Design Guide: TIDA-010019
RTD Replacement for Cold Junction Compensation Reference Design in a Temperature Sensor

TEXAS INSTRUMENTS

Description

Temperature-sensing applications that use a thermocouple (TC) require an accurate local temperature sensor to achieve high accuracy. Solutions for design challenges such as cold-junction compensation (CJC) or including an ultra-low power TC analog front-end are highlighted and addressed in this reference design. Performance in terms of power consumption and accuracy is optimized for accurate 4 to 20 mA sensors while also demonstrating the performance of different CJC and TC front-end implementations.
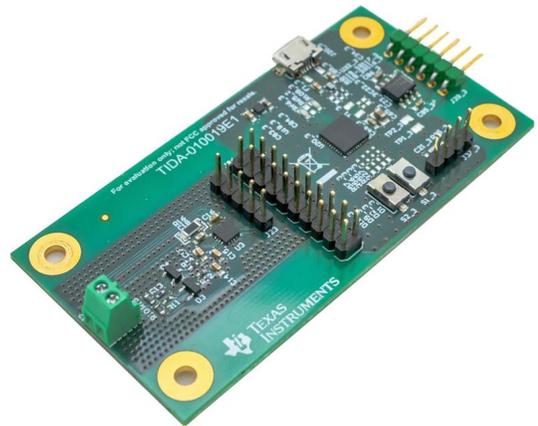
Resources

TIDA-010019	Design Folder
MSP430FR2355	Product Folder
TPS22946	Product Folder
TPS727	Product Folder
ISO7721	Product Folder
ADS112U04	Product Folder
LMT70	Product Folder
TMP235	Product Folder
LMT01	Product Folder
TMP117	Product Folder
REF2125	Product Folder
LPV821	Product Folder
INA317	Product Folder
ADS7142	Product Folder

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Features

- Ultra-low power TC front end: < 200 µA.
- RTD type performance with silicon temperature sensors.
- 16-bit ADC for 0.05 °C resolution.
- Comparing different CJC solutions.
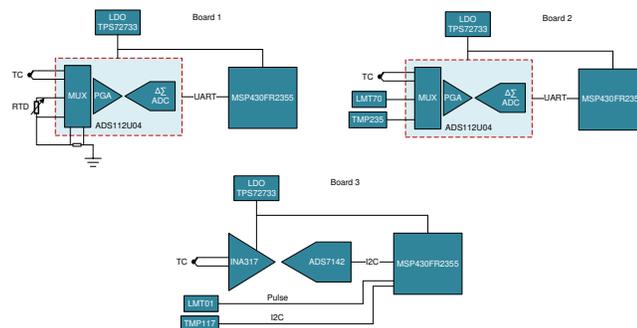- TC temperature from -270 °C to 1200 °C.

Applications

- Temperature transmitter
- Temperature controller
- Analog input module

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1 System Description

The cold-junction compensation is essential in temperature sensing using thermocouples. Every metal junction of different materials gives the thermo voltage. In the termocouple itself, but also where the thermo couple wires connect to the board a voltage is generated. The junction from the wires to the board is the so called cold-junction. The absolute temperature at this point has to be measured correctly to compensate the voltage developed here. The process of this compensation is the cold-junction compensation. This reference design shows different implementations for cold-junction compensation.

The standard approach, using an RTD, is compared to different analog sensors, and integrated digital sensors. The design of a low-power front end for the thermocouple is also shown. The resulting performance of the different solutions are compared to each other.

To compare different solutions, three boards are built using a different approach for CJC.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Input Voltage	5 V via micro USB connector	Section 2.4.4
Input Current	<30 mA	Section 2.4.4
Ambient Temperature	-40 °C to 105°C	Section 2.4.3
Thermocouple Input Range	–6.5 mV to 50 mV (Type K –270 °C to 1200 °C).	Section 2.4.1

2 System Overview

2.1 Block Diagram

Figure 1. TIDA-010019 Block Diagram
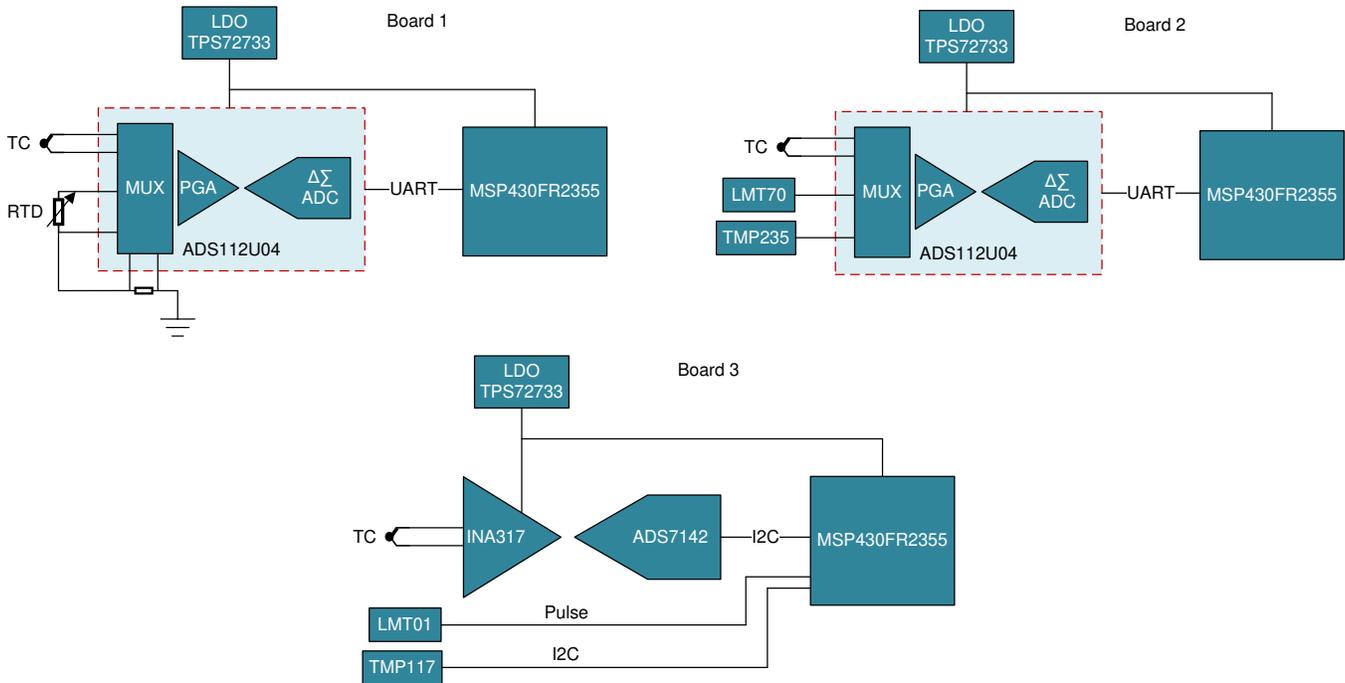
2.2 Design Considerations

This design is separated into several boards implementing different solutions for the thermocouple front end, and for the necessary cold junction compensation.

All boards have the same digital circuit consisting of an MSP430FR2355 as the MCU, and an ISO7721 to realize an isolated interface.

The digital part can be disconnected from the analog circuit, including the ADC, to connect TIDA-010018 to add an isolation of power and data interface.

Three boards containing different solutions are built to compare the performance:

1. Board 1: Thermocouple interface using delta sigma ADC with integrated MUX and PGA. Cold junction compensation realized with internal temperature sensor and RTD.
2. Board 2: Thermocouple interface using delta sigma ADC with integrated MUX and PGA. Cold junction compensation realized with external analog temperature sensors.
3. Board 3: Thermocouple interface using an instrumentation amplifier and low-power SAR ADC. Cold junction compensation is realized with digital temperature sensors.

2.3 Highlighted Products

This section includes a short introduction of the devices used in this design, and highlights the key features.

2.3.1 MSP430FR2355

The MSP430FR215x and MSP430FR235x microcontrollers (MCUs) are part of the MSP430™ MCU value-line portfolio of ultra-low-power low-cost devices for sensing and measurement applications. MSP430FR235x MCUs integrate four configurable signal-chain modules called smart analog combos, each can be used as a 12-bit DAC or a configurable programmable-gain Op-Amp to meet the specific needs of a system while reducing the BOM and PCB size. The device also includes a 12-bit SAR ADC and two comparators. The MSP430FR215x and MSP430FR235x MCUs all support an extended temperature range from –40° up to 105°C, so higher temperature industrial applications can benefit from the devices' FRAM data-logging capabilities. The extended temperature range allows developers to meet requirements of applications such as smoke detectors, sensor transmitters, and circuit breakers.

The MSP430FR215x and MSP430FR235x MCUs feature a powerful 16-bit RISC CPU, 16-bit registers, and a constant generator that contributes to maximum code efficiency. The digitally controlled oscillator (DCO) allows the device to wake up from low-power modes to active mode typically in less than 10 µs.

The MSP430 ultra-low-power (ULP) FRAM microcontroller platform combines embedded FRAM and a holistic ultra-low-power system architecture, allowing system designers to increase performance while lowering energy consumption. FRAM technology combines the low-energy fast writes, flexibility, and endurance of RAM with the nonvolatile behavior of flash.

Figure 2. MSP430FR235x Functional Block Diagram
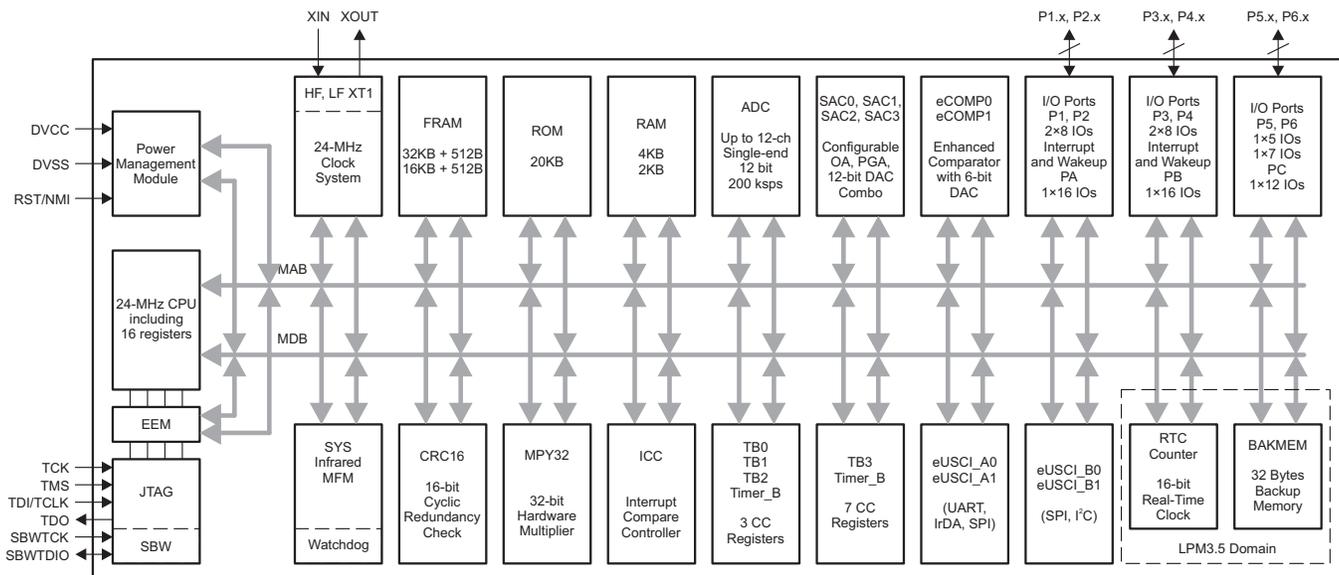
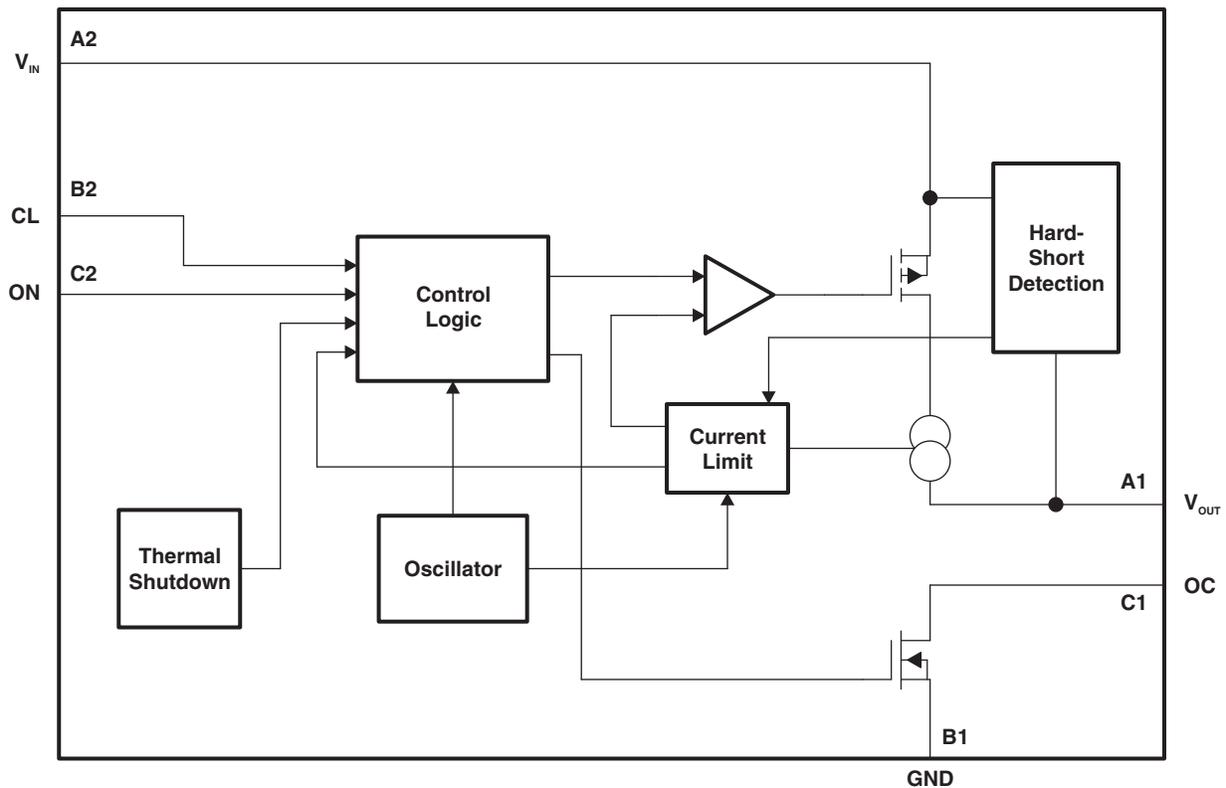Key features that make it suitable for this application:

- 16-Bit RISC Architecture up to 24 MHz
- Extended Temperature: –40°C to 105°C
- Wide Supply Voltage Range From 1.8 V Down to 3.6 V
- Active Mode: 142 µA/MHz
- Up to 32KB of Nonvolatile FRAM Memory
- Two Enhanced USCI_A (eUSCI_A) Modules Support UART, IrDA, and SPI
- Two Enhanced USCI_B (eUSCI_B) Modules Support SPI and I²C
- External 32-kHz Crystal Oscillator (LFXT)
- External High-Frequency Crystal Oscillator up to 24 MHz (HFXT)

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2.3.2   TPS22946

The TPS22946 is an ultra-low power load switch that provides protection to systems and loads in high-current conditions. The device contains a 300-mΩ current-limited P-channel MOSFET that can operate over an input voltage range of 1.62 V to 5.5 V. The switch is controlled by an on/off input (ON), which can interface directly with low-voltage control signals. The TPS22946 includes thermal shutdown protection that prevents damage to the device when a continuous over current condition causes excessive heating, by turning off the switch.

When the switch current reaches the maximum limit, the TPS22946 operates in a constant-current mode to prohibit excessive currents from causing damage. The current limit can be selected using the CL input; a high CL input sets the current limit to 155 mA, a low CL input sets the current limit to 70 mA, and a floating CL input sets the current limit to 30 mA.

Figure 3. TPS22946 Functional Block Diagram

Key features that make it suitable for this application:
- Ultra Low Quiescent Current: 1 μA
- Input Voltage Range: 1.62 V to 5.5 V
- Selectable Minimum Current Limit: 155 mA, 70 mA, or 30 mA

2.3.3   TPS72733

The TPS727 family of low-dropout (LDO) linear regulators are ultra-low quiescent current LDOs with excellent line and ultra-fast load transient performance, designed for power-sensitive applications. The LDO output voltage level is preset by the use of innovative factory EEPROM programming. A precision band-gap and error amplifier provides overall 2% accuracy over load, line, and temperature extremes. The TPS727 family is available in 1.5-mm × 1.5-mm SON and wafer chip-scale (WCSP) packages that make the devices ideal for handheld applications. This family of devices is fully specified over a temperature range of T J = −40°C to +125°C.

Figure 4. TPS727 Functional Block Diagram
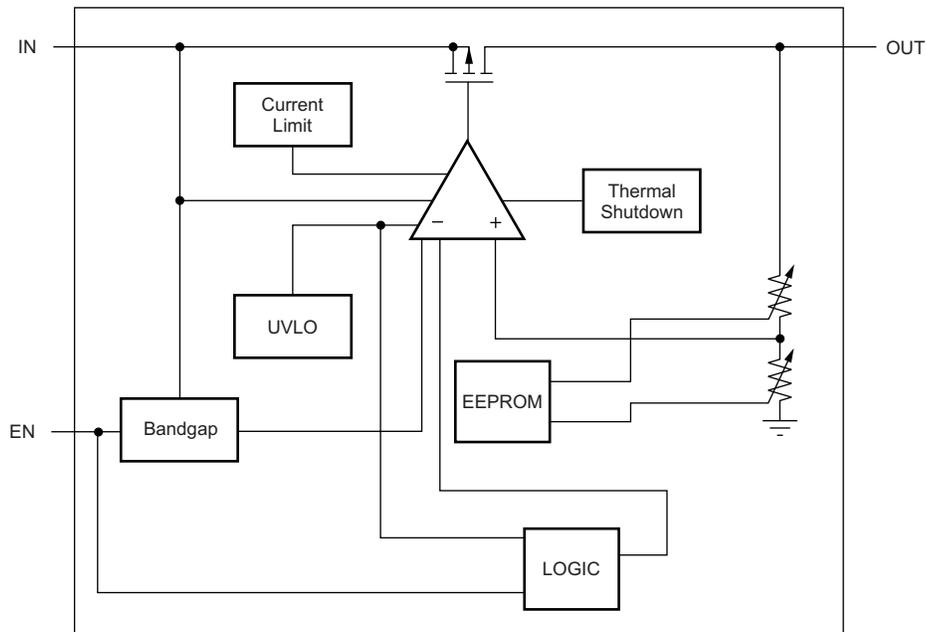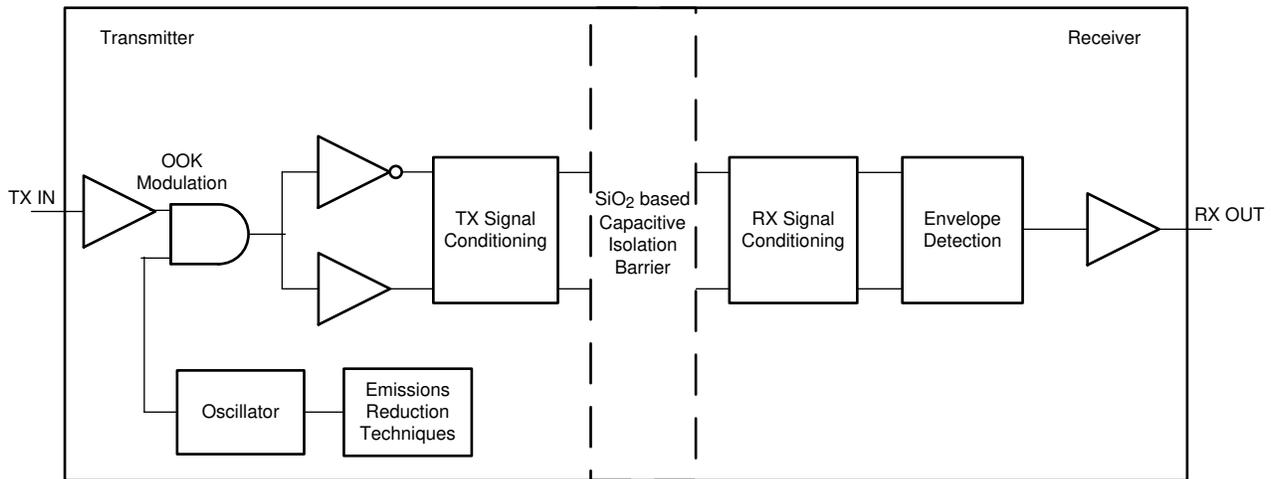

Key features that make it suitable for this application:

- Very Low Dropout
- Ultra-low I Q : 7.9 µA
- Excellent Load Transient Performance: ±50 mV for 200 mA Loading and Unloading Transient
- Available in Fixed-Output Voltages From 0.9 V to 5 V Using Innovative Factory EEPROM Programming
- High PSRR: 70 dB at 1 kHz

2.3.4 ISO7721

The ISO772x devices are high-performance, dual-channel digital isolators with 5000-V RMS (DW and DWV packages) and 3000-V RMS (D package) isolation ratings per UL 1577. These devices are also certified by VDE, TUV, CSA, and CQC.

The ISO772x devices provide high electromagnetic immunity and low emissions at low-power consumption, while isolating CMOS or LVCMOS digital I/Os. Each isolation channel has a logic input and output buffer separated by a silicon dioxide (SiO 2) insulation barrier. The ISO7720 device has both channels in the same direction, while the ISO7721 device has both channels in the opposite direction. In the event of input power or signal loss, the default output is high for devices without suffix F and low for devices with suffix F.

Used in conjunction with isolated power supplies, these devices help prevent noise currents on a data bus or other circuits from entering the local ground and interfering with or damaging sensitive circuitry. Through innovative chip design and layout techniques, the electromagnetic compatibility of the ISO772x devices has been significantly enhanced to ease system-level ESD, EFT, surge, and emissions compliance. The ISO772x family of devices is available in 16-pin SOIC wide-body (DW), 8-pin SOIC wide-body (DWV), and 8-pin SOIC narrow-body (D) packages.

Figure 5. ISO7721 Functional Block Diagram

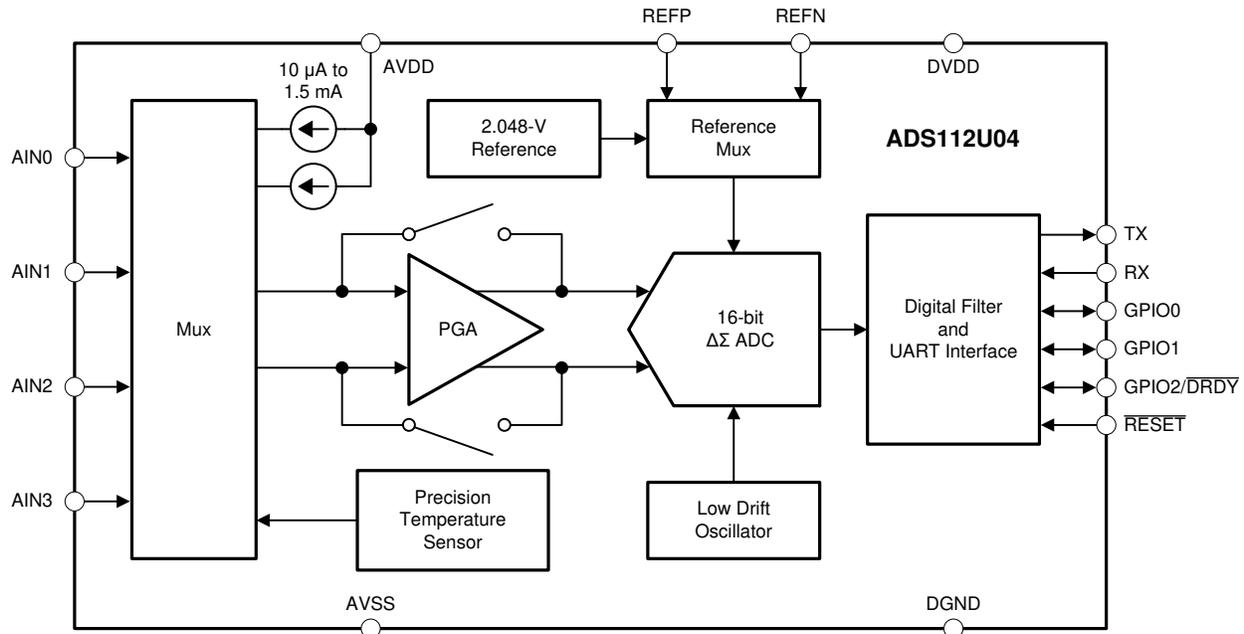Key features that make it suitable for this application:

- Wide Supply Range: 2.25 V to 5.5 V
- 2.25-V to 5.5-V Level Translation
- Wide Temperature Range: –55°C to +125°C
- Low Power Consumption, Typical 1.7 mA per Channel at 1 Mbps

2.3.5 ADS112U04

The ADS112U04 is a precision, 16-bit, analog-to-digital converter (ADC) that offers many integrated features to reduce system cost and component count in applications measuring small sensor signals. The device features two differential or four single-ended inputs through a flexible input multiplexer (MUX), a low-noise, programmable gain amplifier (PGA), two programmable excitation current sources, a voltage reference, an oscillator, and a precision temperature sensor.

The device can perform conversions at data rates up to 2000 samples-per-second (SPS) with single-cycle settling. At 20 SPS, the digital filter offers simultaneous 50-Hz and 60-Hz rejection for noisy industrial applications. The internal PGA offers gains up to 128x ist. This PGA makes the ADS112U04 designed for applications measuring small sensor signals, such as resistance temperature detectors (RTDs), thermocouples, thermistors, and resistive bridge sensors.

The ADS112U04 features a 2-wire, UART-compatible interface. In applications that require galvanic isolation, this universal asynchronous receiver/transmitter (UART) interface minimizes the number of digital isolation channels, saving cost, board space, and power.

Figure 6. ADS112U04 Functional Block Diagram

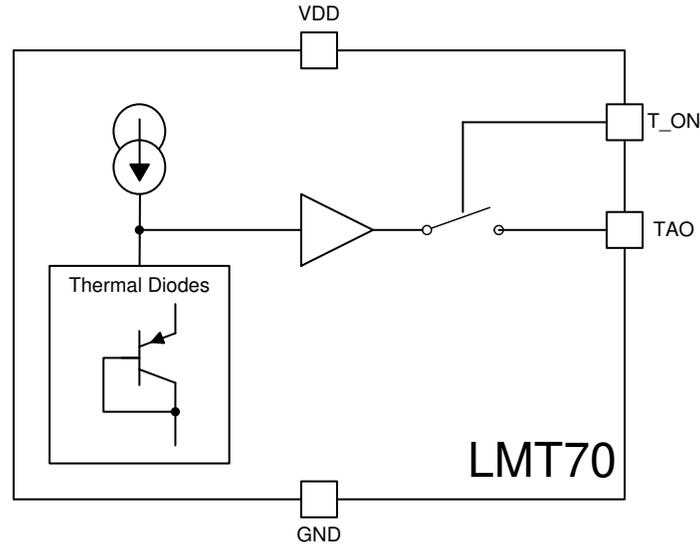Key features that make it suitable for this application:

- Current Consumption as Low as 315 µA (typ)
- Wide Supply Range: 2.3 V to 5.5 V
- Programmable Gain: 1 to 128
- Programmable Data Rates: Up to 2 kSPS
- 16-Bit, Noise-Free Resolution at 20 SPS
- Two Differential or Four Single-Ended Inputs
- Dual-Matched Programmable Current Sources: 10 µA to 1.5 mA
- Internal 2.048-V Reference: 5 ppm/°C (typ) Drift
- Internal Temperature Sensor: 0.5°C (typ) Accuracy
- 2-Wire UART Compatible Interface (8-N-1 Format) With Baud Rates up to 120 kBaud and Auto-Baud-Rate Detection

2.3.6 LMT70

The LMT70 is an ultra-small, high-precision, low-power CMOS analog temperature sensor with an output enabled pin. Applications for the LMT70 include virtually any type of temperature sensing where cost-effective, high precision and low power are required, such as Internet of Things (IoT) sensor nodes, medical thermometers, high-precision instrumentation, and battery-powered devices. The LMT70 is also a great replacement for RTD and precision NTC/PTC thermistors.

Its output-enabled pin allows multiple LMT70s to share one ADC channel, simplifying ADC calibration and reducing the overall system cost for precision temperature sensing. The LMT70 also has a linear and low-impedance output, allowing seamless interface to an off-the-shelf MCU/ADC. Dissipating less than 36 µW, the LMT70 has ultra-low self-heating supporting its high-precision over a wide temperature range.

The LMT70A provides unparalleled temperature matching performance of 0.1°C (max) for two adjacent LMT70As picked from the same tape and reel. Therefore, the LMT70A is an ideal solution for energy metering applications requiring heat transfer calculations.

Figure 7. LMT70 Functional Block Diagram

Key features that make it suitable for this application:

- Accuracy:
    - ±0.05°C (typ) or ±0.13°C (max) from 20°C to 42°C
    - ±0.2°C (max) from −20°C to 90°C
    - ±0.23°C (max) from 90°C to 110°C
    - ±0.36°C (max) from −55°C to 150°C
- Wide Temperature Range: −55°C to 150°C
- Matching of Two Adjacent LMT70A on Tape and Reel: 0.1°C (max) at 30°C
- Very Linear Analog Temperature Sensor with Output Enable Pin
- NTC Output Slope: −5.19 mV/°C
- Wide-Power Supply Range: 2.0 V to 5.5 V
- Low-Power Supply Current: 9.2 μA (typ)

2.3.7 TMP235

The TMP23x devices are a family of precision CMOS integrated-circuit linear analog temperature sensors with an output voltage proportional to temperature that engineers can use in multiple analog temperature-sensing applications. These temperature sensors are more accurate than similar pin-compatible devices on the market, featuring typical accuracy from 0°C to +70°C of ±0.5°C and ±1°C. The increased accuracy of the series is designed for many analog temperature-sensing applications. The TMP235 device provides a positive slope output of 10 mV/°C over the full −40°C to +150°C temperature range and a supply range from 2.3 V to 5.5 V. The higher gain TMP236 sensor provides a positive slope output of 19.5 mV/°C from −10°C to +125°C and a supply range from 3.1 V to 5.5 V.

The 9-μA typical quiescent current and 800-μs typical power-on time enable effective power-cycling architectures to minimize power consumption for battery-powered devices. A class-AB output driver provides a strong 500-μA maximum output to drive capacitive loads up to 1000 pF, and is designed to directly interface to analog-to-digital converter sample and hold inputs. With excellent accuracy and a strong linear output driver, the TMP23x analog output temperature sensors are cost-effective alternatives to passive thermistors.

Figure 8. TMP235 Functional Block Diagram
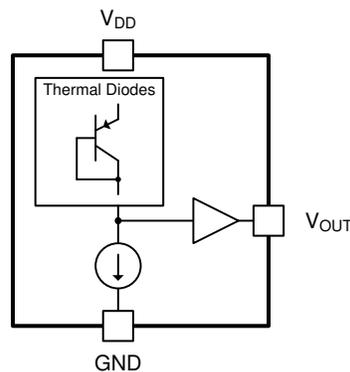
Key features that make it suitable for this application:

- Cost-Effective Alternative to Thermistors
- Wide Temperature Measurement Range: –40°C to +150°C
- Available in Two Accuracy Level Variants:
  - A2 Level: ±0.5°C (Typical)
  - A4 Level: ±1°C (Typical)
- Positive Slope Sensor Gain, Offset (Typical): 10 mV/°C, 500 mV at 0°C
- Wide Operating Supply Voltage Range: 2.3 V to 5.5 V
- Low Power: 9 μA (Typical)

2.3.8 LMT01

The LMT01 device is a high-accuracy, 2-pin temperature sensor with an easy-to-use pulse-count current loop interface, which makes it suitable for onboard and offboard applications in automotive, industrial, and consumer markets. The LMT01 digital pulse count output and high accuracy over a wide temperature range allow pairing with any MCU without concern for integrated ADC quality or availability, while minimizing software overhead. TI's LMT01 device achieves a maximum ±0.5°C accuracy with fine resolution (0.0625°C) over a temperature range of –20°C to 90°C without system calibration or hardware and software compensation.

The LMT01's pulse count interface is designed to directly interface with a GPIO or comparator input, thereby simplifying hardware implementation. Similarly, the LMT01's integrated EMI suppression and simple 2-pin architecture makes it suitable for onboard and offboard temperature sensing in a noisy environment. The LMT01 device can be easily converted into a two-wire temperature probe with a wire length up to two meters.

Figure 9. LMT01 Functional Block Diagram
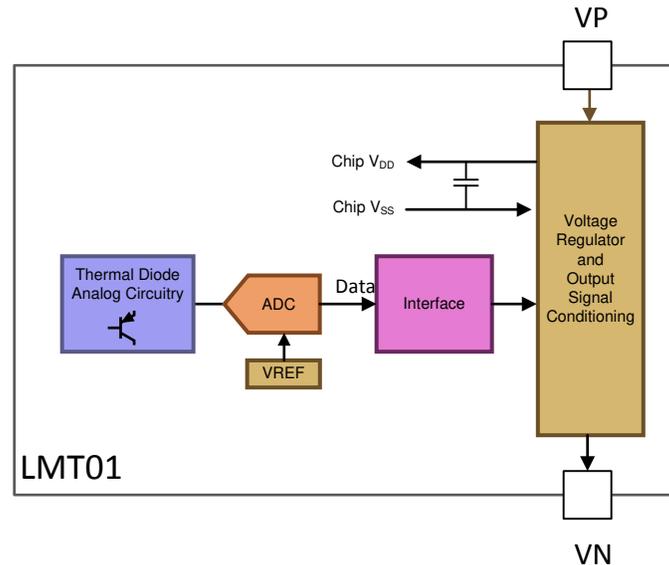
Key features that make it suitable for this application:

- High Accuracy Over –50°C to 150°C Wide Temperature Range
  - –20°C to 90°C: ±0.5°C (Maximum)
  - 90°C to 150°C: ±0.625°C (Maximum)
  - –50°C to –20°C: ±0.7°C (Maximum)
- Precision Digital Temperature Measurement Simplified in a 2-Pin Package
- Pulse Count Current Loop Easily Read by Processor. Number of Output Pulses is Proportional to Temperature With 0.0625°C Resolution
- Communication Frequency: 88 kHz
- Conversion Current: 34 µA
- Continuous Conversion Plus Data-Transmission Period: 100 ms

2.3.9   TMP117

The TMP117 is a high-precision digital temperature sensor. It is designed to exceed ASTM E1112 requirements for electronic patient thermometers. The TMP117 provides a 16-bit temperature result with a resolution of 0.0078°C and an accuracy of up to ±0.1°C across the temperature range of 25°C to 50°C with no calibration. The TMP117 is I²C- and SMBus™-interface compatible, has programmable alert functionality, and can support up to four devices on a single bus. Integrated EEPROM is included for device programming with an additional 48 bits of memory available for general use.

The low-power consumption of the TMP117 minimizes the impact of self-heating on measurement accuracy. The TMP117 operates from 1.8 V to 5.5 V and typically consumes 3.5 µA.

For non-medical applications, the TMP117 can serve as a single-chip digital alternative to a Platinum RTD. With an accuracy of ±0.2°C from –55°C to 150°C, the TMP117 offers comparable if not better accuracy than can be achieved with a Class A RTD, while only using a fraction of the power typically needed for a PT100 RTD. The TMP117 simplifies the design effort by removing many of the complexities of RTDs such as precision references, matched traces, complicated algorithms, and calibration.

The TMP117 units are 100% tested on a production setup that is NIST-traceable and verified with equipment calibrated to ISO/IEC 17025 accredited standards.

Figure 10. TMP117 Functional Block Diagram

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Key features that make it suitable for this application:

- TMP117 High Accuracy Temperature Sensor
  - ±0.1°C (Maximum) From 25°C to +50°C
  - ±0.2°C (Maximum) From −40°C to +125°C
  - ±0.3°C (Maximum) From −55°C to +150°C
- Temperature Operating Range: −55°C to +150°C
- Low-Power Consumption:
  - 3.5-µA, 1-Hz Conversion Cycle
  - 250-nA Shutdown Current
- Supply Range: 1.8 V to 5.5 V
- 16-Bit Resolution: 0.0078°C (1 LSB)
- Programmable Temperature Alert Limits
- Digital Offset for System Correction
- General-Purpose EEPROM: 48 Bits
- NIST Traceability
- SMBus™, I²C Interface Compatibility

2.3.10 REF2125

The REF2125 device is a low temperature drift (6 ppm/°C), low-power, high-precision CMOS voltage reference, featuring ±0.05% initial accuracy and low operating current with power consumption less than 95 µA. This device also offers low output noise of 5 µV p-p /V, which enables it to maintain high signal integrity with high-resolution data converters and noise-critical systems.

Stability and system reliability are further improved by the low output-voltage hysteresis of the device and low long-term output voltage drift. Also, the small size and low operating current of the devices (95 μA) are designed for portable and battery-powered applications.

Figure 11. REF2125 Functional Block Diagram

Key features that make it suitable for this application:

- Initial Accuracy: ±0.05% (maximum)
- Temperature Coefficient : 6 ppm/°C (maximum)
- Output Current: ±10 mA
- Low Quiescent Current: 95 μA (maximum)
- Wide Input Voltage: 12 V
- Output 1/f Noise (0.1 Hz to 10 Hz): 5 μV PP /V
- Excellent Long-Term Stability 30 ppm/1000 hrs

2.3.11 LPV821

The LPV821 is a single-channel, nanopower, zero-drift operational amplifier for "Always ON" sensing applications in a wireless and wired equipment where low input offset is required. With the combination of low initial offset, low offset drift, and 8 kHz of bandwidth from 650 nA of quiescent current, the LPV821 is the industry's lowest power zero-drift amplifier that can be used for end equipment to monitor current consumption, temperature, gas, or strain gauges.

The LPV821 zero-drift operational amplifier uses a proprietary auto-calibration technique to simultaneously provide low offset voltage (10 μV, maximum) and minimal drift over time and temperature. In addition to having low offset and ultra-low quiescent current, the LPV821 amplifier has pico-amp bias currents which reduce errors commonly introduced in applications, monitoring sensors with high output impedance and amplifier configurations with megaohm feedback resistors.

Figure 12. LPV821 Functional Block Diagram
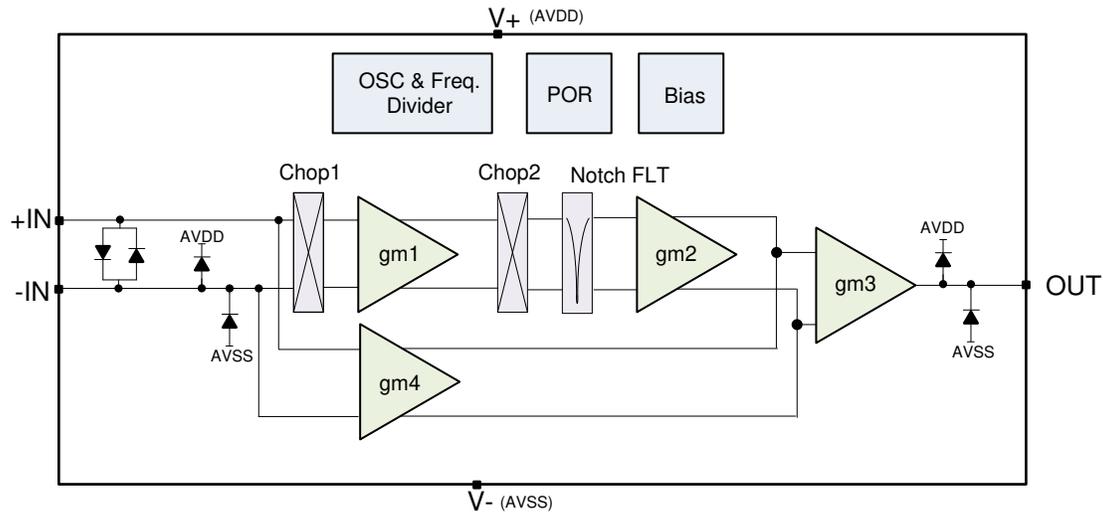
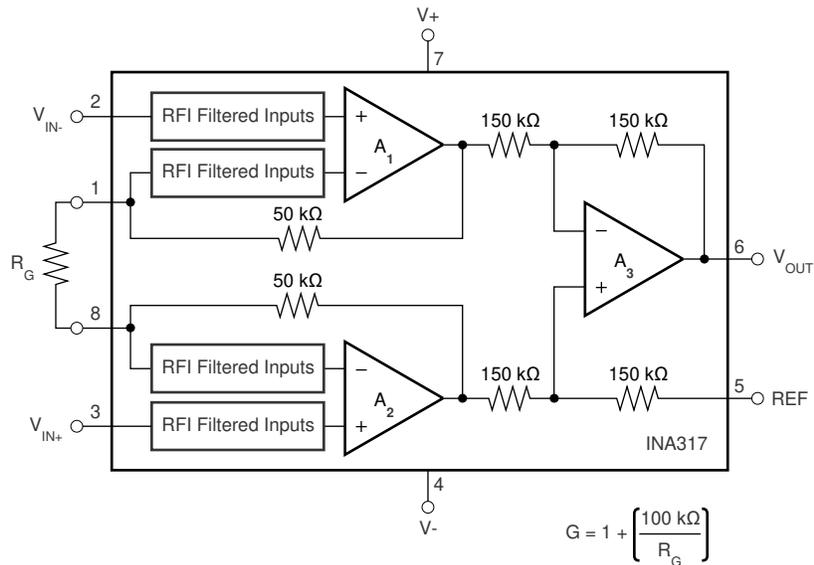
Key features that make it suitable for this application:

- Quiescent Current: 650 nA
- Low Offset Voltage: ±10 μV (Maximum)
- Offset Voltage Drift: ±0.096 μV/°C (Maximum)
- 0.1-Hz to 10-Hz Noise: 3.9 μV PP
- Input Bias Current: ±7 pA
- Supply Voltage: 1.7 V to 3.6 V
- Rail-to-Rail Input/Output

2.3.12 INA317

The INA317 is a low-power, precision instrumentation amplifier offering excellent accuracy. The versatile 3-operational amplifier design, small size, and low power make the INA317 a wide range of portable applications.

A single external resistor sets any gain from 1 to 1000, as defined by the industry-standard gain equation: $G = 1 + (100 \text{ k}\Omega / R_G)$.

The instrumentation amplifier provides low offset voltage (75 μV, G ≥ 100), excellent offset voltage drift (0.3 μV/°C, G ≥ 100) and high common-mode rejection (100 dB at G ≥ 10). The INA317 operates with power supplies as low as 1.8 V (±0.9 V) and a quiescent current of 50 μA, making the device for battery-operated systems. Using autocalibration techniques to ensure precision over the extended industrial temperature range, the INA317 device offers low noise density (50 nV/√Hz) that extends down to DC.

Figure 13. INA317 Functional Block Diagram

$$G = 1 + \left[\frac{100 \text{ k}\Omega}{R_G}\right]$$
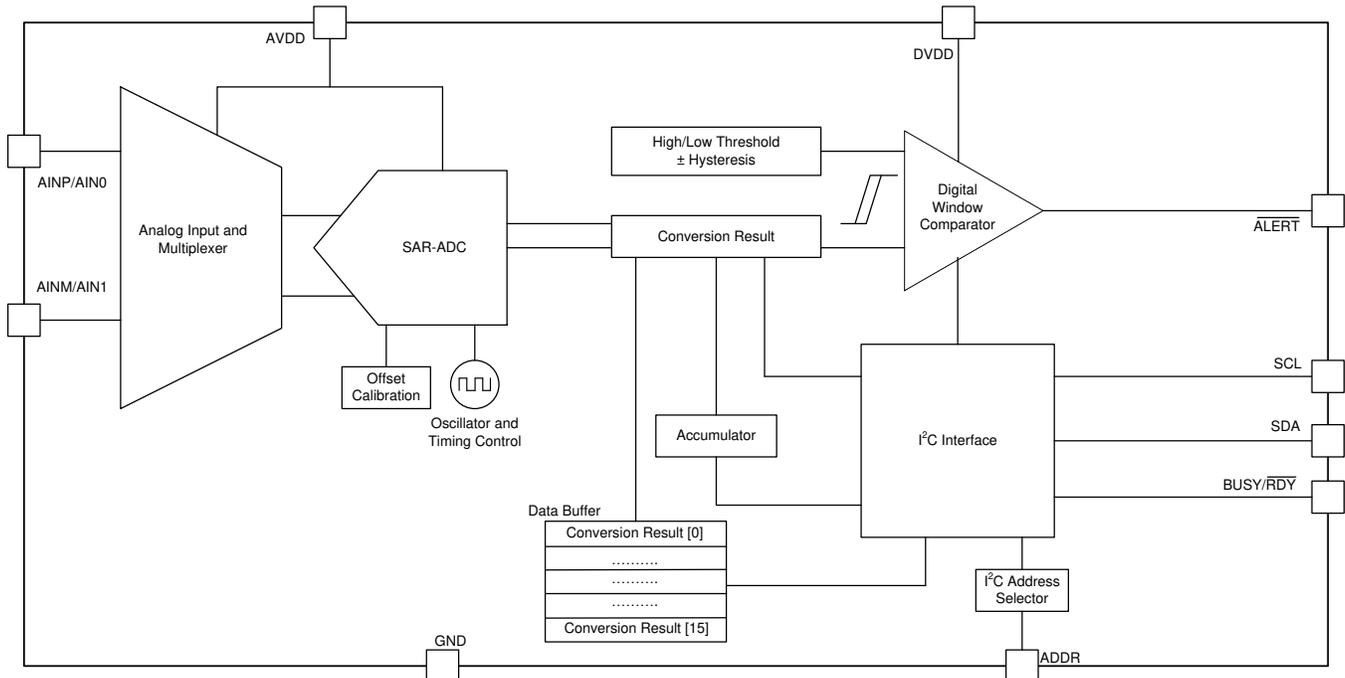
Key features that make it suitable for this application:

- Low Offset Voltage: 75 µV (Maximum), G ≥ 100
- Low Drift: 0.3 µV/°C, G ≥ 100
- Low Noise: 50 nV/√Hz, G ≥ 100
- High CMRR: 100 dB (Minimum), G ≥ 10
- Low Input Bias Current: 200 pA (Maximum)
- Supply Range: 1.8 V to 5.5 V
- Input Voltage: (V–) 0.1 V to (V+) –0.1 V
- Output Range: (V–) 0.05 V to (V+) –0.05 V
- Low Quiescent Current: 50 µA

2.3.13 ADS7142

The ADS7142 autonomously monitors signals while optimizing system power, reliability, and performance. It implements event-triggered interrupts per channel using a digital windowed comparator with programmable high and low thresholds, hysteresis, and event counter. The device includes a dual-channel analog multiplexer in front of a successive approximation register analog-to-digital converter (SAR ADC) followed by an internal data buffer for converting and capturing data from sensors.

The ADS7142 is available in 10-pin QFN package and consumes only 900 nW of power. The small form-factor and low-power consumption make this device suitable for space-constrained and or battery-powered applications.

**Figure 14. ADS7142 Functional Block Diagram**

Key features that make it suitable for this application:

- Standalone, Nanopower Sensor Monitor for Cost-sensitive Designs
- Small Package Size: 1.5 mm × 2 mm
- Autonomous Monitoring at 900 nW
- Internal Calibration improves Offset and Drift
- High Precision Mode for 16-bit Accuracy
- Analog Supply: 1.65 V to 3.6 V
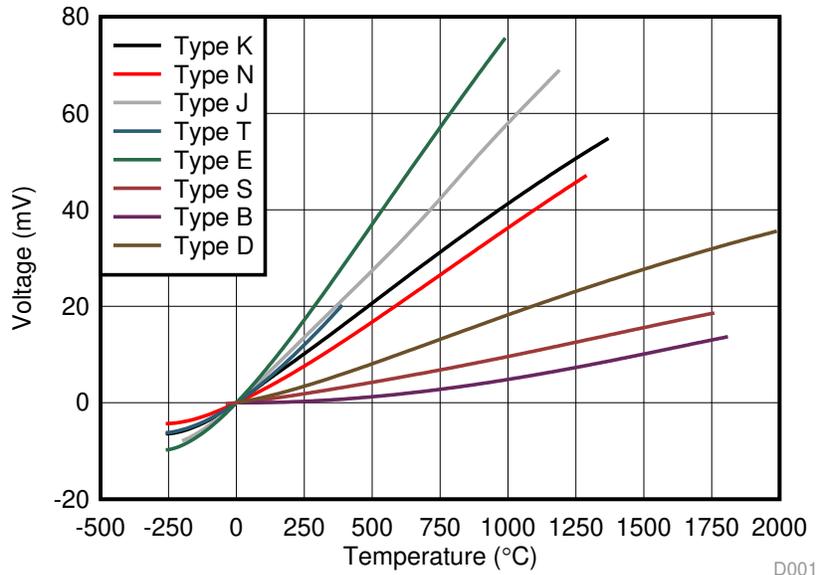- Temperature Range: –40°C to 125°C

2.4 System Design Theory

Temperatures are an important process parameter. All temperature measurements rely on physical changes on material, depending on the temperature. Commonly used sensors are thermocouples, RTDs (PT100, PT500, PT1000), semiconductor sensors (ICs and diodes), and thermistors (NTC/PTC).

As shown in Figure 15, thermocouples are basically two different metals joined at one point. You can measure voltage at the other end of the metals, depending on the temperature difference. This is called Seebeck voltage and depends on the temperature and the metals used. The Seebeck voltage is typically in the range of µV or mV, and non linear over temperature. It is necessary to amplify the voltage before it can be digitized and linearized in the software. The connection from the thermocouple to the connector also develops a thermovoltage that must be compensated. To compensate it, it is necessary to know the ambient temperature at the connector to be able to calculate the voltage developed at this point.

Figure 15. Thermocouple Type K
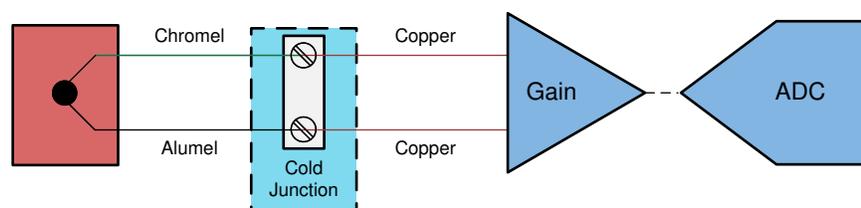
Different materials will have different slopes and temperature ranges. Figure 16 gives a quick overview of the different sensor types used and their voltage range. A commonly used general purpose sensor is type K, but others are selected based on criteria such as cost, sensitivity, temperature range, and chemical inertness.

Figure 16. Overview Thermocouples

RTDs usually consist of a fine wire or a thin film of pure metal, typically platinum, nickel, or copper. These materials have an accurate temperature/resistance relation. RTDs are typically used in a temperature range from –200 °C to 500 °C, and are more accurate than thermocouples but limited in temperature range. Also the response time is higher than for thermocouples. Besides thermocouples, RTDs need power to receive a reading that heats them up. To measure the resistance of an RTD, use a constant current of 100 µA - 1 mA to develop a voltage drop that can be measured.

Semiconductor temperature sensors are limited to a narrow range, typically –55 °C to 150 °C. This group of sensors covers a wide range of different types. From a simple diode to complex ICs with integrated ADC, different implementations are possible.

The simplest solution is a diode in series with a resistor connected to a voltage source. The voltage drop over the diode changes with approximately –2 mV/K and is a simple low-cost, low-performance temperature sensor. However the temperature coefficient changes with the current through the device, so to ensure an accurate reading, you must have a stable constant current source. Also, the current through the diode heats it up and influences the reading. The initial accuracy is device-dependent and must be calibrated.

IC silicon sensors are also limited to this temperature range, but include everything necessary to get a linear voltage output or an integrated ADC so it can be interfaced, for example, with I^{2}C. These sensors usually offer usually an initial accuracy better than 1 °C. See Section 2.4.3 for the sensors presented in this work and their performance.

A forth category of temperature sensors are thermistors, such as NTC and PTC elements. As for RTDs, their resistance changes over temperature but is not as linear. Thermistors are limited to a narrower temperature range of approximately –90 °C to 130 °C. Instead of using metal as a sensing element, ceramic or polymers are used. NTCs have a negative temperature coefficient, for example, where the resistance decreases when the temperature increases, whereas PTCs have a positive temperature coefficient.

For thermistors, a current flow is necessary to measure the resistance, but current can be low due to the high resistance. NTCs are often used as temperature sensors: for a small temperature range, the NTC is linear and needs no calibration, for larger temperature range, calibration is necessary.

Thermistors are used for both temperature sensing, and current limitation or heating.


2.4.1 TC Front End Design

This section highlights the different implementations for the analog front end.

The front end offers protection, filtering, and most importantly, signal condition in the form of adding an offset and amplification. The typical thermocouple type K has a voltage range of –6.5 mV to 50 mV (–270 °C to 1200 °C). This voltage must be amplified to fit to the input voltage range of the ADC. Some ADCs have an integrated PGA, where a thermocouple can be directly connected without the need for a discrete amplifier.

For the thermocouple, an ADS112U04 is used here. This 16 bit ADC has an integrated PGA supporting a gain up to 128 and an internal reference voltage of 2.048 V. The input can be configured to do a differential measurement supporting the negative voltage from the TC.

As shown in Figure 17 the signal from the thermocouple must be in a valid common-mode voltage range for the ADC, therefore the input is pulled to mid of the supply voltage by two resistors (R10, R15). This resistor network must have a high impedance to keep the current through the thermocouple low, usually in the range of mega ohms. By connecting the resistors to both ends of the thermocouple, it is possible to detect if the cable breaks by getting an off-scale reading. It is also possible to connect the voltage divider to only one input: then no current is in the thermocouple, but it can not be detected if the cable is broken.

Figure 17. TC Front End with ADS112U04
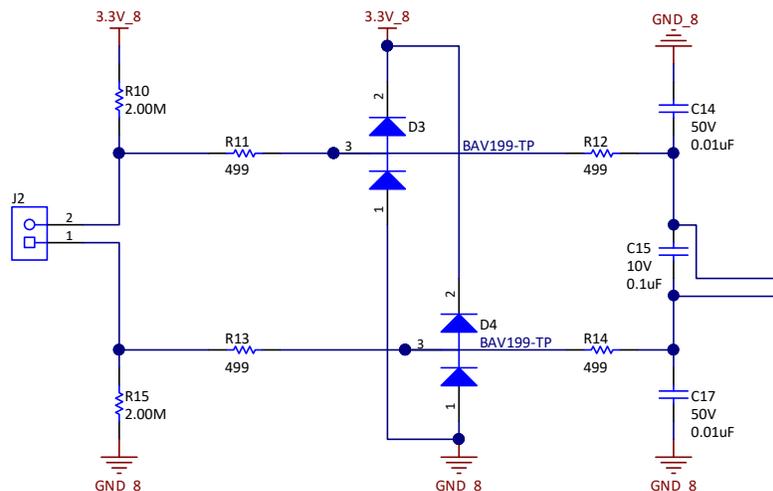
The internal block diagram Figure 17 explains how the ADS112U04 works. For digitizing a thermocouple voltage, it is necessary to configure the MUX to connect to the inputs routed to the connector for the thermocouple. Also the PGA must be set accordingly to the maximum possible gain. When the reference voltage is 2.048 V, the maximum output voltage of the PGA can be 2.048 V. The maximum input voltage is expected to be 50 mV at 1200 °C, and the maximum gain is: 2048 mV / 50 mV = 40. The next possible value 32 is selected.

The integrated iDAC must be switched off and the internal reference voltage used. The lowest data rate is chosen for highest accuracy. This results in the register configuration shown in Table 2.

Table 2. Register configuration ADS112U04 Thermocouple

REGISTER	CONFIGURATION	VALUE
0x00	AINp = AIN0; AINn = AIN1; PGA = 32	0x0a
0x01	Datarate = 20 Sps; Single shot; Internal reference	0x00
0x02	iDAC off; No CRC; No data counter	0x00
0x03	iDAC off	0x00
0x04	all GPIOs as input -> not used	0x00

The MUX has a configuration at which both inputs are shorted and tied to mid-supply level. This setting can be used to determine the offset of the ADC and PGA. TI recommends determining the offset voltage and subtracting it from the ADC reading.

Figure 18. ADS112U04 Block Diagram
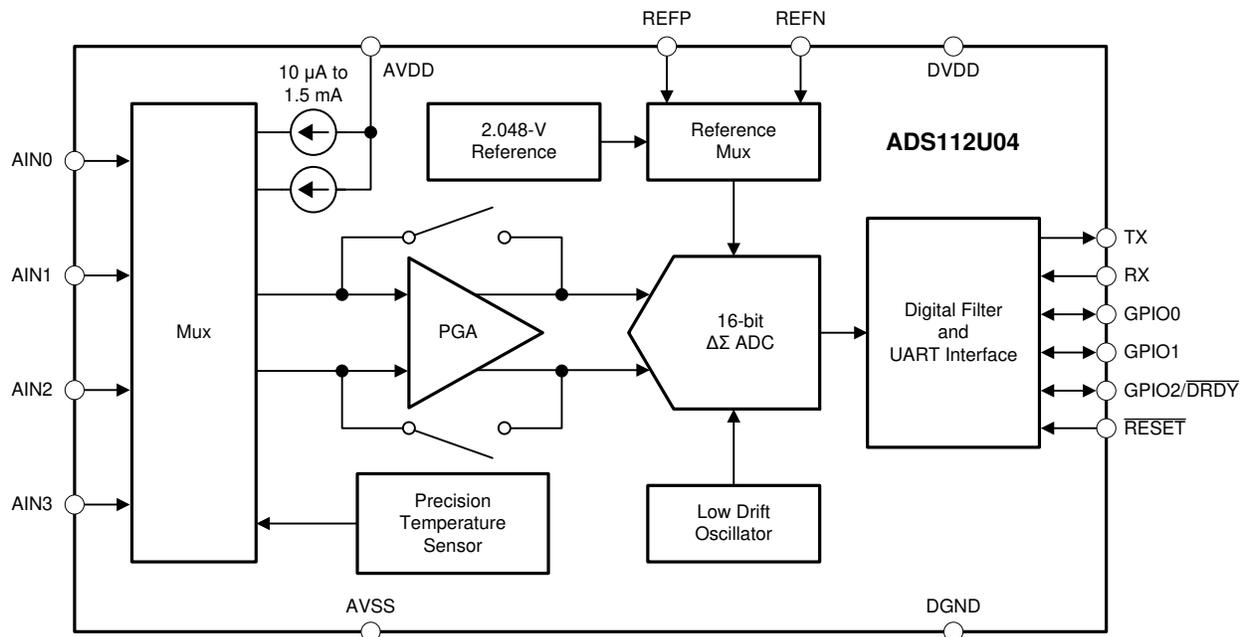
The UART interface makes it simple to interface with the ADC, and it is easy to isolate. As the ADS112U04 has a baud rate detection, it can be interfaced with any baud rate up to 120 kBaud. During communication, you must start with a synchronization word, followed by a command word. Some commands expect additional arguments, and other commands generate a response.

To get a reading from the ADC, after configuration, send the START command and wait until the conversation is finished (check the DRDY bit in register 2 or the DRDY pin). Then the result can be read using the RDATA command. From the 16-bit value, the determined offset voltage must be subtracted, then the input voltage from the thermocouple can be calculated. TC = ADC * 2.048 / 32768 / 32.

2.4.2 Low-Power Analog Front End using the Instrumentation Amplifier and 16 -Bit SAR ADC

The instrumentation amplifier amplifies the low voltage signal of a thermocouple to a higher voltage. This circuit uses an INA317 with a low-power consumption of only 50 µA and a high input resistance. The supply voltage range of 1.8 V to 5.5 V makes it suitable for applications with a power requirement of 3.3 V or less.

The voltage from the thermocouple can be negative, which requires biasing to always get a positive voltage.

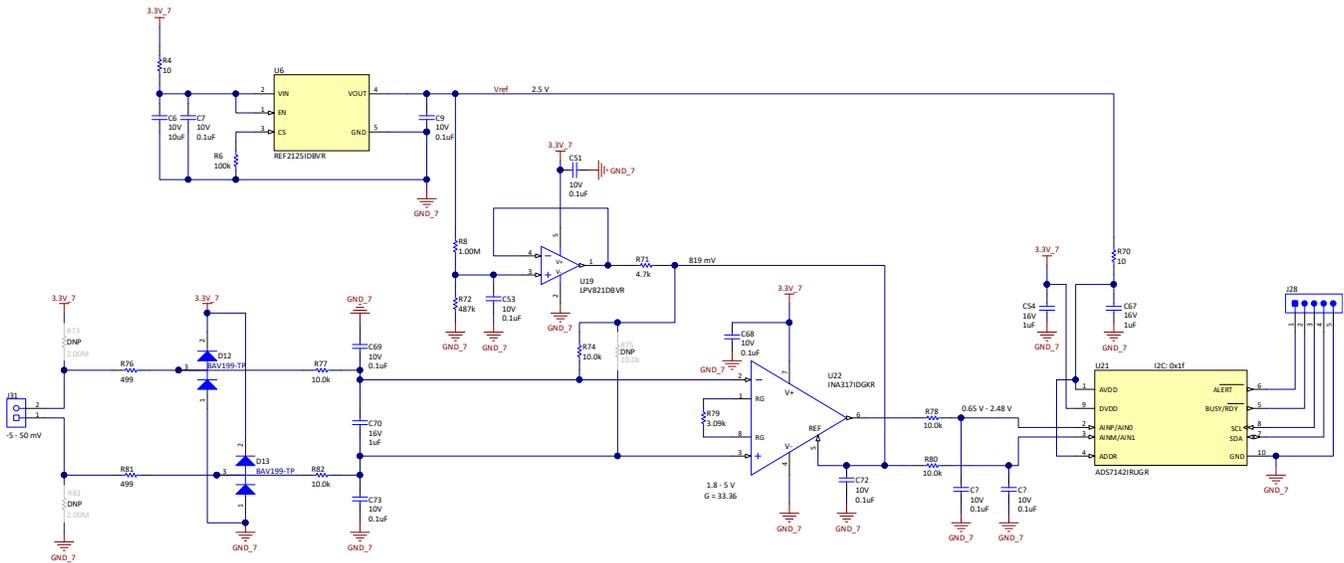**Figure 19. Front End with INA317 for ADS7142**

[Figure 20](#) shows the schematic of the input stage. A simple filter and protection network is connected directly at the input. A bias voltage of approximately 0.82 V is derived from the 2.5-V reference (U6) and buffered by U19. This reference voltage is used to shift the output of the instrumentation amplifier and the thermocouple voltage. The absolute voltage is not affected, because the ADC is connected to make a differential measurement. The reference voltage must be in a certain range to maintain the amplifier in a valid common mode voltage range.

The output of the amplifier is connected through an RC network to the ADC, to filter the signal and provide a low impedance for the internal sampling capacitor.

The gain of the instrumentation amplifier is set with R79 to a fixed value of 33.36. This results in an output voltage ranging from –5 mV * 33.36 + 0.816 = 650 mV to 2.48 V.

**Figure 20. Front End Simulation with INA317**
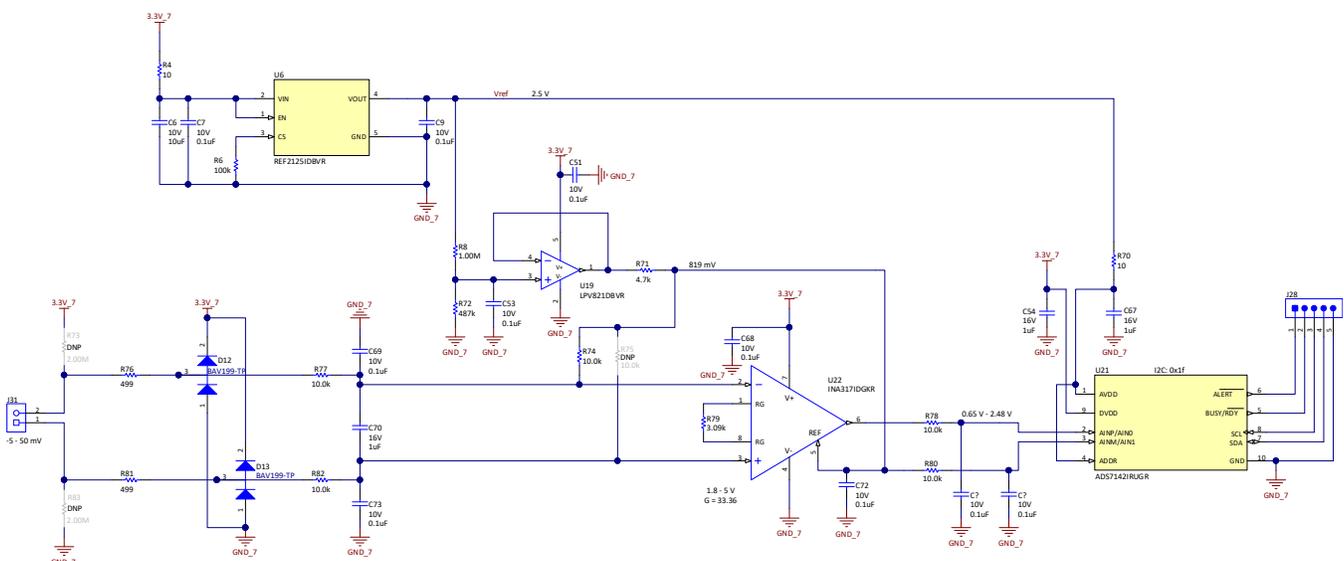
It is beneficial to simulate the analog stage, to verify that it covers the desired output voltage range and is working without oscillating. Most importantly, the capacitive load at the output of the amplifiers can cause issues. Figure 21 shows the simulation file. Here the analog stage is shown in TINA, not including the ADC. The differential output voltage and the absolute value is relevant. The thermocouple is simulated as voltage source VS1 and the supply voltage is set to 3.3 V as it is in the real application. The reference voltage is replaced by a voltage source. However, the bias voltage is generated with an operational amplifier, to verify that it will not oscillate.

Figure 21. Front End Simulation Results
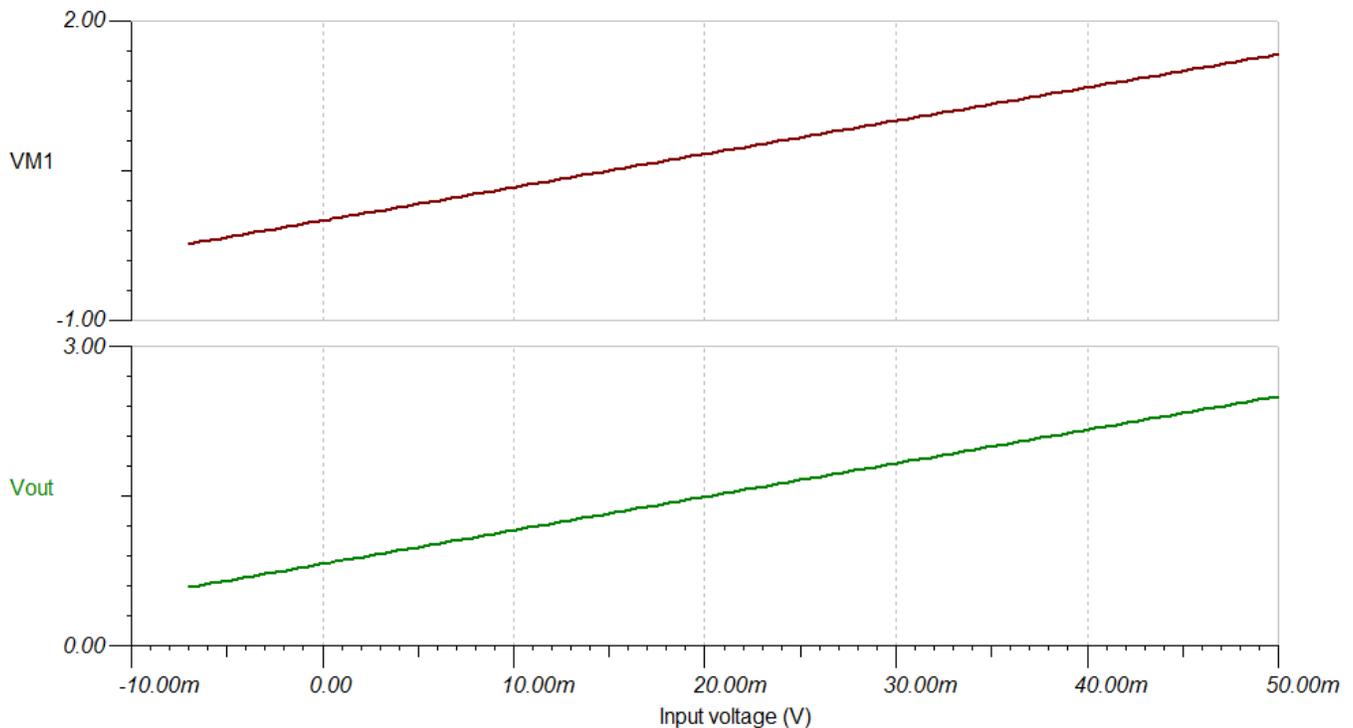
A DC transfer analysis runs on this circuit to show the output voltage change, depending on the input voltage. To achieve a good resolution, it is necessary to have a large differential voltage span on VM1. However, it is necessary to keep Vout referenced to GND within the voltage range of the ADC (0 V to 2.5 V). The simulation results in Figure 21 show a voltage for Vout from 0.58 V for −7 mV input up to 2.5 V for 50 mV. These values are within the voltage range of the ADC. The differential voltage ranges from −0.23 V to 1.67 V.

Also, an AC simulation is useful to see the low pass characteristics. To reduce influences in the 50– to 60–Hz range, the input has a low pass filter with −3 dB at 10 Hz. The results of the AC simulation can be seen in Figure 22.

Figure 22. Front End AC Simulation
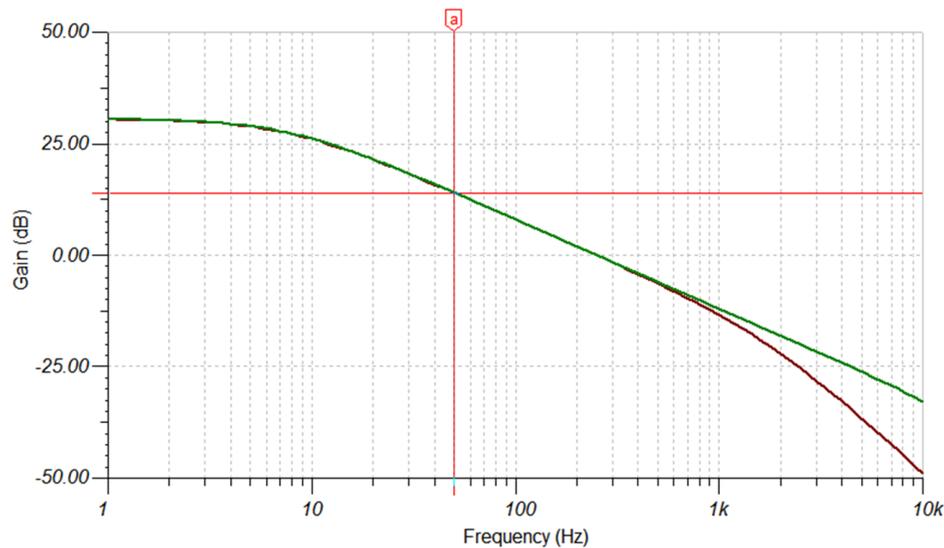
2.4.3 Cold Junction Compensation

Due to the working principle of thermocouples, the ambient temperature at the connector from the sensor to the board must be known and compensated. The thermocouple generates a voltage on a junction between two different metals. At the connector, this is the same as the voltage generated here that influences the measurement and must be compensated.

Therefore, a temperature sensor must be in place at the connector to measure its temperature. The software is then able to do the compensation.

Usually, highly accurate sensors such as the PT100 are used here. This type of sensor changes its resistance more or less linearly with temperature from 84.27 - 140.39 Ω (-40 °C - 105 °C). To measure this resistance, a constant current source is necessary to generate a voltage drop over the PT100. Using a ratio metric algorithm moves the need from an accurate current source and voltage reference to only an accurate resistor. Figure 23 shows the current flow in this example. The current is sourced from two matched current sources through the RTD, and a reference resistor is used to ground. The voltage drop of the resistor is used as reference for the ADC, and the voltage drop over the RTD is measured. The measured resistance only depends on the resistance of the reference resistor, not on any reference voltage or current source. This resistor has to be of good temperature stability and tolerance, as it influences the accuracy of the temperature measurement. This requirement makes it a rather expensive part. Also, a rather high current in the range of 100 µA to 500 µA per current source is necessary as an excitation current to receive a good reading.

Figure 23. 3-Wire RTD Measurement
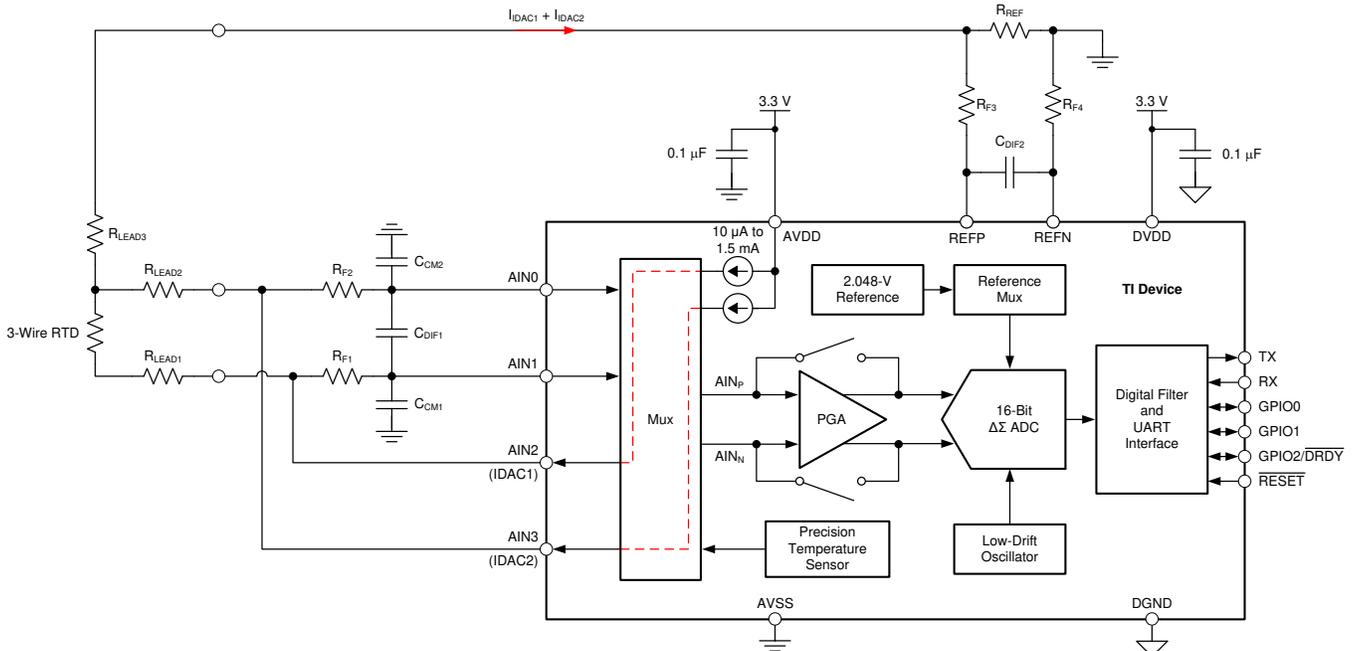
To measure the RTD, the MUX and the PGA must be configured as shown in the Table 3. This enables the current sources, set to 250 µA each, and routes them to the RTD and the reference resistor. The voltage drop over the reference resistor is selected as a reference for the ADC. This gives a ratio metric measurement for the RTD in a 3-wire configuration, canceling out the wire resistance.

The RTD resistance can then be calculated as a function of the PGA gain and the reference resistance: RTD = ADC * 3240 / 32768 / 32 * 2. This resistance can be converted to a temperature by the MCU using a look up table or an approximation function.

Table 3. Register Configuration ADS112U04 Thermocouple

Register	Configuration	Value
0x00	AINp = AIN3; AINn = AIN2; PGA = 32	0x7A
0x01	Datarate = 20 Sps; Single shot; External reference	0x02
0x02	iDAC set to 250 uA; No CRC; No data counter	0x04
0x03	iDAC connected to AIN2 and AIN3	0x70
0x04	all GPIOs as input -> not used	0x00

The RTD is placed as close as possible to the connector to the thermocouple. Figure 24 shows where the SMD thermocouple is placed.

Figure 24. RTD Placement
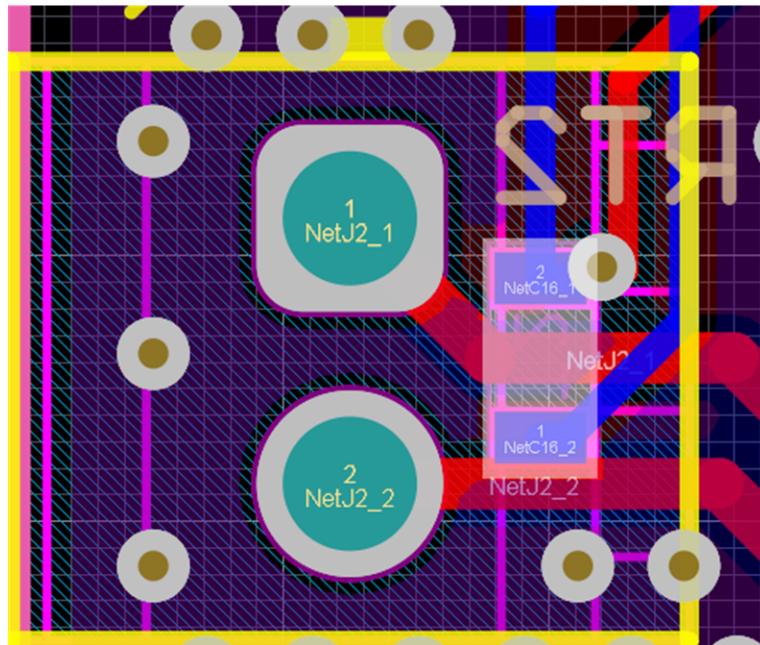
By using other types of temperature sensors, you can remove the excitation current and the reference resistor.

To compare the systems, one setup is built as reference with a cold junction compensation as described above, using an excitation current of 250 µA through the RTD and 500 µA in total through the reference resistor.

2.4.3.1 LMT70

The LMT70 is a temperature sensor with a linear output voltage in the range of 1.4 V to 0.3 V (–55 °C to 150 °C). This makes it easy to replace the RTD. The reference resistor is no longer required and the LMT70 can be directly connected to one of the inputs of the ADS112U04. The output of the sensor is mostly linear, however to get the best accuracy, use a look-up table to reduce linearity errors.

For power consumption, the LMT70 typically requires only 9.2 µA, which is less than the RTD solution.

The WLCSP package of this sensor might be a drawback in some applications, but can be beneficial in others. It can not be directly hooked to an isothermal block, but it can be placed close to one of the soldering points on the PCB. As Figure 25 shows, the sensor is placed directly next to the solder joint and the trace for the TC connection, then the sensor can measure the temperature at the connection.

Figure 25. LMT70 Placement
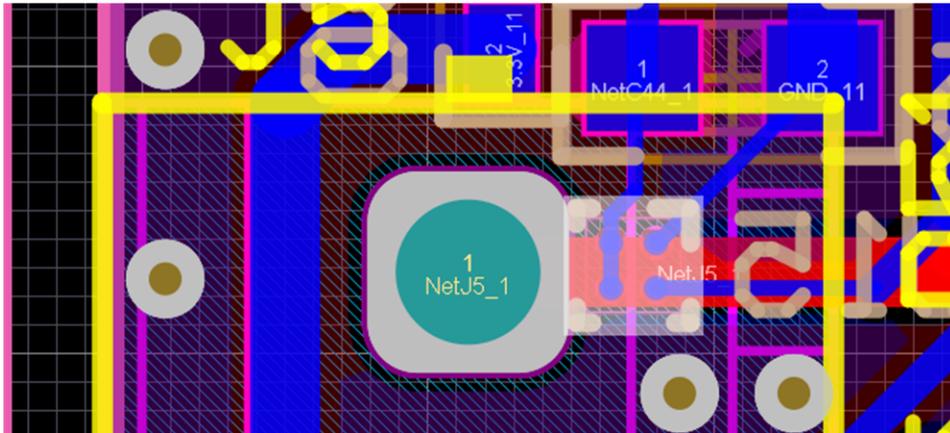
The sensor is specified to have an error of ± 0.36 °C in the range of –55 °C to 150 °C, so it can be a good replacement. See Section 3.2.1.3 for the test results.

2.4.3.2   TMP235

The TMP235 is another analog sensor with a linear output of 10 mV/°C and a range from 100 mV to 2 V. This sensor can also be directly connected to an ADC such as the ADS112U04. Because the output voltage is very linear, no look-up table is required and the voltage can easily be calculated to a temperature.

Typically, the current consumption is specified with 9 µA, less than the RTD solution, even if the lowest possible current is chosen.

The TMP235 comes in a SOT23 or SC70 package, and cannot be hooked into an isothermal block. It can be (as the LMT70) assembled close to the solder point of the connector. Figure 26 shows how this is done on the test board. Since there is no large heat gradient on the PCB, this should not cause an error, even if the heat transfer from the connector to the sensor is not the best.

The heat transfer can be improved by adding a bit of thermal conductive glue.

Figure 26. TMP235 Placement
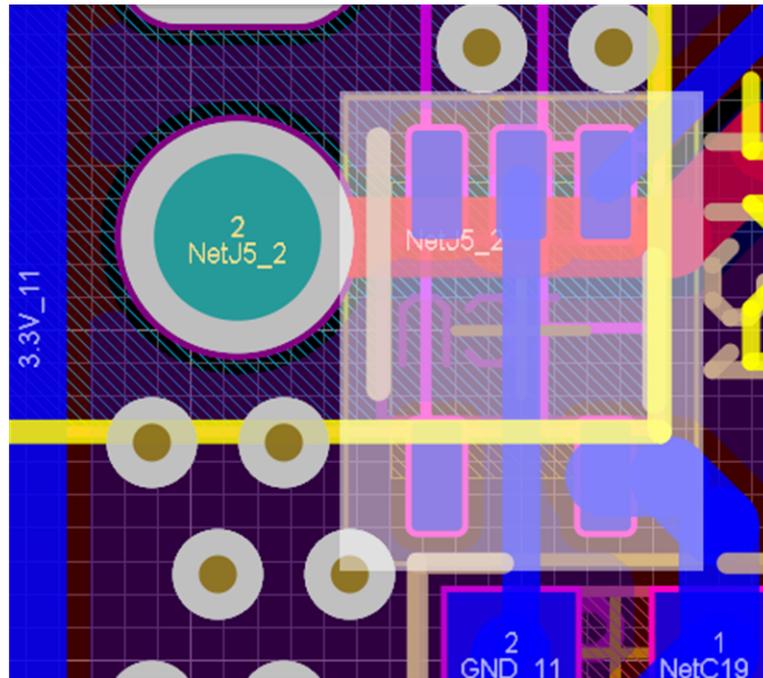
The sensor is specified to have an error of ± 0.5, see Section 3.2.1.3 for test results.

2.4.3.3 TMP117

The TMP117 is a digital temperature sensor with an I²C interface. This eliminates the need for an ADC for the cold-junction compensation. The sensor directly provides a digitized temperature with 0.0078 °C per digit. The calculation does not require too many resources on the MCU side.

The TMP117 is specified with a typical current consumption of 3.5 µA. However, I²C uses an open drain bus with the need for pull-up resistors that increase the current consumption during communication. Typically, these resistors are in the range of 1 – 10 kΩ, resulting in 0.33 – 3.3 mA pulses at 3.3-V level. This current can be reduced by choosing a higher resistance, with the drawback of a slower data rate.

The WSON package has an exposed thermal pad where the die is placed with a possible low thermal resistance, giving a good contact to a heat source. However, soldering this pad introduces mechanical stress. TI recommends not soldering the pad, and placing the part close to the heat source.
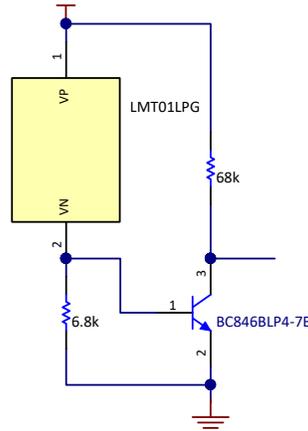
The sensor is specified to be in a ± 0.1 °C range from 25° to 50 °C and ± 0.3 °C from –55° to 150 °C. The results on how this influences the TC measurement can be found in Section 3.2.1.5

2.4.3.4 LMT01

The LMT01 is a digital temperature sensor with integrated ADC and has a resolution of approximately 0.0625 °C per digit. The output is not completely linear, so for highest accuracy, use a look-up table.

The sensor has a pulse train output by acting as a current sink. To send data, it changes its current from 34 µA to 125 µA with a frequency of 88 kHz. The number of pulses between an idle time must be counted. The interface can either be connected to an MCU by using an integrated comparator or by an external transistor and an interrupt capable input. Figure 27 shows how the LMT01 can be connected to any MCU pin.

Figure 27. LMT01 Schematic

The sensor is available in a TO92 type package that can be directly connected to an isothermal block. As this design uses a screw terminal, the sensor is placed next to the terminal.

The accuracy is specified to be in a ± 0.5 °C range, and the resulting accuracy when using it for cold-junction compensation is shown in Section 3.2.1.3.

2.4.3.5 ADS112U04 Internal Sensor

When the ADS112U04 is used as ADC for the thermocouple, it can also be used as thermal sensor. It has a linear temperature sensor that can be easily read out. The sensor has 0.03125 °C per digit resolution. However the ADS112U04 cannot be placed as close to the connector as other sensors, which can reduce the performance of the system.

2.4.3.6 Summary

Table 4 provides an overview of the different CJC solutions. The temperature range for the accuracy of –20 °C to 90 °C is used. All parameters are typical values from the data sheet.

Table 4. Overview of Different CJC Variants

| PARAMETER	RTD (PT100 Class B)	LMT70	TMP235	TMP117	LMT01
Accuracy [°C]	0.75	0.2	0.5	0.2	0.5
Current	500 uA + ADC + MCU	9.2 uA + ADC + MCU	9 uA + ADC + MCU	3.5 uA + MCU [1]	34 / 125 uA [2]
Size	1.3 mm² (RTD) + 5.1 mm² (Resistor)	0.8 mm²	2.5 mm²	4 mm² or 1.6 mm²	12.6 mm² or 4.3 mm²
Cost	$$$	$$	$	$$$	$$
Software Complexity	LUT	LUT	Linear	Linear	LUT
Hardware Complexity	ADC + careful routing	ADC	ADC	Connect directly to MCU	Additional transistor

[1] Additional current during communication depending on pull-up resistors.
[2] Low/high current during communication, additional current for signal condition might be necessary.

2.4.4 Power Supply

The design is powered through a micro-USB connector. To limit the current from the USB port powering the circuit, a TPS22946 power switch is used, as shown in the Figure 28. This switch has a selectable current limit of three steps: 30 mA, 70 mA, or 155 mA. This design is designed to draw less then 4 mA, and the current is limited to 30 mA. In the case of a short circuit or any fault, the current limit protects it from overheating. This protection can be changed in current by changing the assemble option resistors. If not used, it can be replaced by a standard PTC fuse.

Figure 28. USB Protection
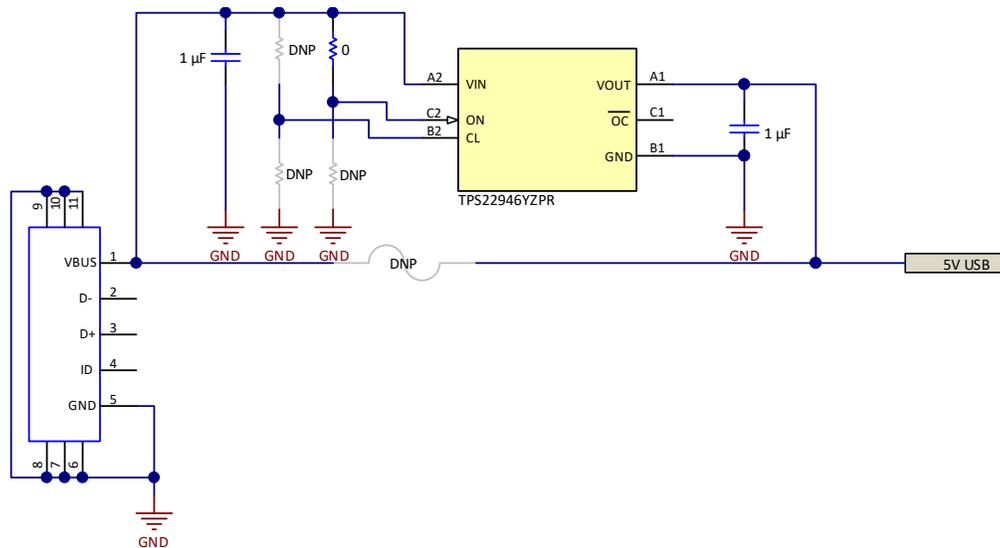
To regulate down from the 5 V from USB, a TPS72733 is used, as shown in Figure 29, for generating 3.3 V to supply the digital part and the analog circuit.

Figure 29. LDO for 3.3 V
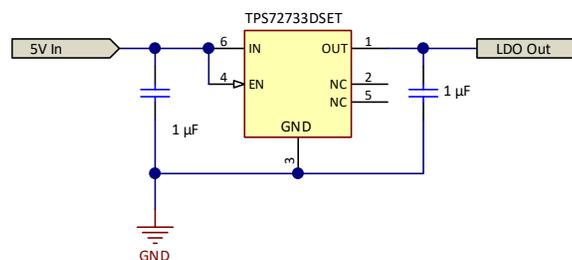
The input voltage, after the protection circuit, is routed to a connector, where the TIDA-010018 can be connected to isolate power and data. Figure 30 shows the connector on the first board with the ADS112U04. For standalone operation, the jumpers must be placed as shown in the next section.

## Figure 30. Connector for the TIDA-010018
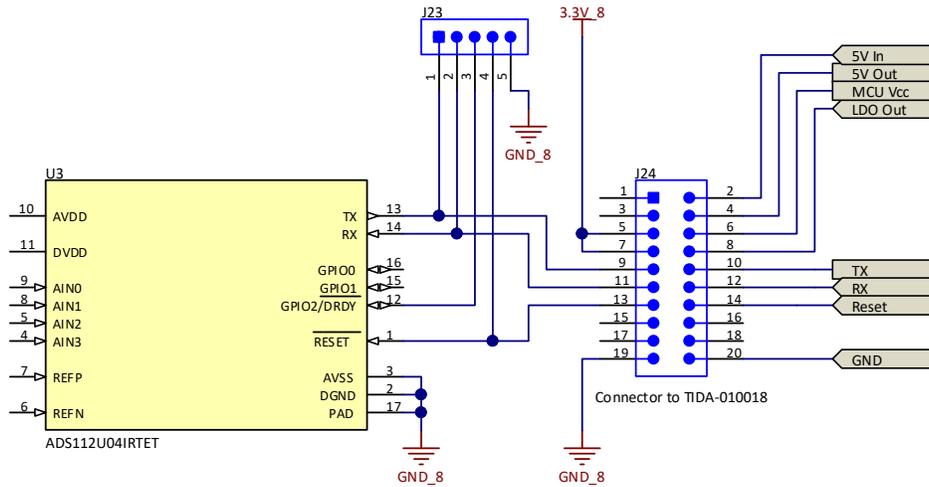
2.4.5 Digital Part

To read out the sensor data, process, then transmit it further, use a MSP43FR2355. It works in a voltage range of 1.8 V to 3.6 V in an ambient temperature range of –40 °C to 105 °C, which makes it suitable for this type of application. In this design, it reads out the different sensor data and transmits it through UART to a PC. As shown in Figure 31, the software on the MSP can sense three resistors that encode the PCB variant. A table in the software encodes which variant includes which sensor to unify the software.

The UART is isolated by a ISO7721 offering a level translation on one side, on the other side it eliminates interference or ground loops coming from the PC.

Figure 31. MSP430 Variant Encoding
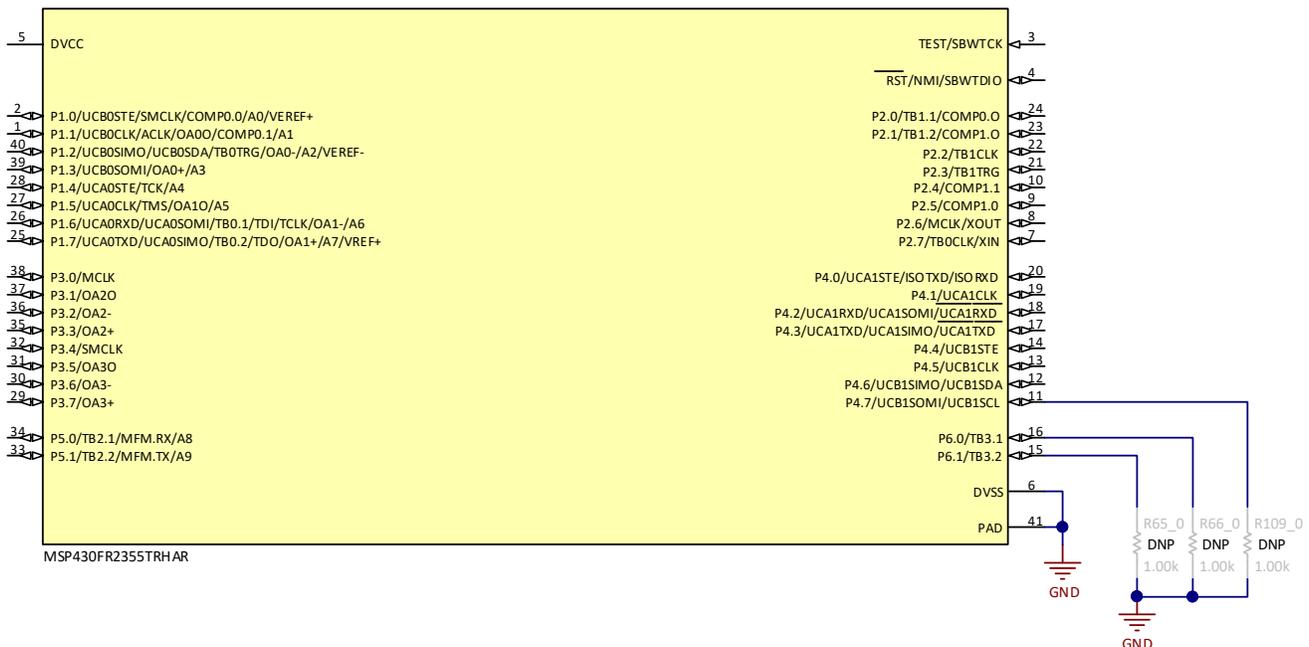
As shown in Figure 30, all interfaces to the sensors and ADCs are brought out to a standard 2.54-mm header for debug and development access. This can either be used to monitor and debug the communication, or to attach an external microcontroller without modification of the board.
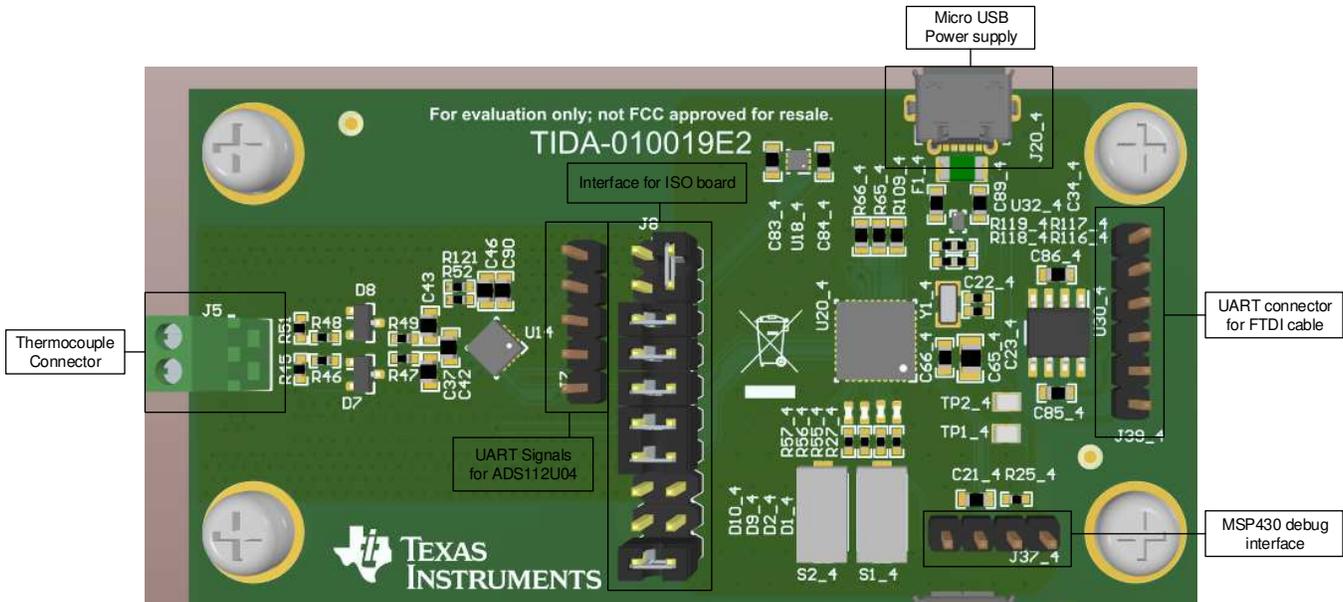
3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

To test that the boards can stand alone, apply some jumpers to route the voltage and signals accordingly. See Figure 32 for the connectors, and place the jumpers as shown.
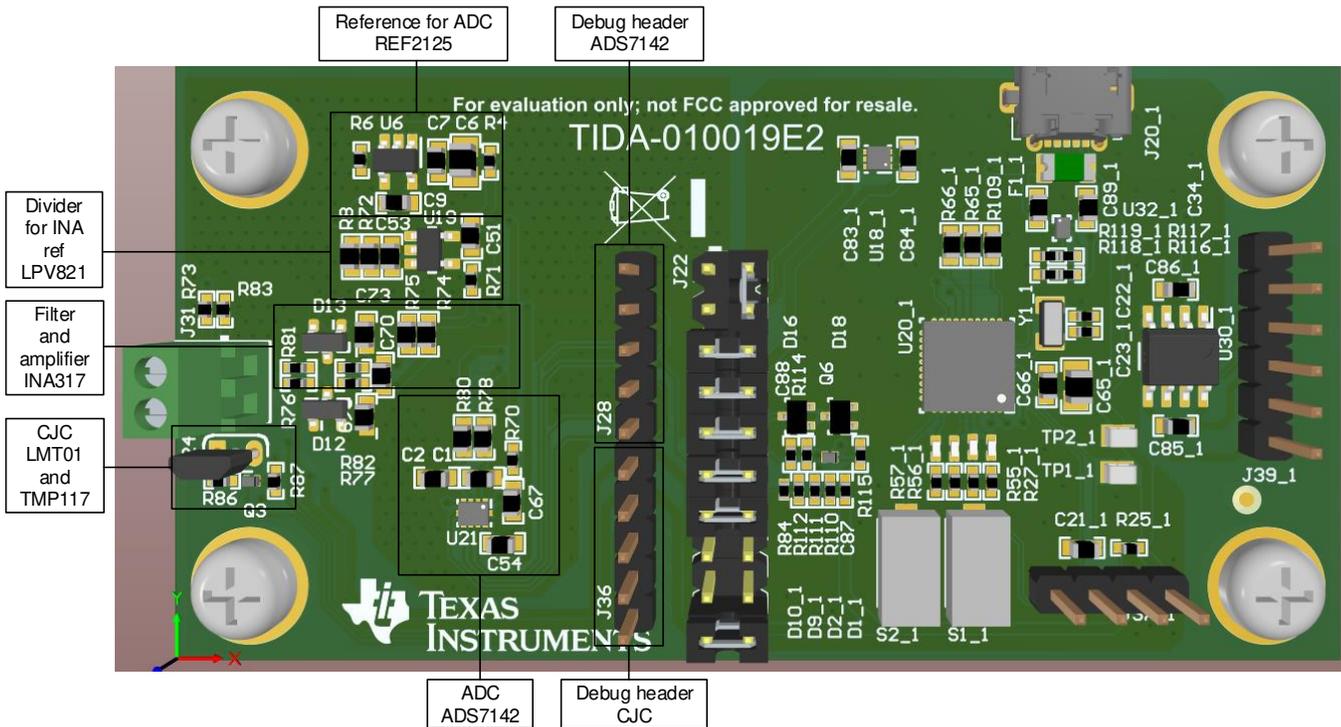
Figure 32. Board Jumpers and Connectors

A thermocouple (or voltage source simulating TC) must be connected to the screw terminal on the left. Power must be supplied through micro USB from a PC or 5-V power supply through the connector as shown. The connector on the right is used to connect to a PC through an FTDI USB cable. Either a 3.3-V or 5-V cable can be used here. To reprogram the MSP430FR2355, the debug connector brings out the necessary signals. For analyzing or debugging the UART communication to the ADS112U04, use the debug header.

The connectors are the same for all three boards.

Figure 33 shows the placement of the functional blocks on the board. The digital blocks are the same for all boards, whereas the analog part on the left is different. Two inputs of the ADS112U04 are used for the thermocouple input, and the remaining two are used for the two analog sensors. Analog filtering is done for the thermocouple and can be added for the other sensors.

Figure 33. Analog Sensors Board Functional Blocks

Shown in the example is the variant with the analog temperature sensors. As seen in Figure 34, sensors are placed as close as possible to the pins of the connector. U15 (LMT70), in particular, can be moved close to the copper of the connector.

Figure 34. Analog Sensors Placement

The board with the RTD for cold junction compensating looks similar, but using the RTD instead of the analog sensors.

The board using TMP117 and LMT01 for CJC uses an instrumentation amplifier and a SAR ADC to digitize the thermocouple voltage, as described in Section 2.4.2. Figure 35 shows the placement of the different subcircuits.

Figure 35. ADS7142 Functional Blocks

The test setup for specific tests is described in Section 3.2.

3.1.2 Software

To get a temperature reading from a thermocouple, it is necessary to first measure the voltage and the ambient temperature. The actual temperature of the thermocouple can then be calculated from these values. This is usually done by an MCU.

In this design, the software detects on which board it is running by a set of resistors encoding the variant. A look-up table stores which sensors are present, and the corresponding handling functions can be called. Two output formats are implemented to simplify testing.

For automated testing (for example, in the thermal chamber), the software can be switched to use a simple format outputting the raw values from the ADC and the CJCs. PC software can then perform the necessary calculations with high precise look-up tables and double precision. A PC generates user-readable output, in this scenario.

In a standalone operation, the software on the MSP430FR2355 reads out the ADC and calculates the voltage of the thermocouple. Also, the CJC sensor is read out and converted to a temperature using a formula or look-up table, depending on the sensor. This temperature can be calculated to a corresponding thermo voltage used for compensating the voltage from the thermocouple. This resulting voltage is converted to a temperature using a look up table and corresponding to the thermocouple temperature. All values are shown in a user-friendly screen, as shown in Figure 36.

Figure 36. User Software Screen Image

```
Config 4
ADC     ADS112U04    Raw     5        uV      9        dTemp   23
CJC     LMT70        Raw     15460    aTemp   2555     uV      1022    Temp    2575
        TMP235       Raw     12000    aTemp   2500     uV      1000    Temp    2521
        ADS112U04    Raw     3250     aTemp   2539     uV      1015    Temp    2558
```

3.2 Testing and Results

3.2.1   Test Results

3.2.1.1   *Cold Junction Compensation With ADS112U04 and RTD*

The implementation with RTD as cold junction compensation is basically the reference implementation that other types of cold junction compensations are compared to.

For this test, the board is placed in a thermal chamber, and the ambient temperature is varied from –35 to 85 °C. The temperature reading from the CJC sensor is compared to a reference. Included in this plot are all errors, and no gain calibration or offset calibration is done. Also, the thermal chamber might add some errors. For reference, an additional RTD in a 4-wire configuration connected to a Keysight 34980a is used.

Figure 37. Temp Error CJC
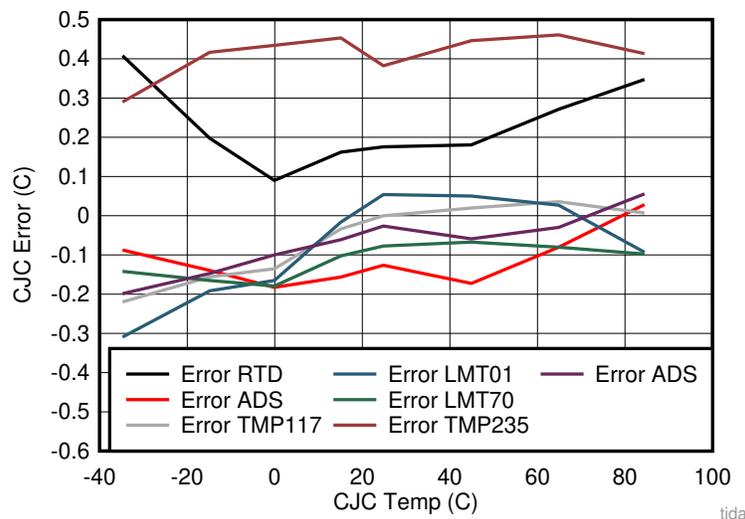
Figure 37 shows the offset of the different sensors from the reference sensor. All boards are placed in the chamber at the same time. After reaching one temperature point, the setup remains for 20 minutes at the same time to settle before a measurement starts. The offset and error can be determined by fitting a trend line to the error plot, the offset can then be seen on the equation. The error of the reading is the maximum deviation of the trend line from the sensor value.

Compared to the reference, the RTD has an offset error of approximately 0.2 °C, that might be caused by the tolerance of the reference resistor. The reading then is in a range of ± 0.2 °C.

The internal sensor of the ADS112U04 also has an offset of approximately 0.1 °C and a reading approximately ± 0.1 °C off.

TMP117 also has an offset of 0.1 °C and an error of ± 0.1 °C.

The LMT01 is basically the same, with an offset of 0.1 °C and an error slightly above ± 0.1 °C.

LMT70 also has an offset of 0.1 °C and an error of 0.05 °C.

For the TMP235, the offset error is almost 0.4 °C and the error of the reading is 0.1 °C.

3.2.1.2   *ADS7142 and INA317 Performance*

For testing the analog performance of the input stage with the INA317 and ADS7142, the input is connected to an SMU providing a voltage from –5 mV to 50 mV.

In a first test, the linearity, slope, and offset without calibration is observed. A small offset and slope failure can be expected, caused by offset voltages of the ADC and amplifier and the inaccuracy of the resistors. This error is constant, and can be calibrated by determining the slope error and offset voltage.

The error of the circuit is tested by applying a voltage at the TC input and calculating the theoretical voltage from the raw value. The formula used here is U = ADC*2500 / 65535 / 33.36, where 65535 is the maximum value of the ADC and 33.36 the gain of the amplifier. In Figure 38, the results can be seen and the curve can be fitted closely with a linear equation. This shows the linearity failure (caused by the inaccuracy of R79), the offset caused by the ADC, and the offset voltage of the amplifier.

TI recommends applying the determined equation for calibration to receive a close reading The resulting error using a slope and offset calibration can be seen in Figure 38.

Figure 38. Linearity ADS7142
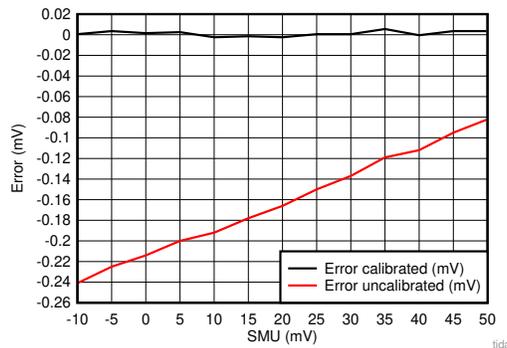
A second important parameter is the effective resolution the ADC this front end can achieve. Therefore, the input voltage is set to a value resulting in an ADC value half of the full-scale range (in this example, 32768 digits). Because the ADC is operated in a pseudo-differential mode, one channel is measuring the reference voltage shifting up the instrumentation amplifier, and the other is at the output.

The reference voltage is at around 0.817 V, resulting in 21418 digits. Figure 39 displays the resulting histogram of the ADC input data.

Figure 39. Histogram of REF ADC Channel
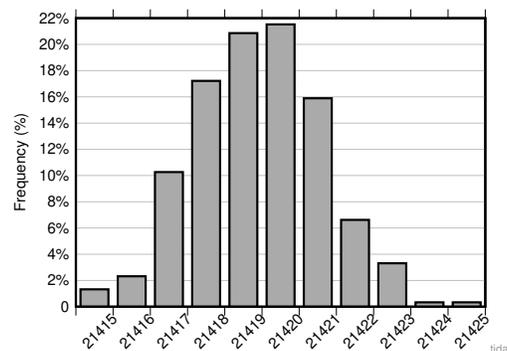
The same test is repeated with the other channel of the ADC. For this test, the input voltage is set to a level resulting in a voltage about half of the full scale voltage. Figure 40 shows the histogram of this voltage. The resulting noise is larger than the reference channel, as it includes an additional amplifier, an external voltage source, and the cabling. Depending on the length and the placement of the cables, the noise changes as it collects electromagnetic noise.

Figure 40. Histogram of INA ADC Channel
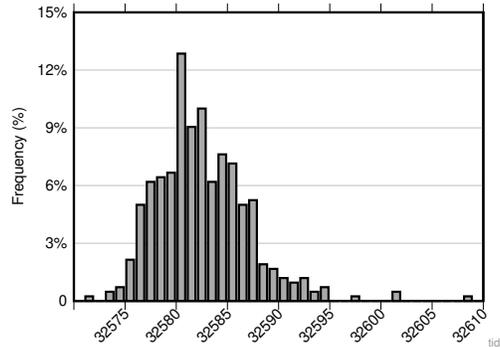
These channels mentioned previously are combined in software, giving a third histogram. Figure 41 shows the histogram of the overall system. These results show an effective number of bits of 13.4. This can be improved by adding a software filter, such as a moving average.

Figure 41. Histogram of TC Input
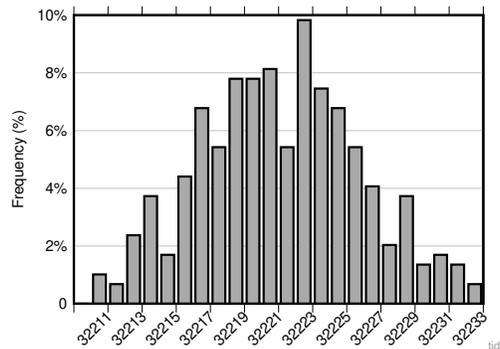
The current consumption of the front end, consisting of reference voltage, instrumentation amplifier, and ADC, is measured at a supply voltage of 3.3 V. The results can be seen in Table 5.

Table 5. Current Consumption of Front End

INPUT VOLTAGE [mV]	CURRENT CONSUMPTION [uA]
-5	121
0	121
10	122
20	126
30	131
40	136
50	130

3.2.1.3 Current ADS112U04

To get a realistic overview of the current consumption, it is measured in different configurations. Figure 42 shows the current consumption of the ADS112U04 with an RTD (PT100) with 250 µA excitation current. The scope plot shows clearly when both current sources are switched on and when sampling starts. Also switching to the internal temperature sensor, and switching to the thermocouple input, and using the PGA can be seen in the current consumption.

The IDACs configured to 250 µA results in circa 900 µA, during sampling this increases to 1.4 mA and takes about 65 ms.

Sampling the internal temperature sensor results in 600 µA for 50 ms

For the thermocouple input about 650 µA are necessary for 50 ms.

Figure 42. Current Profile RTD no Offset Compensation
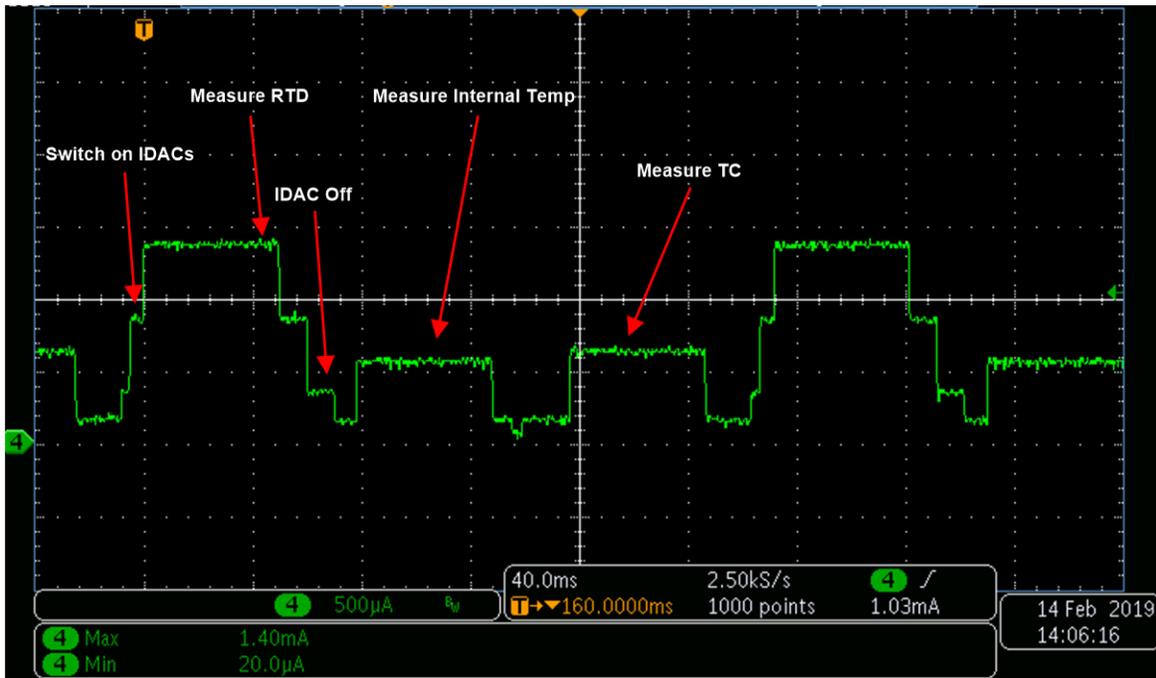
If the offset voltage of the ADS112U04 is not determined initially when the systems starts, but before every measurement, the total measurement takes twice as long. Figure 43 shows the current profile in this example. Before every measurement, the internal MUX is configured to AVdd/2 on both inputs and should give a zero reading.

Figure 43. Current Profile RTD with Offset Compensation
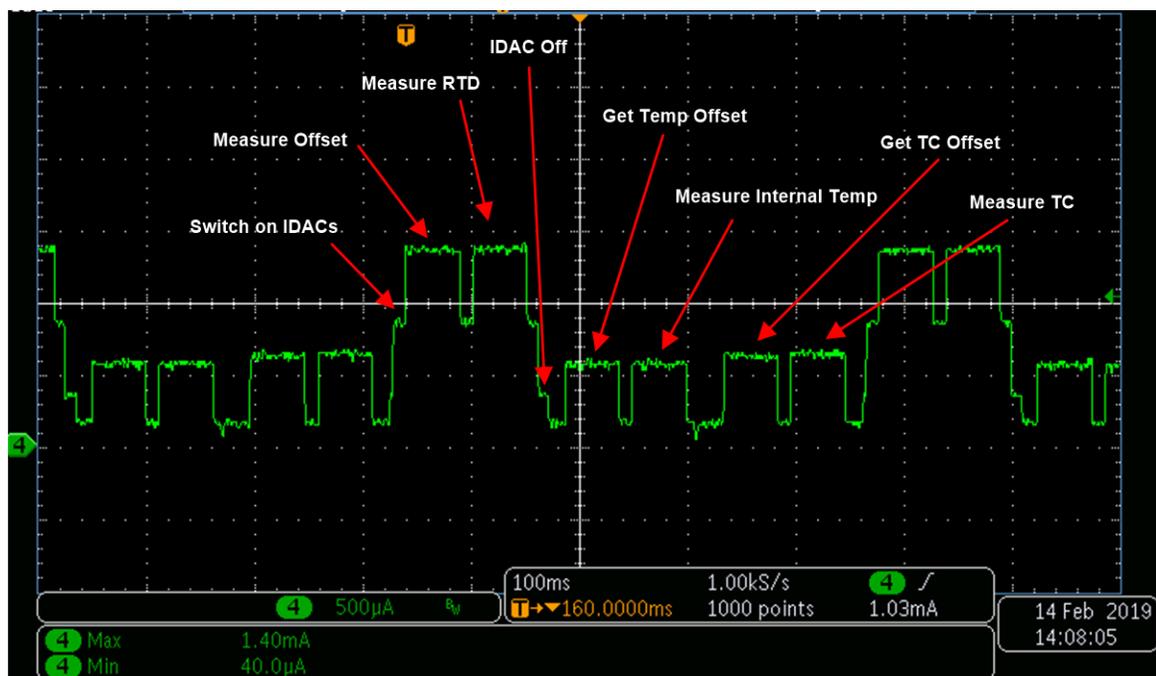
In Figure 44, the current profile of ADS112U04 is shown in connection of TMP235 and LMT70. The current of the two analog temperature sensors is included. Sampling takes about 50 ms per sensor, including the internal one. The current for TMP235 and LMT70 is approximately 500 µA.

Figure 44. Current Profile Analog Sensors no Offset Compensation
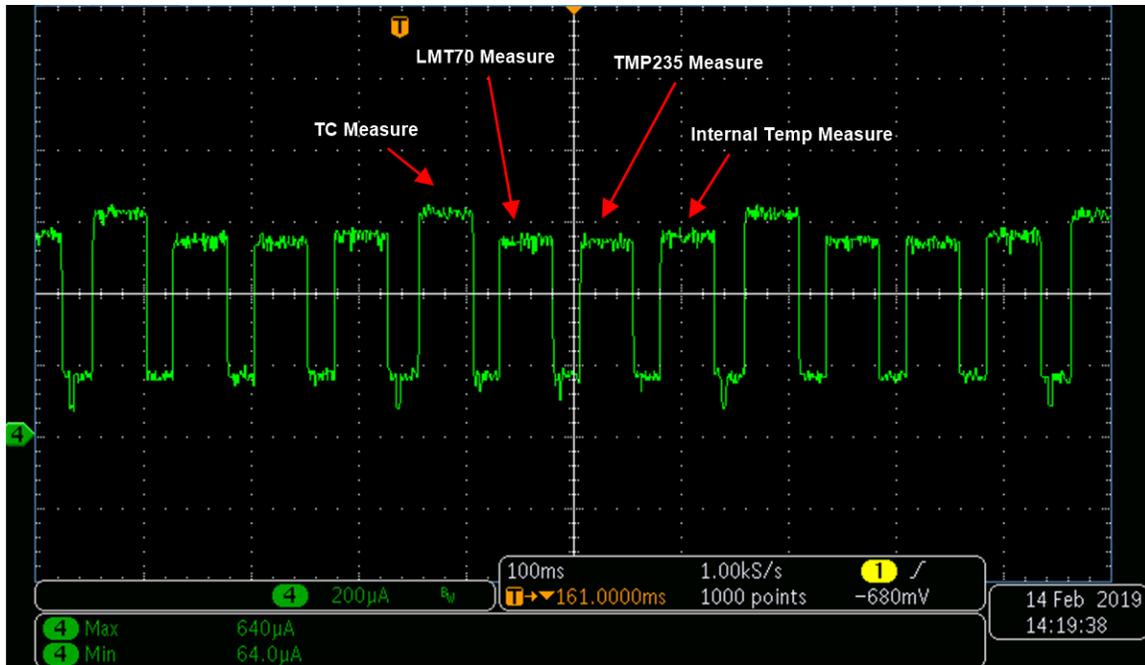
To cancel the offset, before every measurement, the offset can be determined. Resulting in a longer time at higher current levels. See Figure 45 for the profile.

Figure 45. Current Profile Analog Sensors with Offset Compensation
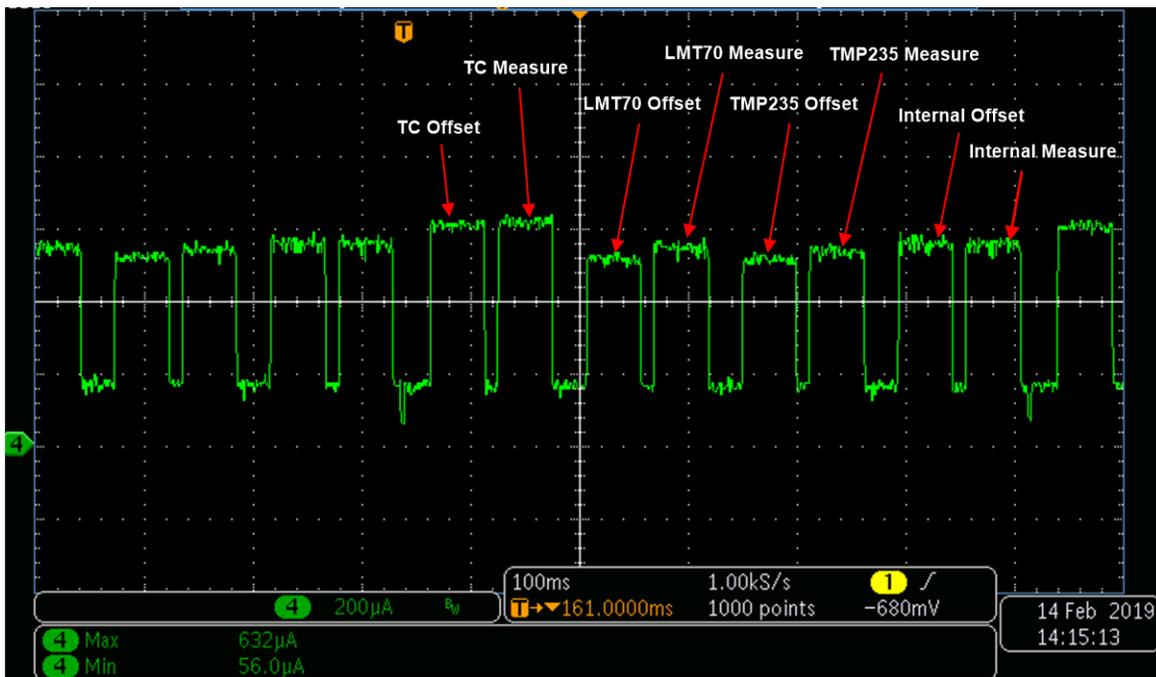
3.2.1.4   *Histogram ADS112U04*

The deviation of the input reading of the ADS112U04 is shown in Figure 46.

Figure 46. Histogram of ADS112U04 Input
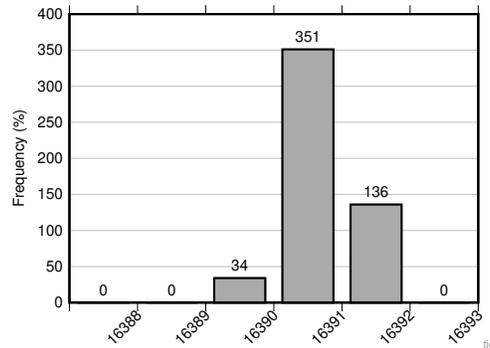
3.2.1.5   *Current Consumption ADS7142, TMP117, and LMT01*

Figure 47 gives an overview of the total current consumption of the front end including amplifier, reference, ADC, and temperature sensors for cold junction compensation. It shows clearly when the TMP117 samples the temperature (150 µA above average), also the I^{2}C communication and the bursts of the LMT01 are visible.

Figure 47. Current Profile ADS7142 with TMP117 and LMT01
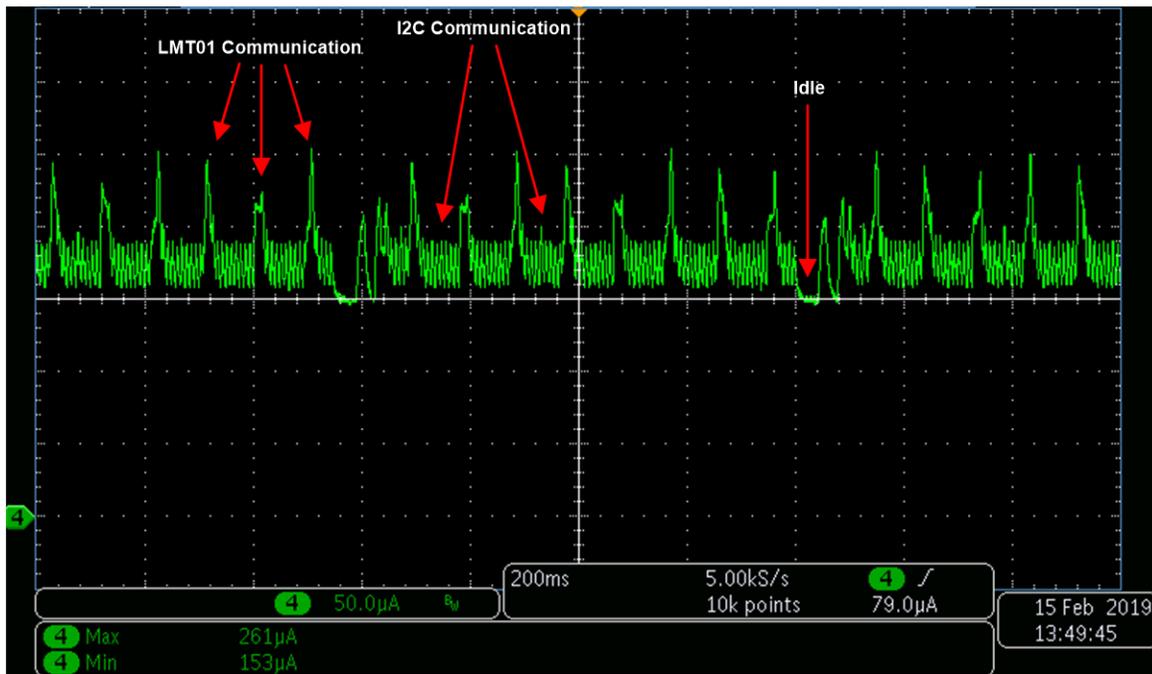
Figure 48 shows the current consumption of the analog front end including the INA317, the REF2125 and the ADS7142, additionally, the pull resistors for the I^{2}C bus are included in this measurement. The current consumption is at approximately 110 µA with an additional ripple during communication resulting in a peak current of about 140 µA.

Figure 48. Current Profile ADS7142 Reference and Amplifier
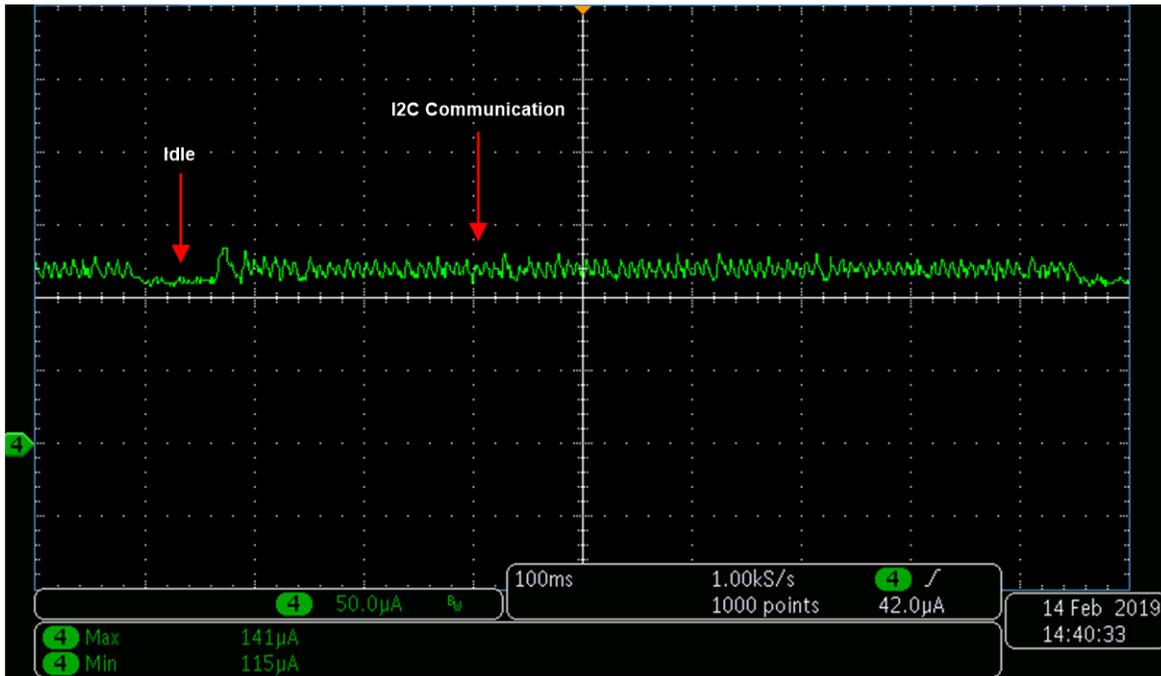
In Figure 49, the current consumption of the TMP117 and the analog part is shown. This combination results in an idle current of approximately 125 µA and peaks up to 300 µA.

Figure 49. Current Profile ADS7142 with TMP117
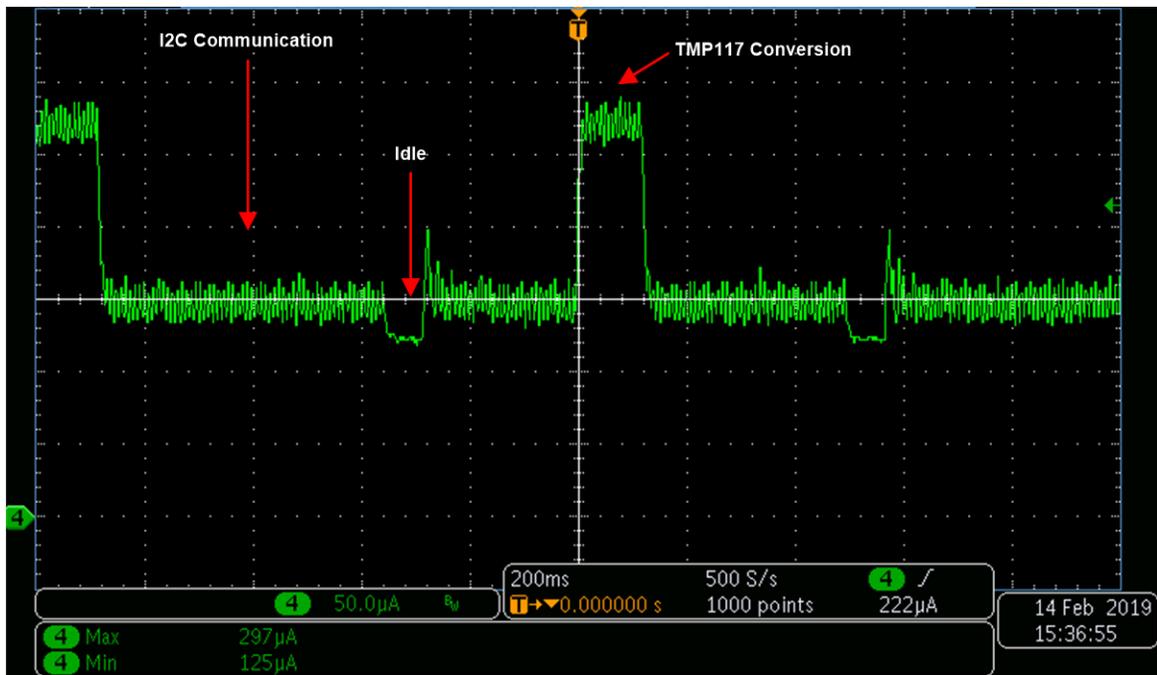
As shown in Figure 50 with the LMT01 and ADS7142 the idle current is at 150 µA with peaks up to 250 µA during communication of the LMT01. Also, the I²C communication to the ADS7142 can be seen.

Figure 50. Current Profile ADS7142 with LMT01
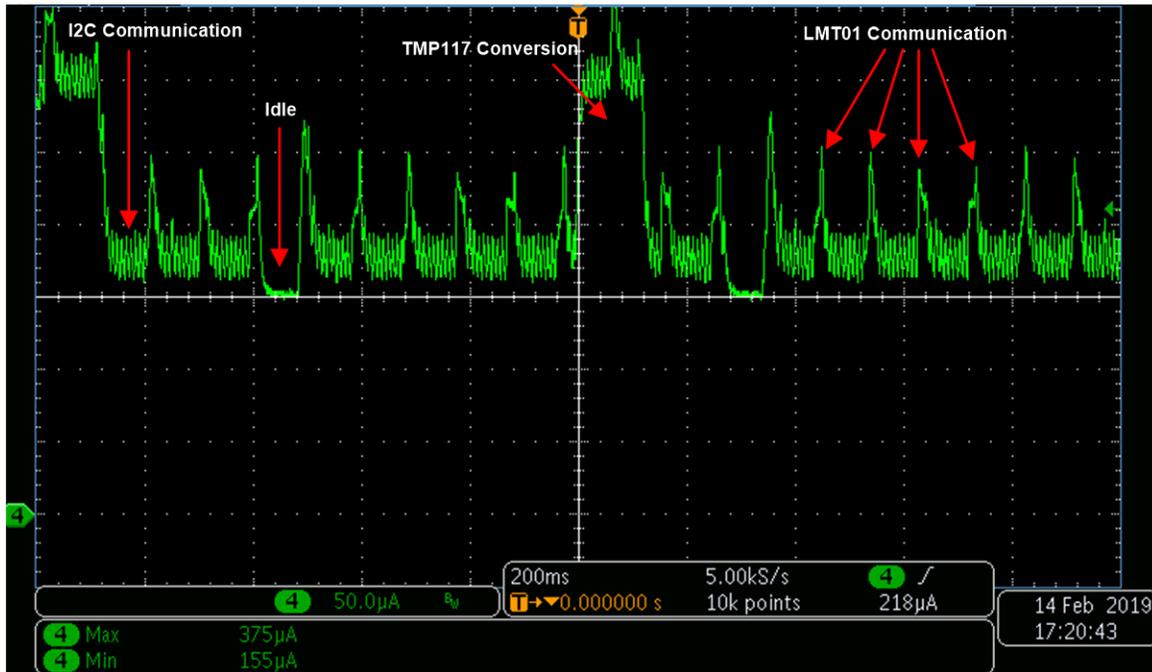
Figure 51 shows the current consumption of the LMT01. The current consumption without communication is well below 50 µA with the communication on top it peaks at 150 µA.

Figure 51. Current Profile LMT01
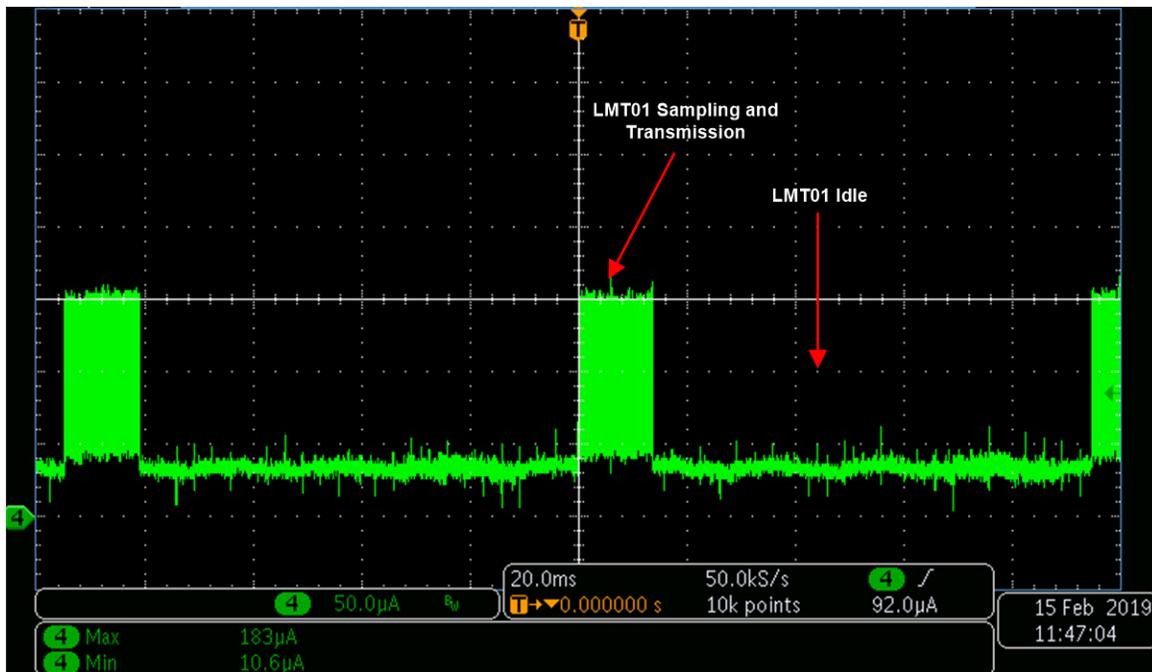
As shown in Figure 52, TMP117 has an idle current of about 25 µA with a peak of 165 µA during conversation for about 123 ms every second.

Figure 52. Current Profile TMP117

RTD Replacement for Cold Junction Compensation Reference Design in a Temperature Sensor

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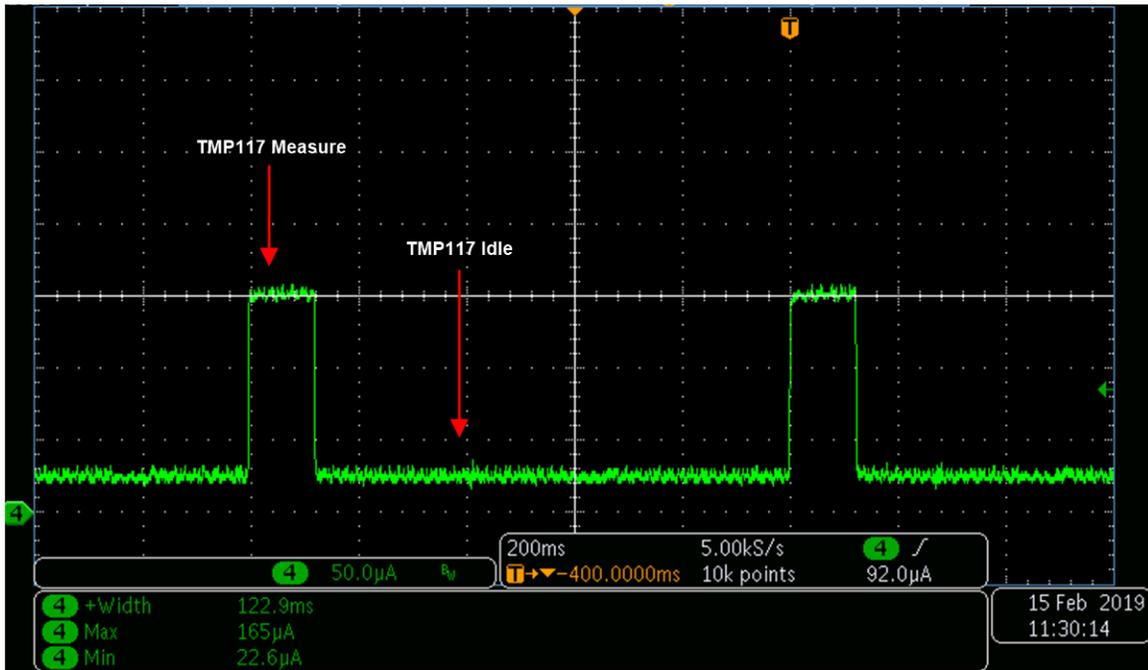
4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-10019.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-10019.

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-10019.

4.4 Altium Project

To download the Altium Designer® project files, see the design files at TIDA-10019.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-10019.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-10019.

5 Software Files

To download the software files, see the design files at TIDA-10019.

6 Related Documentation

1. Texas Instruments, *RTD class-AA replacement with high-accuracy digital temperature sensors in field transmitters application report*
2. Texas Instruments, *ADS112U04 16-bit, 4-channel, 2-kSPS, delta-sigma ADC with UART interface data sheet*
3. Texas Instruments, *ADS7142 nanopower,dual-channel, programmable sensor monitor data sheet*
4. Texas Instruments, *TMP117x high-accuracy, low-power, digital temperature sensor with SMBus™- and I2C-compatible interface data sheet*
5. Texas Instruments, *LMT70, LMT70A ±0.05°C precision analog temperature sensor, RTD and precision NTC thermistor IC data sheet*
6. Texas Instruments, *TMP23x low-power, high-accuracy analog output temperature sensors data sheet*
7. Texas Instruments, *LMT01 0.5°C accurate 2-pin digital output temperature sensor with pulse count interface data sheet*

6.1 Trademarks

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7 About the Author

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Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (March 2019) to A Revision	Page
• Changed block diagram	1

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