Application Report
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Implementing a Thermocouple Interface With ADC12_A

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ABSTRACT

This application report shows how to implement a single-chip thermocouple interface. The thermocouple interfaces with the MSP430F5529's integrated 12-bit analog/digital converter (ADC12_A) through an operational amplifier circuit. The MSP430 encodes the thermocouple readings into a digital value, converts them to temperature, and stores them in memory. Project collateral and source code discussed in this document are available for download from http://www.ti.com/lit/zip/slaa501.

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1 Introduction

This application report shows how to implement a thermocouple interface. The thermocouple circuit interfaces with the MSP430F5529 microcontroller from Texas Instruments. The MSP430F5529 is a 16-bit ultra-low-power microcontroller with 20-bit addressing and an integrated high-performance 12-bit analog-to-digital converter (ADC). The integrated ADC is used to convert the thermocouple voltage into digital values, and the MSP430F5529 CPU is used to convert the digital values into temperature and store them in memory. A complete code set accompanies this document. For this document, a Type K thermocouple is used, and the measured temperature range is limited to 0°C to 100°C.

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2 Thermocouples

When the junction of two dissimilar metals is exposed to a thermal gradient, a voltage proportional to the temperature is observed between the two metals. This phenomenon, shown in Figure 1, is known as the thermoelectric effect and was discovered by Thomas Seebeck in 1821. The voltage observed is typically on the order of microvolts.

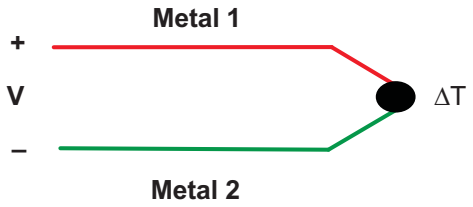

Figure 1. Thermoelectric Effect

Any two dissimilar metals/alloys present this effect. For any two metal alloys, the electric potential produced for a specific temperature is always the same. Therefore, a junction of specific alloys can be used for practical measurements of temperature. A thermocouple is a temperature sensor that consists of two dissimilar metals welded at one end. In industry, certain combinations of alloys have been standardized. In this application, a Type K thermocouple is used. Given their low cost and large temperature range (-200˚C to +1350˚C), Type K thermocouples are the most commonly used general-purpose thermocouples.

Compared to thermistors, thermocouples sacrifice precision and accuracy for an extremely wide temperature range. Because of this, thermocouples tend to be used in industrial applications where very high temperatures may be encountered.

3 Measuring Thermocouple Voltage

When a voltmeter is connected to a thermocouple, additional metal junctions J2 and J3, known as cold junctions, are created between the leads of the meter and the metal alloys of the thermocouple.

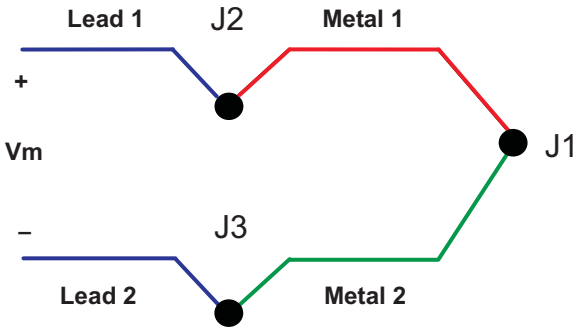

Figure 2. Measuring Thermocouple Voltage with a Voltmeter

Note that thermocouples measure the temperature difference across the full length of the metal exposed to the temperature gradient, not the absolute temperature at the target junction. In other words, the resulting voltmeter reading Vm is proportional to the temperature difference between J1, J2, and J3. Therefore, to find the temperature at J1, the temperature at the other end of the metal must be known – this is the reference temperature.

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One solution for thermocouple implementation is to create an isothermal block around the cold junctions created by the measurement device and the thermocouple, as shown in Figure 3, and maintain the reference temperature at a known value. Because energy is required to maintain a block in isothermal conditions, this method is often impractical. Another method is to measure the temperature within the cold-junction block with an accurate device, like a thermistor, and then use the measurement from the target junction as an offset to this reference temperature. This is called *cold-junction compensation* and it is the solution chosen for this application. The isothermal block may be as simple as pouring copper on the printed circuit board around the thermocouple connection and the cold junction temperature sensor, or it may be more sophisticated and involve mechanical assemblies.

The voltage that thermocouples produce is standardized by the National Institute of Standards and Technology (http://www.nist.gov). Data tables for thermocouple voltages are available from the NIST at http://srdata.nist.gov/its90/main/. Because these tables were created for a reference temperature of 0˚C, they can only be directly implemented without compensation if the reference temperature of the system is kept at 0˚C. This condition is not possible in most practical applications; therefore, compensation is usually required.

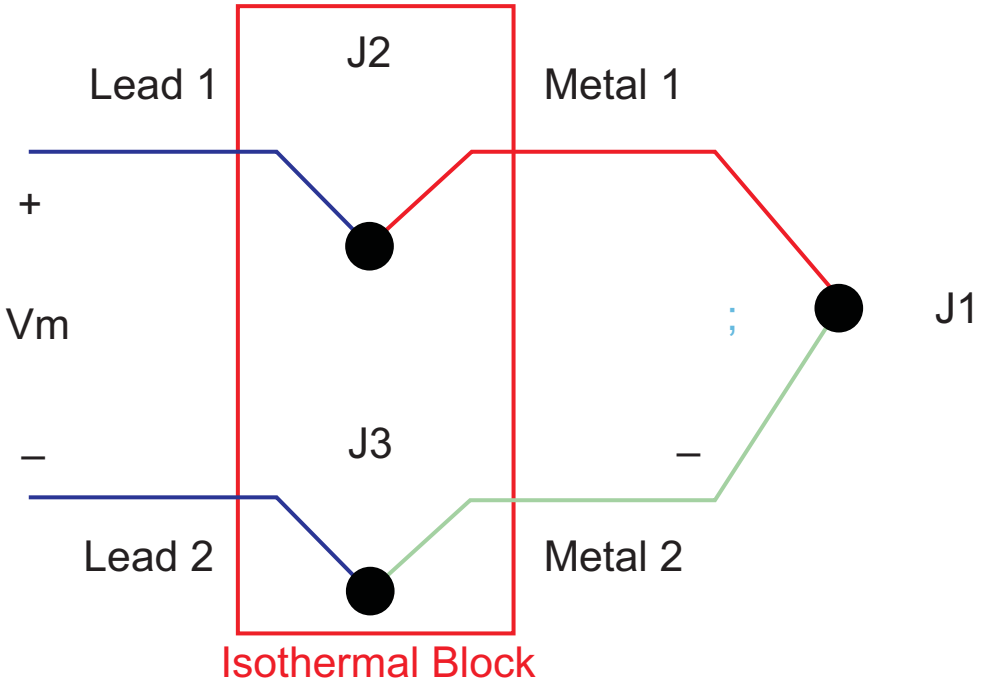

Figure 3. Isothermal Block for Absolute Temperature Measurement

Various methods can be implemented to compensate for the cold junction temperature. In the application described by this document, a thermistor is used to measure the absolute temperature of the cold junctions. After the reference temperature is known, it is added to the uncompensated thermocouple temperature to determine the absolute thermocouple temperature. This process is known as software compensation and is summarized by the following steps:

1. Measure Rref, the resistance of the thermistor.
2. Convert Rref to its equivalent temperature Tref.
3. Measure Vm and convert to thermocouple temperature TC.
4. Add Tref to TC to obtain the absolute thermocouple temperature.

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4 Hardware

A block diagram of the circuit used in this application report is shown in Figure 4. A difference amplifier is used to amplify the thermocouple voltage. The difference amplifier output is fed to the MSP430F5529's integrated 12-bit ADC converter. Amplification is used to maximize precision. This is because the thermocouple voltage ranges from 0 V to 4.096 mV for the chosen temperature range (0°C to 100°C), and the ADC12 internal reference voltage is 1.5 V. Without amplification, the entire voltage range would need to be represented by only 11 12-bit A/D steps. This is insufficient for the level of precision many applications require. Amplification, therefore, allows the input voltage to span the entire A/D input range. Note that some MSP430 devices have an integrated 16-bit A/D plus amplifier – see application report *SLAA216* for an implementation that uses this module.

Two analog channels of the ADC are used: one for the amplified thermocouple voltage and the other one for the thermistor's resistance. The thermistor is used for the cold junction compensation. A resistor divider is formed with an 8.2-kΩ resistor and the thermistor to produce a voltage input to the ADC. The top of the divider is connected to the 1.5-V reference output, and the full-scale input of the ADC converter is 1.5 V. The voltage for the top of the divider was chosen to be 1.5 V, because the output of the reference voltage module provides a very stable voltage (1.5 V). Any voltage value at the top of the divider less than or equal to the ADC reference voltage ensures that the analog input does not saturates the ADC reading for any temperature at the cold junction. A lookup table was then created based on the thermistor's specifications provided by the manufacturer in the data sheet of the device. Note that if a different voltage reference is used, this table must be modified accordingly.

The thermistor resistance decreases with increased temperature. When the thermistor is at 25°C, its resistance is 1 kΩ. The 8.2-kΩ resistor keeps the thermistor input voltage well below the ADC full-scale voltage for the temperature range of -20°C to 60°C. An RC filter is used on the thermistor input voltage for noise filtering.

The thermocouple is a Type K. Given the microvolt voltages observed on the thermocouple's leads, a precision chopper-stabilized operational amplifier is used in this application. Moreover, the gain of the amplifier is set to 290. This gain was chosen so that the thermocouple voltage range is amplified to 1.2 V, which is most of the full range of the A/D input (1.5 V). For even more precision, the signal could have been gained to 2.5 V and the ADC12's internal 2.5-V reference could have been used.

The VLO is used to provide a low-frequency clock for Timer A0. Timer A0 is used for generating an interrupt every one second, allowing the temperature to be sample at a frequency of 1 Hz. For this application, the accuracy of the crystal sourcing the Timer A0 is not of extreme importance; therefore, the VLO was used as a source for the Timer A0, thus reducing the cost of the application and the total power consumption.

A bill of materials for the hardware is provided in Appendix A.

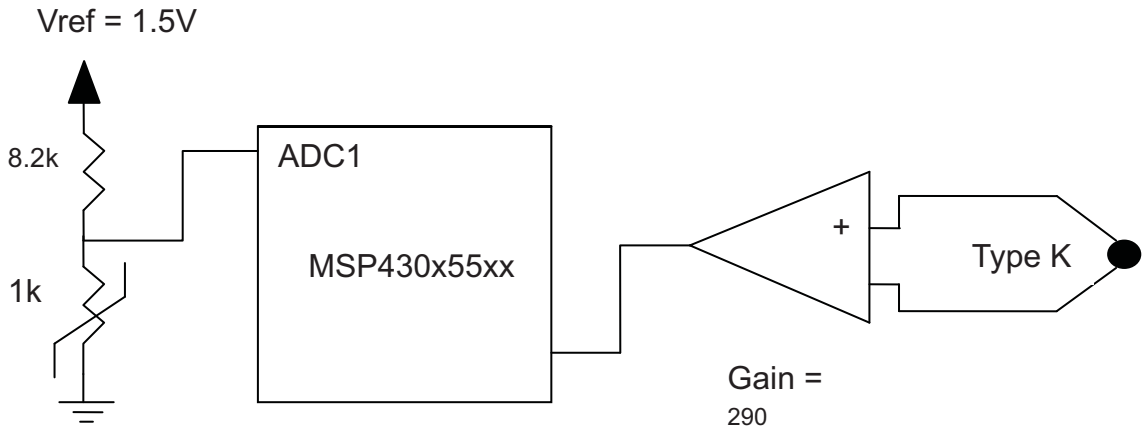

Figure 4. Hardware Block Diagram

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5 Software

The software flow is shown in Figure 5 and discussed in the following sections.

5.1 Overview

The software takes advantage of the MSP430's low-power features. Software normally keeps the MSP430 in low power mode 3 (LPM3), in which only the VLO is running. Timer A0 uses the VLO clock to provide a one-second interrupt that wakes the MSP430 CPU for the temperature measurement.

This application uses two analog inputs of the ADC12_A module. They are grouped together to provide simultaneous sampling of the thermistor and thermocouple. During sampling, 32 conversions are performed on both the thermistor and thermocouple voltage and then averaged into a single conversion value. This is done to improve the accuracy of the resultant ADC reading. Next, the thermistor value is converted to temperature using a look-up table. Similarly, a look-up table is used to convert the thermocouple ADC value to a corresponding thermocouple temperature. The thermocouple look-up table is generated using the chosen reference voltage of the ADC, the gain of the amplifier block, and the data tables for thermocouple voltages from NIST. The equivalent thermistor and thermocouple temperatures are added together to provide the cold-junction-compensated value for the temperature at the thermocouple junction.

This value is then stored in memory. After storing, the MSP430 is put back into LPM3 to wait for the next Timer A0 interrupt. Figure 5 shows the software flow for this application.

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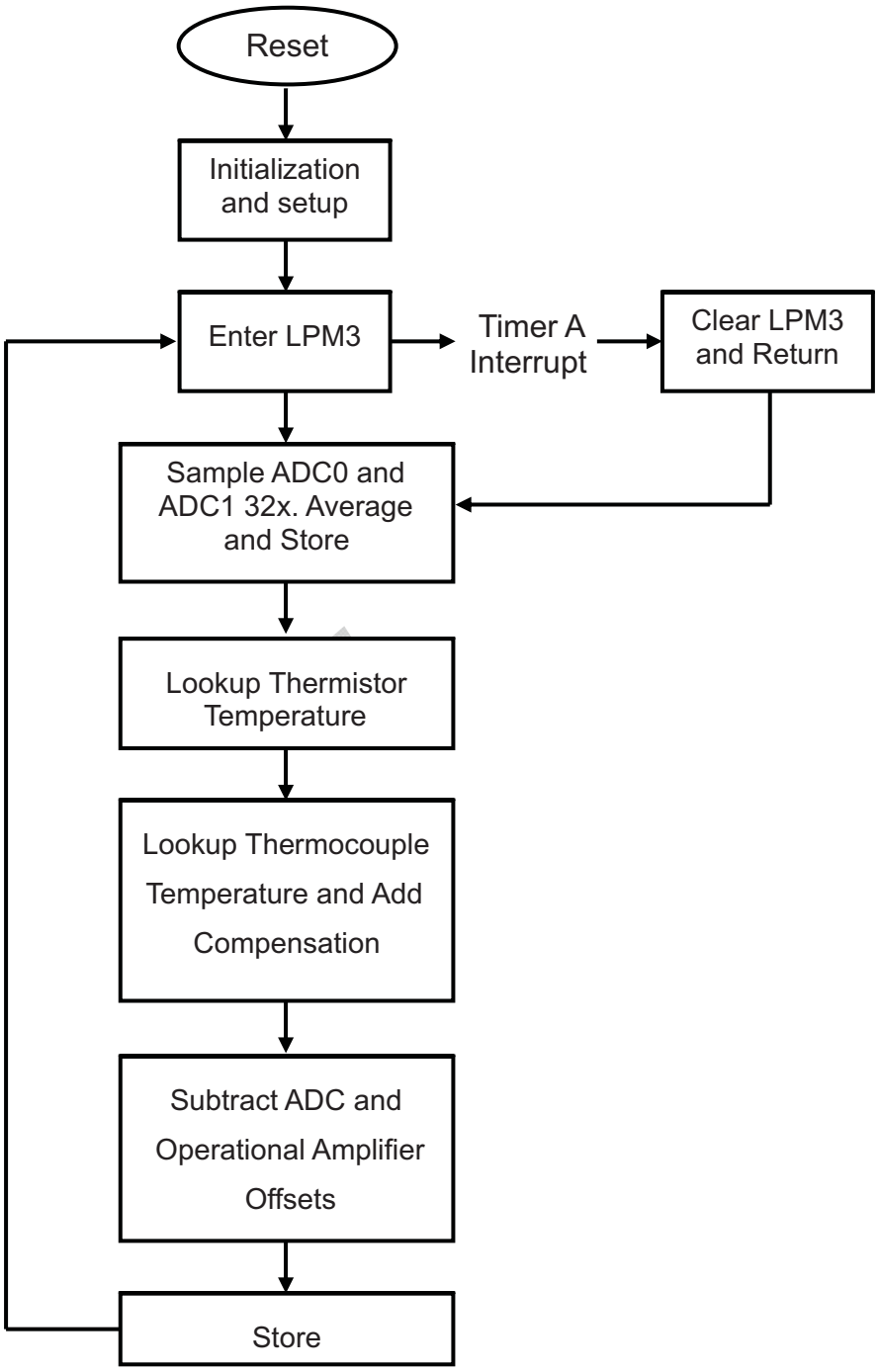

Figure 5. Software Flow

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5.2 Initialization and Setup

During setup, the MSP430 watchdog timer is disabled and the frequency locked loop (FLL) is left at its default setting, resulting in a SMCLK clock speed of 1.048 MHz and a DCO frequency of 2.0971 MHz. The internal very-low-power low-frequency oscillator (VLO) is used as a reference to the FLL, because this is a cost-sensitive application where an external crystal is not desired. The VLO does not consume power when it is not being used. Using the VLO also provides two extra pins for general purpose I/O that can be used for the external oscillator (XTIN and XTOUT pins). Next, the Timer A0 module is initialized for a one-second interrupt, and ADC12_A is initialized for clock source, data format, grouping, and interrupt enable. Finally, the MSP430 enters LPM3.

5.3 Main Loop

The main loop is executed once per second, triggered by the Timer A0 interrupt. First, the sample routine is called. Then the average of 32 ADC inputs is obtained. Next, the thermistor temperature is determined only if it is in the accepted range. Subsequently, the thermocouple ADC value is converted to the corresponding thermocouple temperature. Finally, the thermocouple temperature is added to the reference temperature, and the result is stored in memory.

5.4 Sample

The sample function enables the ADC12_A interrupts and enables and starts conversion, then enters LPM3. When the ADC interrupt occurs, the ADC module buffers 32 simultaneous samples in channels 0 and 1 and stores them in two memory arrays: A0 results and A1results.

5.5 Average

The average function adds all the elements of each of the memory arrays A0results and A1results and divides the sum by the number of elements in each array. The division is done by using a bit-shift operation, because the standard DLIB “/” and “%” are code and cycle inefficient. The results are added to the corresponding ADC offsets and stored in A0_TCave for channel 0 and A1_TRave for channel 1.

5.6 Get_TR_Temp

Get_TR_Temp checks that the average thermistor ADC reading, A1_TRave, and if this value is in the thermistor’s allowable range (ADC values corresponding to temperatures between -20°C and 60°C), a lookup table is used to find the corresponding thermistor temperature. The thermistor temperature is stored in TR_Tenth_Whole. Interpolation is then used to find the thermistor’s temperature to a precision of one-tenth of a degree. The following equation is applied to interpolate to the tenth portion:

```
((higher - ADCvalue) x 10)/(higher - lower)
```

Where,

`ADCvalue` = ADC conversion value of thermistor voltage

`higher` = the next higher value in the table

`lower` = the next lower value in the table

The table of thermistor values shown in the code is specific to this application. It uses measured values for the 8.2-kΩ resistor and for the ADC reference of 1.5 V.

5.7 Get_TC_Temp

Get_TC_Temp checks the average thermocouple temperature A0_TCave and, if in range, a lookup table is used to find the corresponding thermocouple temperature. Finally, the thermistor’s temperature is added to the thermocouple’s temperature, thus obtaining a compensated absolute thermocouple’s temperature.

5.8 How to Observe the Results

A watch window can be used to observe the resultant temperature measurements. Table 1 shows the variable names and their descriptions.

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Table 1. Result Variables

Variable Name	Description
A0_TCave	Thermocouple average ADC value with offset
A1_TRave	Thermistor average ADC value with offset
TR_Temp_Whole	Whole part of Thermistor temperature
TR_Tenth	Tenth part of Thermistor temperature
TC_Temp	Compensated Thermocouple temperature

6 Precision Analysis

1°C steps were chosen for the thermocouple temperature, because the data tables provided by NIST are available at this precision level. The voltage resolution (Rv) of the ADC is equal to the reference voltage divided by the number of discrete voltage intervals: Rv = 1.5 V / 2^12 = 0.366 mV. The total unadjusted error of the ADC for the device in used is ±1.4 LSB. The thermocouple voltage ranges from 0 V to 4.096 mV for the chosen temperature range (0°C to 100°C), and the ADC12's internal reference voltage is 1.5 V. Without amplification, the entire voltage range would need to be represented by only 11 12-bit A/D steps. This is insufficient for the level of precision many applications require. Amplification, therefore, allows the input voltage to span the entire A/D input range resulting in more precise ADC readings of the thermocouple temperature.

The thermocouple look-up table is composed of 101 steps or values in intervals of ~32. Therefore, the error of ±1.4 LSB only affects the resulting temperature if the ADC reading is in the higher or lower end of the look-up table step. For instance, 0°C corresponds to ADC readings between 0 and 32. If the ADC value for the thermocouple input is 25, the real ADC value could be in the interval 23.6 < ADCreal < 26.4, which still corresponds to 0°C. Thus, no error in the temperature reading is observed in this case. However, in the scenario of having an ADC reading of 31, an error of +1.4 LSB results in a thermocouple temperature of 1°C instead of 0°C. This fact is true for the step extremes for all degrees of temperature. To further increase the accuracy of the thermocouple temperature, 32 samples are obtained from each channel during each ADC conversion and the average of the 32 samples is then used to find the associated ADC temperature value in the look-up table. This procedure reduces the influence of outliers in the system, resulting in a more robust solution.

7 Power Analysis

A diagram portraying the power draw of the thermocouple implementation is shown in Figure 6. At reset, all registers are initialized for proper operation (1). During initialization, the MCU is in active mode and draws a current of approximately 290 µA. After all modules are initialized, the MSP430 enters LPM3 (2). While in LPM3, the current draw is approximately 2.1 µA.

The Timer A0 module wakes the MSP430 once every second. While the CPU is active, the main loop is executed: both the thermistor and thermocouple channels are read in and averaged, and the final absolute temperature is obtained. During the main routine, the MCU remains active until the sample function is called (3). In this function, the MSP430 once again enters LPM3 until all the ADC conversions are performed, but the ADC reference voltage output is turned on, which results in a higher current consumption (~1 mA) (4). When the conversion ends, the output reference is turned off and the CPU wakes up to active operation until all the functions of the main loop are executed (5).

To reduce the power consumption, ADC12REFBURST is set to enable burst mode. In burst mode, the internal buffer (ADC12REFOUT = 0) or the external buffer (ADC12REFOUT = 1) is enabled only during a conversion and is automatically disabled at all other times.

After the main loop is executed, the MSP430 enters LPM3 until the next Timer A0 interrupt occurs (6). This cycle repeats periodically at 1 Hz.

The measured average current drawn by the MSP430 in this application is 2.5 µA.

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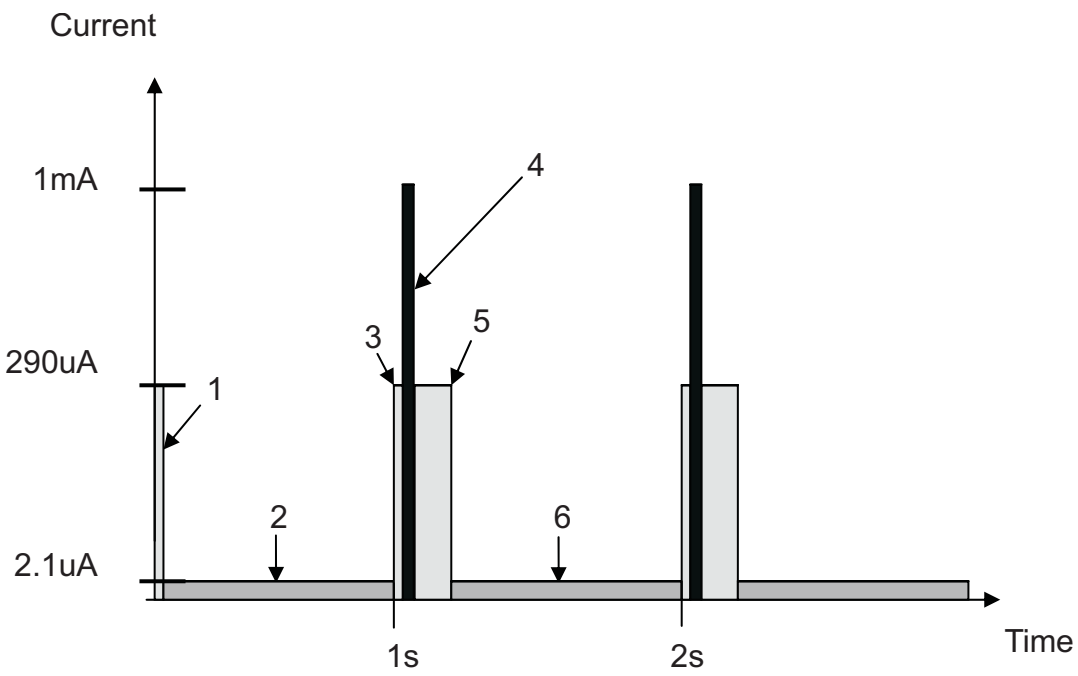

Figure 6. Current Drawn as a Function of Time

8 References

- Kester Walt, James Bryant, and Walt Jung. Section 7 – *Temperature Sensors*
- *Implementing a Single-Chip Thermocouple Interface with the MSP430x42x* (SLAA216)
- *MSP430x5xx/MSP430x6xx Family User's Guide* (SLAU208)
- *MSP430F551x, MSP430F552x Mixed Signal Microcontroller Data Sheet* (SLAS590)

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Bill of Materials

Bill of materials (BOM) for creating a prototype of the thermocouple circuit.

NOTE: This BOM does not include the materials for the MSP430 board (MCU, oscillators, etc); thus, it is to be used in conjunction with an MSP430 FET board.

Table 2. Bill of Materials

Description	Manufacturer's Part Number	Digikey Part Number	Quantity
IC OPAMP CHOP 1.9MHZ SGL 8DIP	TLC2652ACP	296-7318-5-ND	1
CAP CER 0.1UF 50V Y5V RAD	RDEF51H104Z0K1C03B	490-5401-ND	5
THERMOCOUPLE PROBE-2945	TP 29	TP-29-ND	1
THERM NTC 1000OHM -+5% PROBE	MF11-0100005	317-1277-ND	1
BREADBOARD 2.13x6.496 SLDLESS	TW-E40-1020	438-1045-ND	1
RES 1.0K OHM CARBON FILM 1/4W 5%	ERD-S2TJ102V	P1.0KBACT-ND	2
RES 291K OHM .1% 25PPM 1/2W	CMF55291K00BEEB	CMF291KHBTR-ND	2
RES 8.2K OHM CARBON FILM 1/4W 5%	ERD-S2TJ822V	P8.2KBACT-ND	1

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