

Interfacing a TC1047A 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 TC1047A 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 TC1047A in an embedded system.

The firmware required to interface the TC1047A 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 TC1047A demonstration is designed to measure and display temperature in binary-coded decimal (BCD) with the PICKit 1 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, 00938.zip.

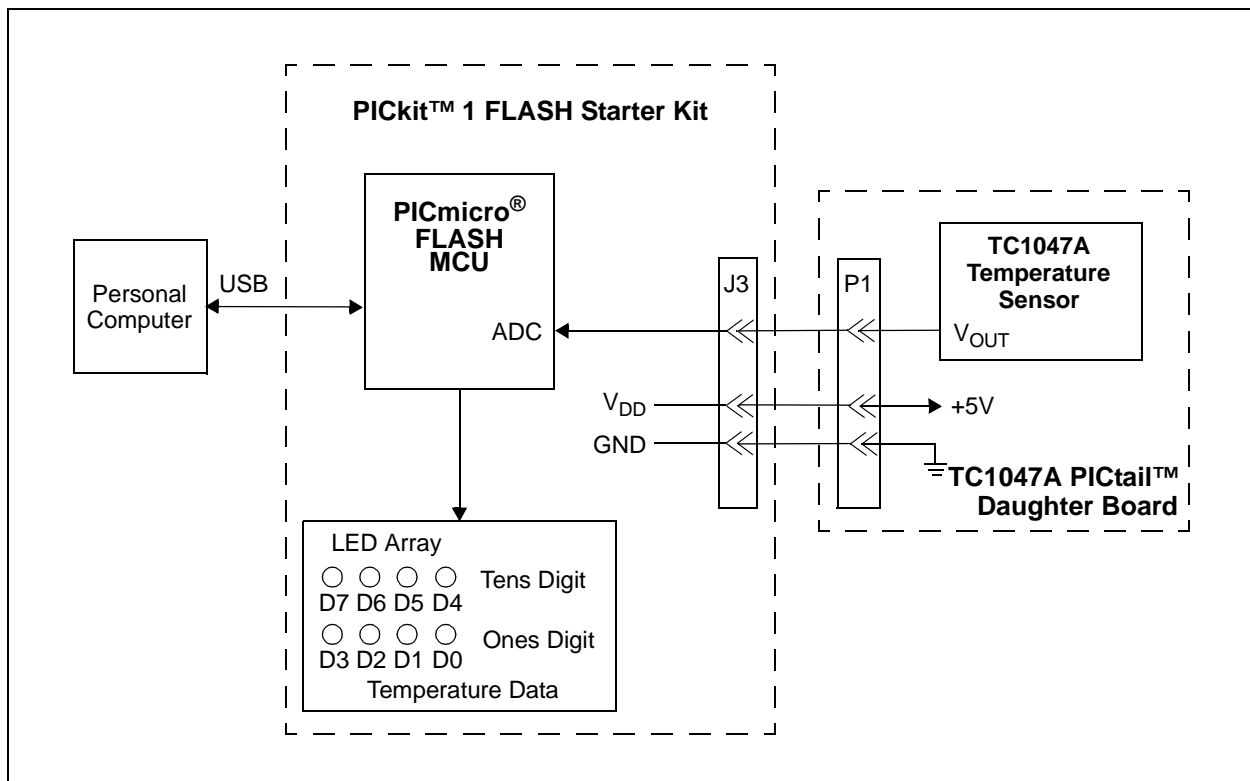


FIGURE 1: Block Diagram of the TC1047A Thermal Sensor Demonstration.

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TC1047A FUNCTIONAL DESCRIPTION

Creating a Temperature-Sensing Diode

IC sensors measure temperature by monitoring the voltage across a diode. The TC1047A 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 2. 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.

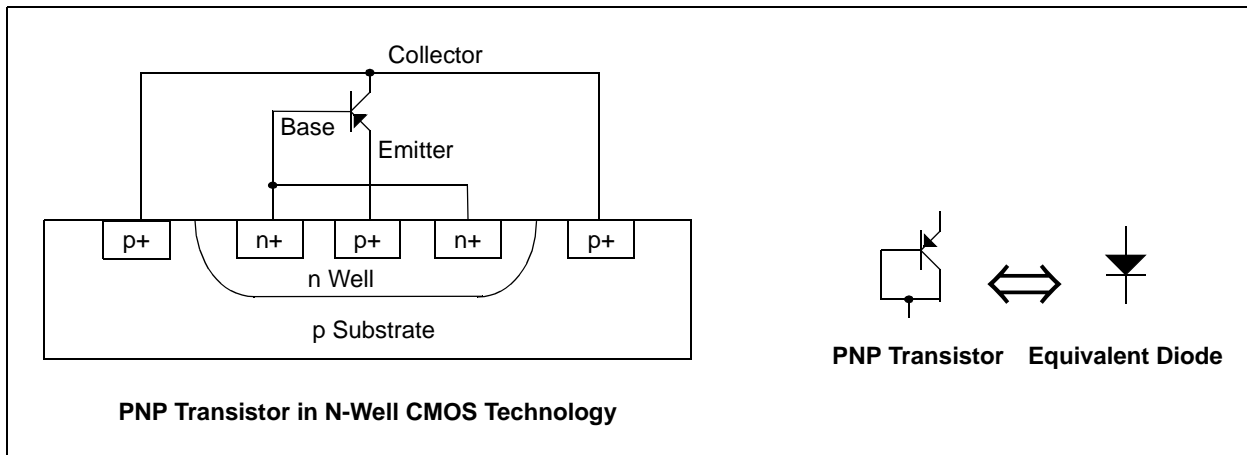


FIGURE 2: *Temperature-Sensing Substrate Diode.*

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-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 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 by using two different current sources and a single diode, while the second method uses a single current source and two different diodes.

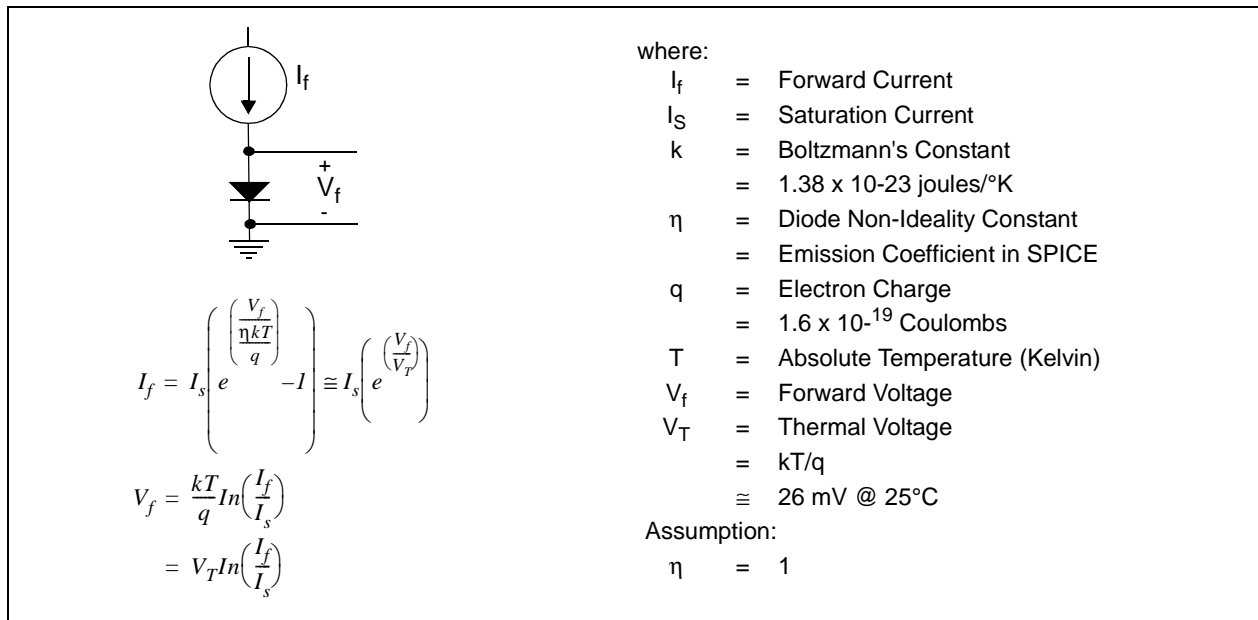


FIGURE 3: Fundamental Diode Equations.

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Creating a Voltage Proportional to Temperature

The TC1047A uses two current sources with a single diode to eliminate I_S , as shown in Figure 4. The equations illustrate that the process-dependant 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. 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 variable I_S .

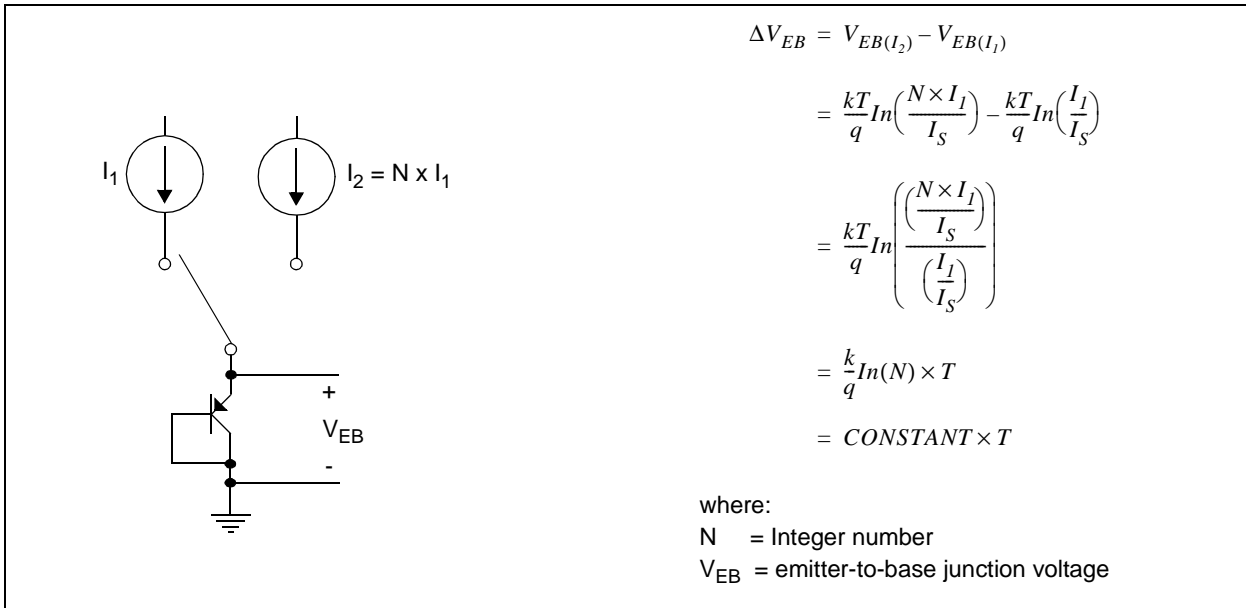


FIGURE 4: Creating a Voltage Proportional to Temperature.

Block Diagram of the TC1047A

Figure 5 shows a simplified schematic of the TC1047A analog output sensor. The voltage of an analog sensor is in the form of a straight line of:

$$y = mx + b$$

or

$$V_{OUT} = (10 \text{ mV}/^{\circ}\text{C}) \times T + 500 \text{ mV}$$

The first stage of the sensor consists of a band gap reference circuit that produces a voltage which is approximately $200 \mu\text{V}/^{\circ}\text{C}$. Next, a switched capacitor op amp amplifier is used to amplify the temperature

coefficient to a voltage of $10 \text{ mV}/^{\circ}\text{C}$. A switched capacitor amplifier is used because of the ease of building capacitors that are a ratio of each other.

The TC1047A has a fixed offset voltage to simplify the interface to an external ADC. For example, the offset of the TC1047A is equal to 500 mV or, in other words, the output voltage is equal to 500 mV at 0°C . Next, a low-pass filter is used to remove the switching noise of the amplified signal. The output signal is then driven by a buffer amplifier.

For simplification, the calibration circuitry is not shown, but an additional offset and gain adjustment circuit is contained in the circuit.

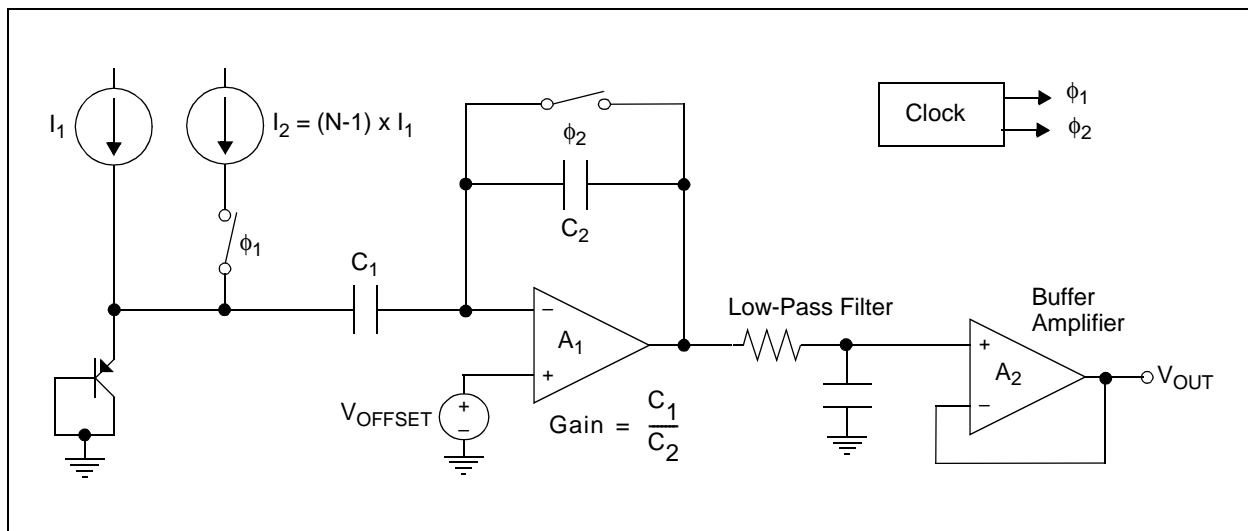


FIGURE 5: Simplified Block Diagram of the TC1047A.

TC1047A APPLICATION GUIDELINES

Interfacing the TC1047A to an ADC

A simplified schematic of a typical ADC system is shown in Figure 6. 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 and the C_{SAMPLE} capacitor form a time constant that must be less than the sampling rate (T_{SAMPLE}) of the ADC as shown.

An external capacitor in the range of 1 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 and 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 sen-

sor 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 TC1047A is less than 1Ω because operational amplifier A_2 functions as a voltage buffer. The output impedance of the sensor is low due to the negative feedback of the buffer circuit topology. The negative feedback results in an output impedance that is equal to the impedance of the amplifier 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 TC1047A 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.

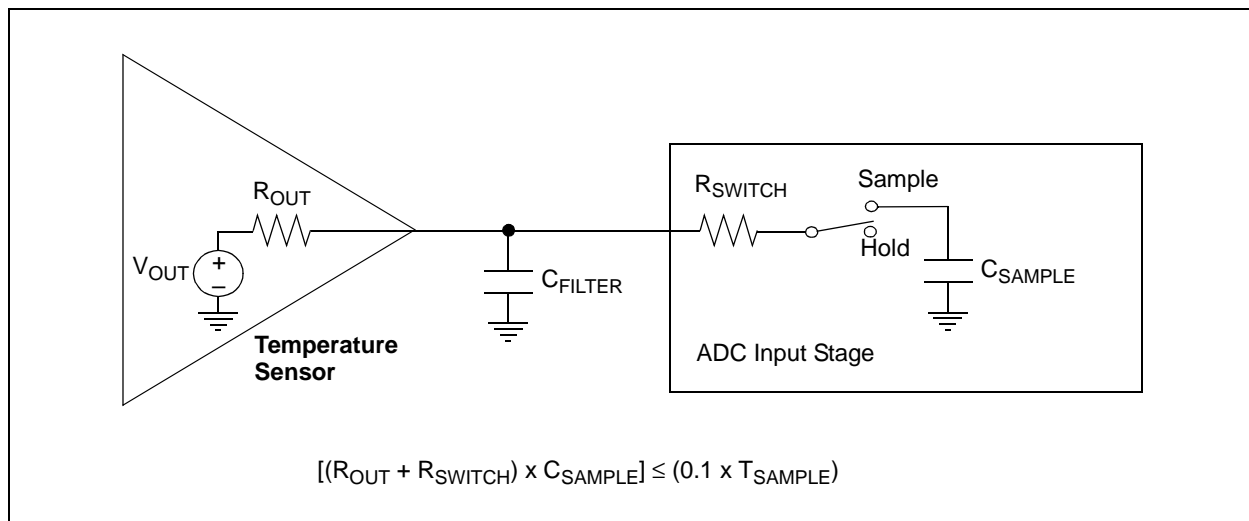


FIGURE 6: Interfacing an Analog Output Temperature Sensor to an ADC.

PCB Layout Recommendations

The TC1047A 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 0.1μF to 1 μF be provided between the power supply and ground pins to provide effective noise protection to the sensor. A ceramic capacitor is recommended and the capacitor should be located as close as possible to the TC1047A's V_{DD} and ground pins.

TC1047A PICtail™ Daughter board

The TC1047A PICtail™ daughter board is plugged to the PICkit 1 FLASH Starter kit via expansion header J3. Figure 7 shows a picture of the TC1047A 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 TC1047A PICtail daughter board consists of a TC1047A temperature sensor and a bypass capacitor. The bypass capacitor C_1 is used to provide noise immunity on the +5 VDC power supply. Figure 8 shows a schematic of the board, while Figure 9 provides a layout drawing of the PCB.

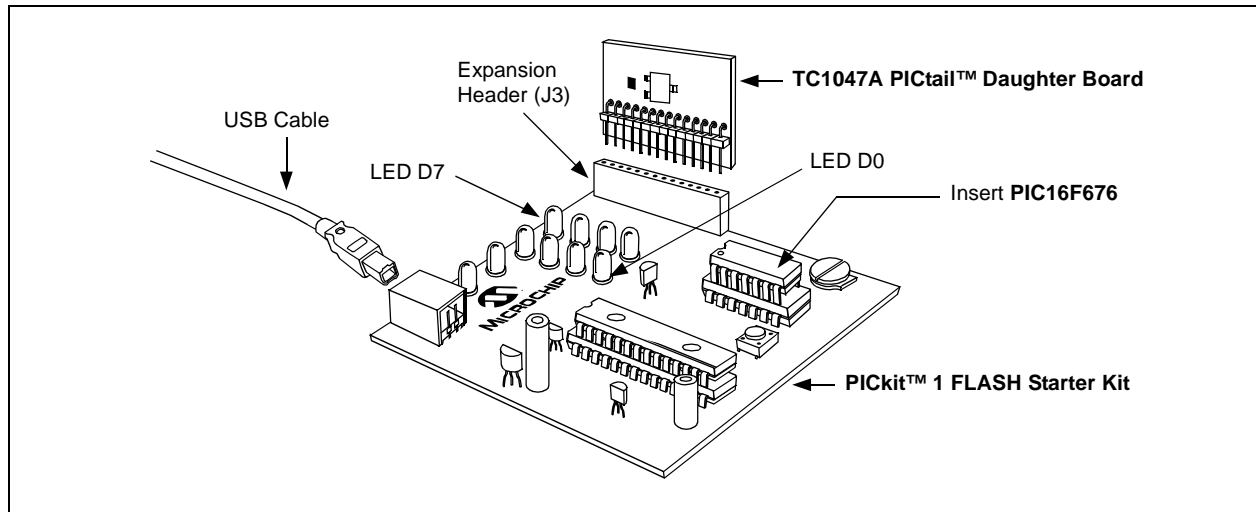


FIGURE 7: TC1047A PICtail™ Daughter Board and PICkit™ 1 FLASH Starter Kit.

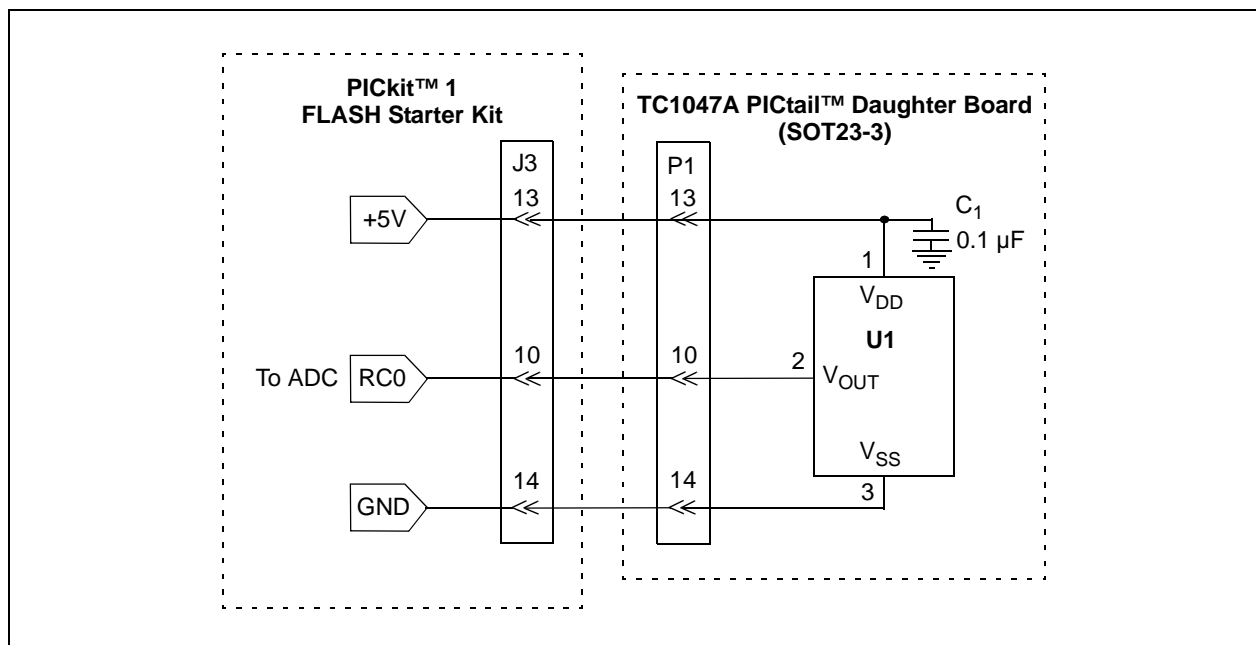


FIGURE 8: TC1047A PICtail™ Daughter Board Schematic.

STAND-ALONE OPERATION

The TC1047A 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 TC1047A requires an operating voltage of 2.5V to 5.5V.

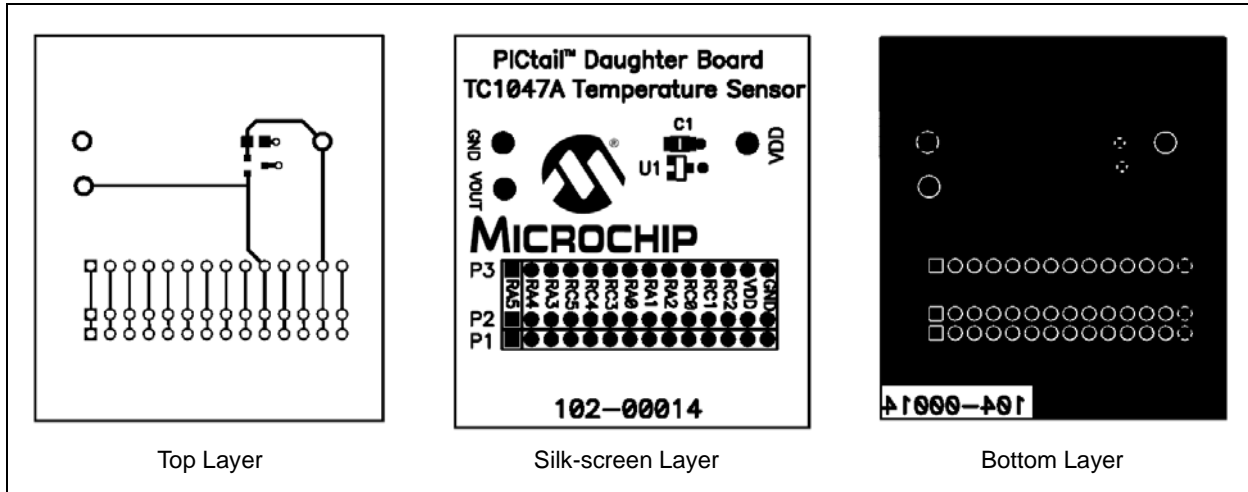


FIGURE 9: TC1047A PICtail™ Daughter Board PCB Layout.

TC1047A Interface Software

A flow diagram for the PICkit 1 software is given in Figure 10. The analog output voltage of the TC1047A 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 TC1047A 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 Fahrenheit. Otherwise, if the push button is pressed, the conversion routine is skipped and the data is displayed in Celsius. Finally, the temperature value is loaded into the LEDREG variable to be displayed on the LEDs by the DISPLAY subroutine.

Fully documented source code and a hex file ready to program into a PIC16F676 is available in the companion zip file, 00938.zip.

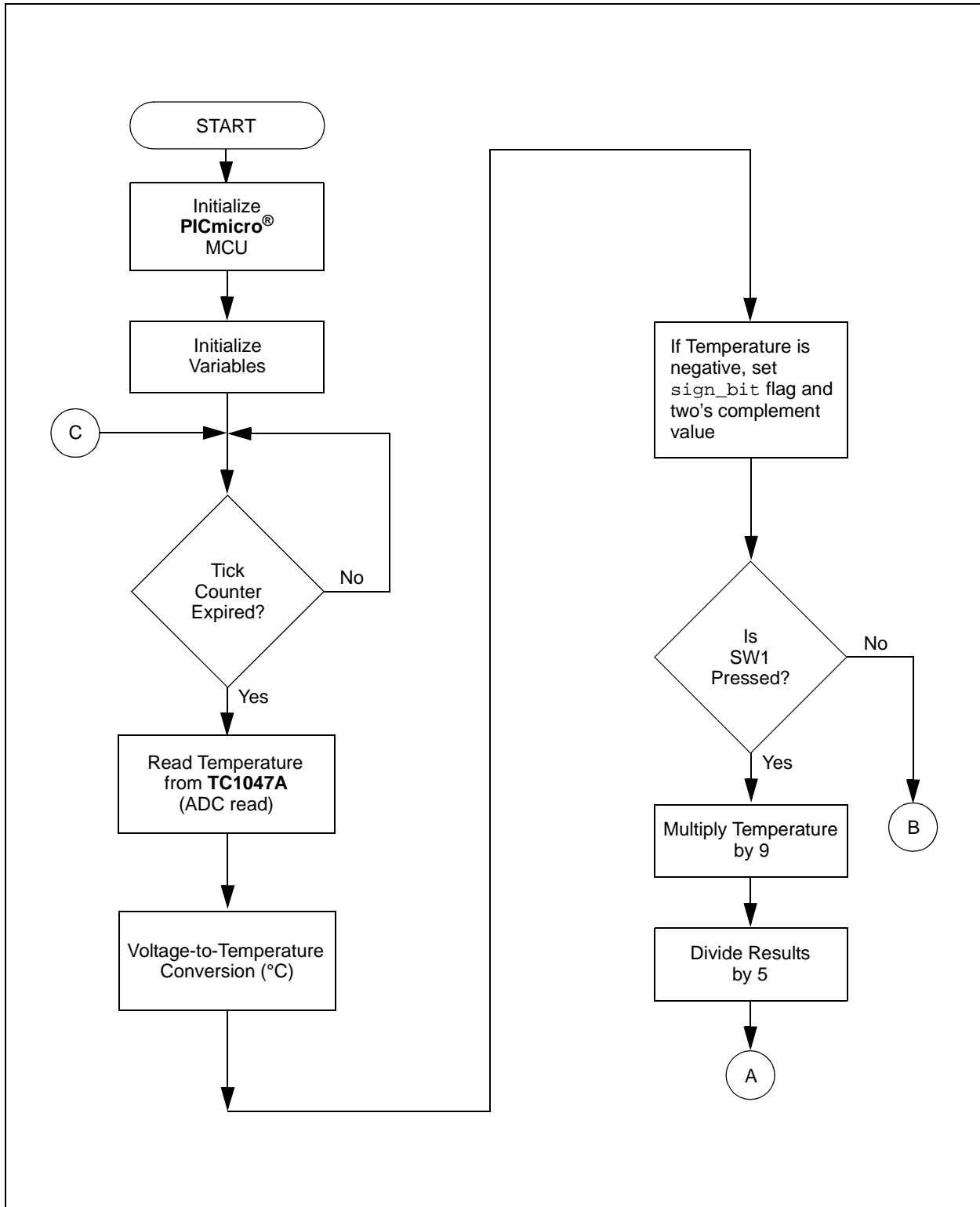


FIGURE 10A: TC1047A PICtail™ Program Flow Diagram.

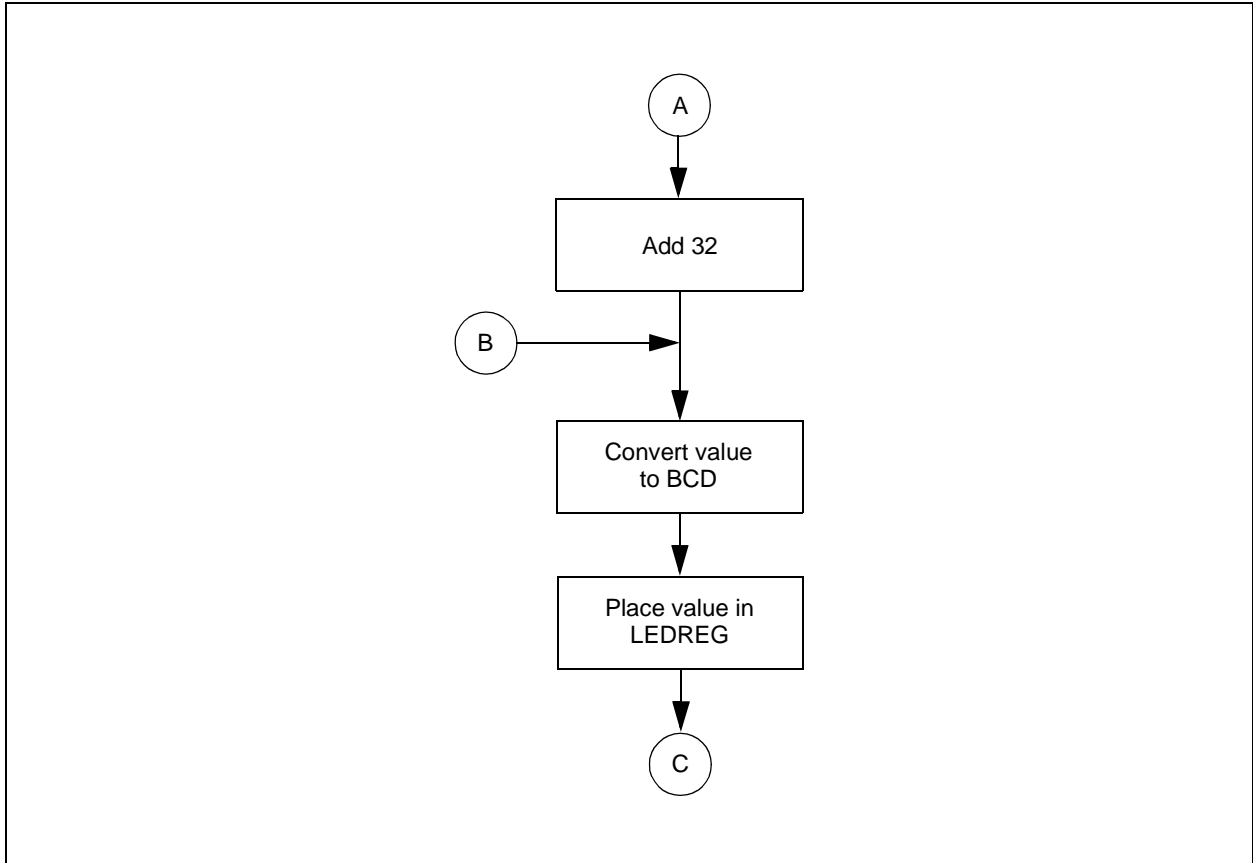


FIGURE 10B: TC1047A PICtail™ Program Flow Diagram (Con't.)

CONCLUSION

The TC1047A temperature sensor PICtail daughter board demonstrates the ease of integrating an analog output IC temperature sensor to a PICmicro microcontroller unit (MCU). The TC1047A is a CMOS silicon digital temperature sensor that provides a linear output voltage measurement to solve thermal management problems. The TC1047A 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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