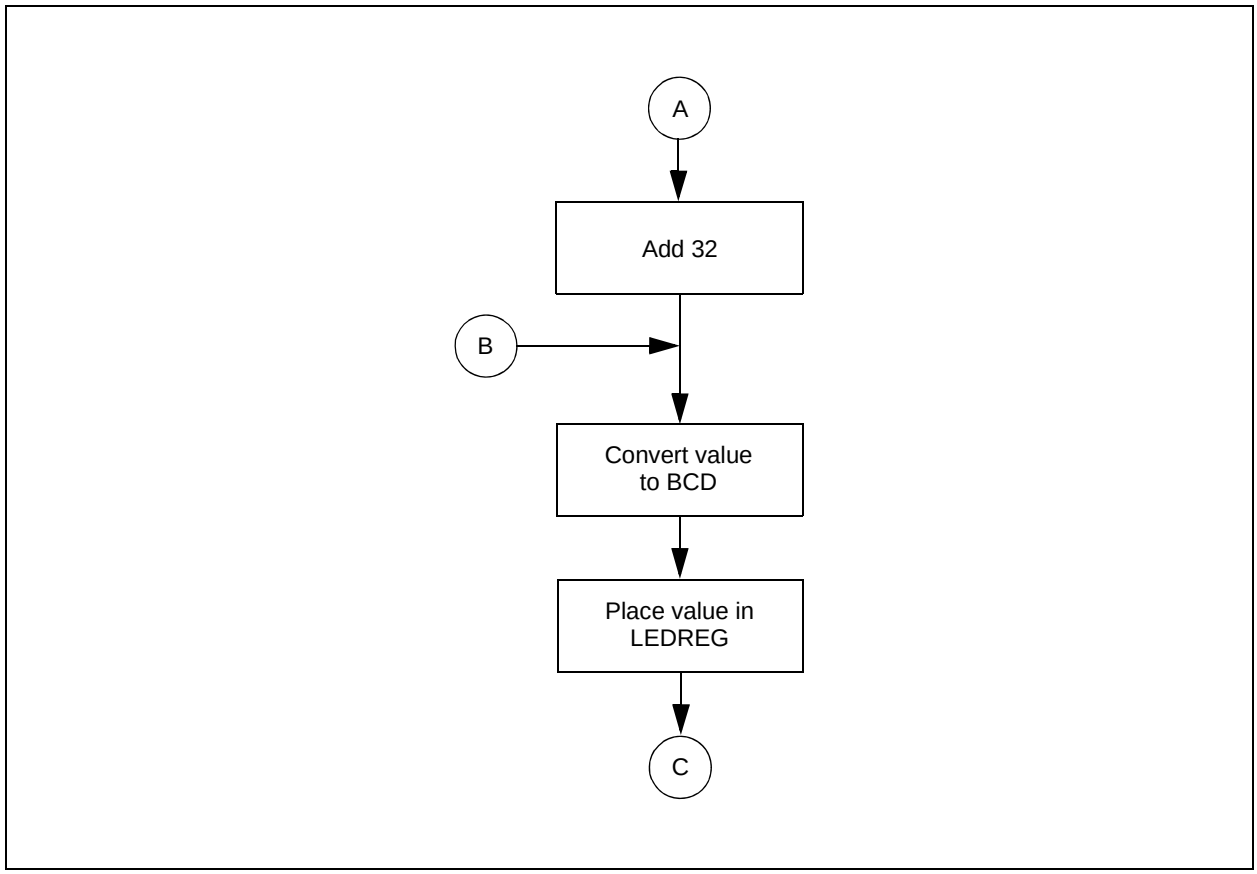

FIGURE 6B: *MCP9700 PICtail™ Daughter Board Program Flow Diagram (Con't.)*

APPENDIX A: FUNCTIONAL DESCRIPTION

Creating a Temperature-Sensing Diode

IC sensors measure temperature by monitoring the voltage across a diode. The MCP9700 uses 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 which is formed by combining the appropriate P and N junctions, as shown in Figure A-1. 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 dependant on the threshold voltage, which is process-dependant.

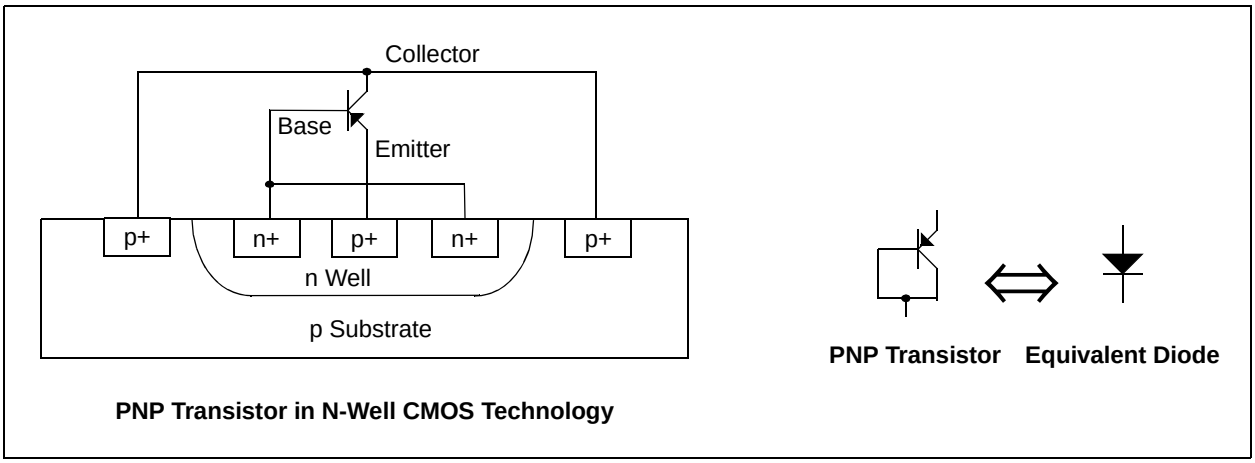

FIGURE A-1: *Temperature-Sensing Substrate Diode.*

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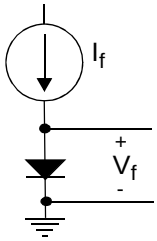
Fundamental Diode Equations

The voltage and current equations for a diode are listed in Figure A-2. 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-dependant issue with a voltage proportional to the 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 1. The assumption of η not being equal to 1 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 by using two different current sources and a single diode, while the second method uses a single current source and two different diodes.



$$I_f = I_s\left(e^{\left(\frac{V_f}{\frac{\eta kT}{q}}\right)} - 1\right) \cong I_s\left(e^{\left(\frac{V_f}{V_T}\right)}\right)$$

$$V_f = \frac{kT}{q} In\left(\frac{I_f}{I_s}\right)$$

$$= V_T In\left(\frac{I_f}{I_s}\right)$$

where:

I_f = Forward Current
I_S = Saturation Current
k = Boltzmann's Constant
= 1.38 x 10-23 joules/°K
η = Diode Non-Ideality Constant
= Emission Coefficient in SPICE
q = Electron Charge
= 1.6 x 10^{-19} Coulombs
T = Absolute Temperature (Kelvin)
V_f = Forward Voltage
V_T = Thermal Voltage
= kT/q
$\cong$ 26 mV @ 25°C

Assumption:

η = 1

FIGURE A-2: *Fundamental Diode Equations.*

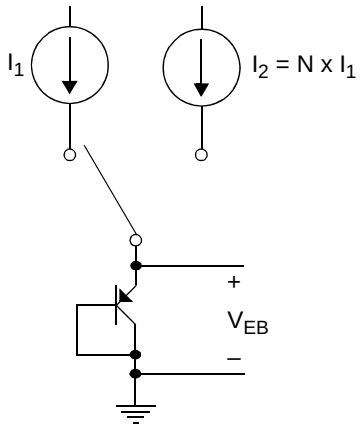
Creating a Voltage Proportional to Temperature

One method is to use two current sources with a single diode to eliminate I_S. Figure A-3 provides a simplified schematic of the circuit that measures the voltage resulting from multiplexing two current sources across a diode. The equations show that the I_S variable is cancelled by subtracting the voltages or, equivalently, by calculating the ratio of the logarithmic equations.

The two-current, one diode method to eliminate I_S is used 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 10, which produces a voltage with a temperature coefficient of approximately 200 µV/°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 which 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 that is proportional to absolute temperature. Figure A-4 shows a graphical representation of the V_{PTAT} voltage, which is linear. The absolute value of the current source is not in the temperature equation and 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). The complete equation for ΔV_{EB} is more complex; however, this complication can be neglected as a second-order effect.

The 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 A-5. 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 number of transistors identical to the first, as shown in Figure A-5. The total current is shared equally between the transistors and the voltage $V_{EB(N)}$ is established.



$$\Delta V_{EB} = V_{EB(I_2)} - V_{EB(I_1)}$$

$$= \frac{kT}{q} In\left(\frac{N \times I_1}{I_S}\right) - \frac{kT}{q} In\left(\frac{I_1}{I_S}\right)$$

$$= \frac{kT}{q} In\left(\frac{\left(\frac{N \times I_1}{I_S}\right)}{\left(\frac{I_1}{I_S}\right)}\right)$$

$$= \frac{k}{q} In(N) \times T$$

$$= CONSTANT \times T$$

where:

N = Integer number

V_{EB} = Emitter-to-base junction voltage

FIGURE A-3: *Creating a Voltage Proportional to Temperature.*

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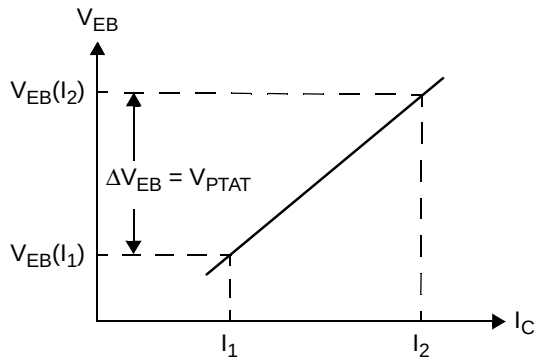
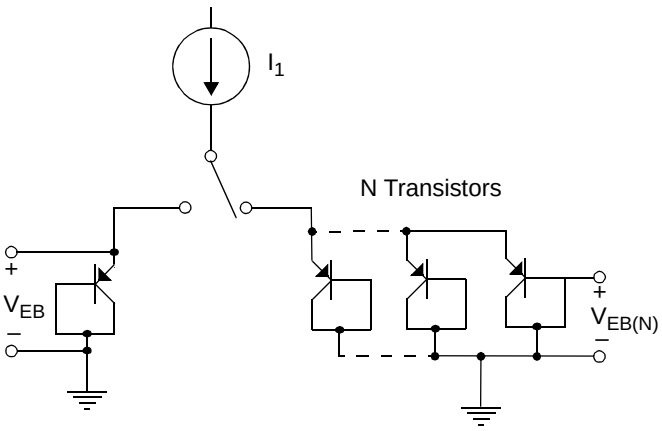


FIGURE A-4: *Graphical Representation of the V_{PTAT} Voltage Created with Two Current Sources and One Diode.*



$$V_{EB} = \frac{kT}{q} In\left(\frac{I_1}{I_S}\right)$$

$$V_{EB(N)} = \frac{kT}{q} In\left(\frac{I_1}{N \times I_S}\right)$$

$$\Delta V_{EB} = V_{EB} - V_{EB(N)}$$

$$= \frac{kT}{q} In\left(\frac{I_1}{I_S}\right) - \frac{kT}{q} In\left(\frac{I_1}{N \times I_S}\right)$$

$$= \frac{kT}{q} In\left(\frac{\left(\frac{I_1}{I_S}\right)}{\left(\frac{I_1}{N \times I_S}\right)}\right)$$

$$= \frac{k}{q} In(N) \times T$$

$$= CONSTANT \times T$$

FIGURE A-5: *Creating a Voltage Proportional to Temperature with One Current Source and Two Diodes.*

MCP9700 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 A-6. The voltage V_{EB} has a temperature coefficient of -2.2 mV/°C, while the V_{PTAT} voltage has a temperature coefficient of +0.085 mV/°C. Next, V_{PTAT} is amplified by K so that the temperature coefficient is scaled to +2.2 mV/°C. When V_{EB} is added to the scaled V_{PTAT} signal, the two temperature coefficients cancel and an output voltage results which is independent of temperature.

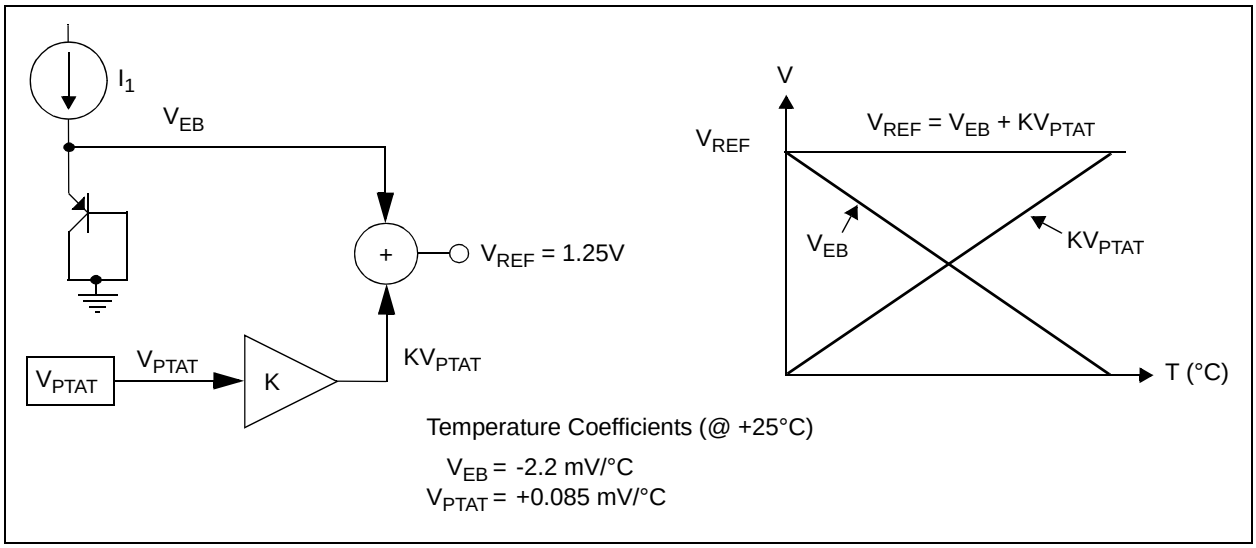


FIGURE A-6: *Band Gap Voltage Reference Concept.*

A simplified schematic of a band gap circuit is shown in Figure A-7. 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).

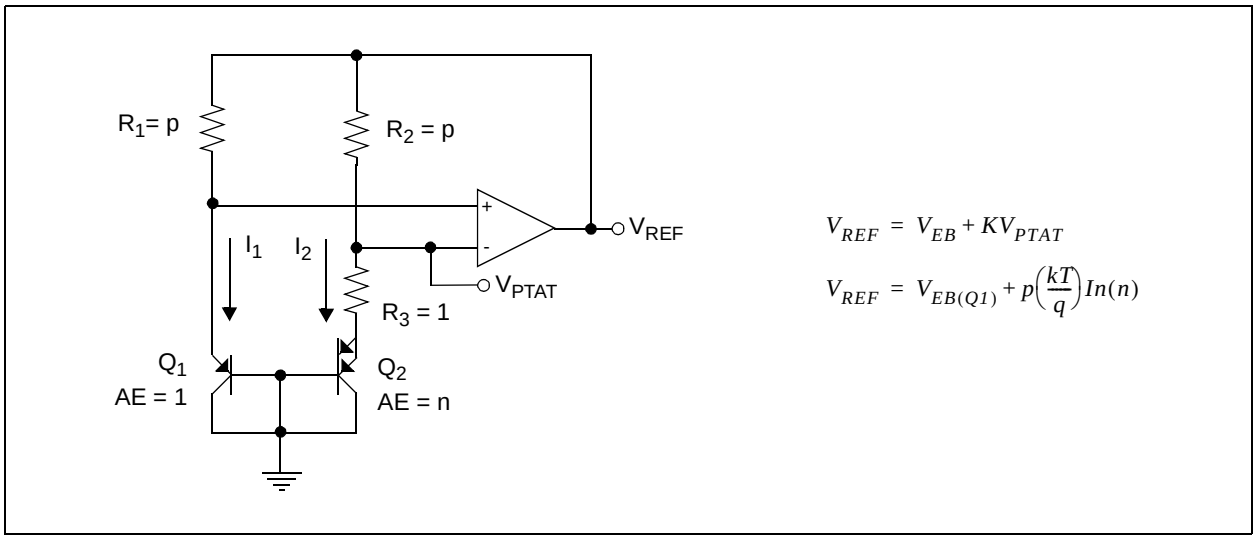


FIGURE A-7: *Band Gap Voltage Reference Building Block.*

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CONCLUSION

The MCP9700 temperature sensor PICtail daughter board demonstrates the ease of integrating an analog output IC temperature sensor to a PICmicro microcontroller unit (MCU). The MCP9700 is a CMOS silicon digital temperature sensor that provides a linear output voltage measurement to solve thermal management problems. The MCP9700 sensor offers 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.

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5. AN571, *"Using Analog Temperature Sensors with ADCs"*, Maxim Semiconductor, 2001.

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