*设计指南：**TIDA-010002***
*将铂 **RTD** 传感器替换为数字温度传感器参考设计*

说明

此*热量冷量计*差温测量 (DTM) 子系统参考设计提供了薄膜铂电阻式温度检测器 (RTD) 传感器的完全数字化替代产品。高精度温度传感器 (PTS) 在无需校准的情况下可实现 A 类 RTD 传感器精度（温度范围为 –55°C 至 125°C），采用单点校准可实现 AA 类精度。数字 RTD 方法通过使用集成式 EEPROM 存储器来存储用户定义的参数，从而简化了制造工艺，并且无需创建和维护随附文档。采用数字 RTD 方法，无需像传统 DTM 系统那样对模数转换器执行偏移和增益校准步骤，因而简化了模拟信号处理。

印刷电路板 (PCB) 上的静电放电 (ESD) 保护器件可防御高达 30kV 的接触或空气 ESD 冲击。小型 PCB 适合外径为 5.2mm 的金属护套（广泛用于标准 PT100/500/1000 传感器）。

此数字 RTD 子系统与 MSP430™和 SimpleLink™微控制器器件系列配合使用，采用四线数字接口。

资源

TIDA-010002	设计文件夹
TMP116	产品文件夹
ESD351	产品文件夹

TI E2E™ Community

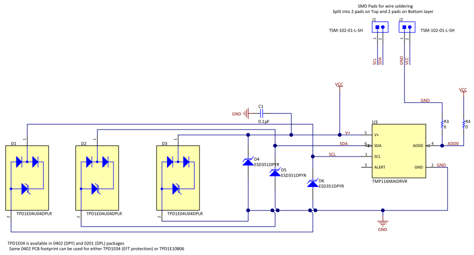
咨询我们的 E2E™ 专家 cc1310

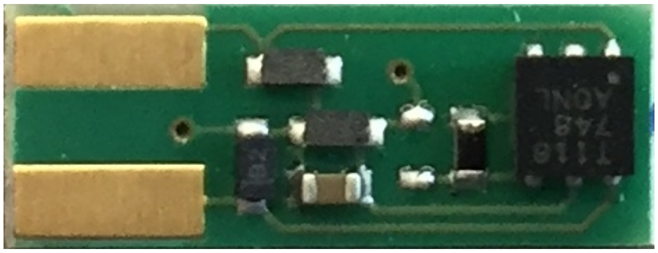
特性

- 完全数字化高精度温度传感器用作铂电阻式温度检测器的替代产品；适合热量计中使用的标准 5.2mm 护套
- 消除了二至四线 RTD 配置中所用的高精度参考电阻、RC 匹配滤波器和阻抗控制信号线迹
- 无需校准即可满足 IEC/EN 60751-2008 A 类精度要求（-55 至 125°C）；采用单点校准即可满足 AA 类精度要求
- 连接主机微控制器的标准 I2C 接口（四线数字接口，带 I2C 总线 + VDD + GND）
- 符合 IEC61000-4-2 4 级静电放电 (ESD) 保护要求
- 此子系统经过测试，所含的固件可与 MSP430FR6047 超声波水流量计套件 (EVM430-FR6047) 连接

应用

- 使用 PT100、PT500 或 PT1000 传感器（–55°C 至 125°C）的热量冷量计
- 使用 PT100、PT500 或 PT1000 传感器（–55°C 至 125°C）的热量计算器
- 各种工业应用（–55°C 至 125°C）中 A 类和 AA 类温度计 (RTD) 的替代产品
- 带有四线接口（I2C 总线、VDD 和 GND）的数字 RTD (DRTD)





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TIDUEA0 — http://www-s.ti.com/sc/techlit/TIDUEA0

1 System Description

Heat Meters are commonly used for billing heat energy for residential users in multi-dwelling units across many countries, while *Cooling Meters* are often found in commercial, storage, or logistic buildings and industrial environments. *Heat Meters* and *Cooling Meters* are both thermal energy meters, as defined in Annex VI of the Measuring Instruments Directive (MID) 2014/32/EU[*] of the European Parliament and of the Council of 26 February 2014. The MID document is the harmonization of the laws of the member states related to creating a common market for measuring instruments across all countries of the EU. Cooling Meters are not part of the MID and are usually regulated nationally.

Thermal energy meters are basically regular flow meters, for example water meters, extended with a precise differential temperature measurement (DTM) subsystem to capture the temperature difference between the inlet and the outlet flow. If the medium temperature flow of the inlet is lower than the temperature of the outlet, then heat is being dissipated, otherwise heat gets absorbed, which means this is a cooling system.

Heat Meters and Cooling Meters are therefore very similar. However, in order to be able to use both types for billing, a type examination certificate is required in each case. For a type examination certificate the requirements of EN 1434 must be fulfilled. Texas Instruments has a close cooperation with JUMO GmbH & Co. KG to fulfil these requirements and create a type examination certificate.

1.1 Key System Specifications

The IEC/EN60751:2008 standard defines four thermometer classes: these are named Class C, B, A, and AA, where C has the lowest and AA the highest accuracy. The lower the accuracy class is, the larger the defined temperature range will be and there are two types of thermometers defined: thin-film or wire-wound. A Class AA thin-film thermometer covers the range of 0°C to 150°C, and a thin-film Class C thermometer has a much wider range of –50°C to 600°C.

The TIDA-010002 reference design demonstrates the excellent temperature measurement accuracy of the TMP116 precision digital sensors, matching the accuracy of the highest Class AA thin-film RTD sensors in the temperature range of –55°C to 125°C.

表 **1. Key System Specifications**

PARAMETER	SPECIFICATIONS	DETAILS
Input power source	Provided by the host MCU or host motherboard, fixed voltage level or thru switched GPIO	表 2
Supply voltage	1.9 V to 5.5 V (minimum 2.05 V when connected to EVM430FR6047, which is powered by an external power supply)	节 3.2.4
Digital RTD sensor configuration	4-wire digital interface (SDA, SCL, VDD and GND)	节 2.4.2
Average active state current consumption	Depends on active state duration	节 2.3.1
Active state duration	Configurable thru CONV[2:0] and AVG[1:0] bits in CONFIG register of the TMP116	节 2.3.1
Average standby-state current consumption	3.5-µA, 1-Hz conversion cycle	节 2.3.1
Standby-state duration	Approximately 876 ms (if 8 averages in 1 s conversion cycle)	节 2.3.1
Average shutdown-state current consumption	250 nA	节 2.3.1
Measurements per minute	60 or less, user configurable per SW	节 3.1.2
Operating temperature	–55°C to 125°C	节 2.3.1
ESD 61000-4-2	±30 kV contact and air discharge	节 3.2.5
Form factor	4 mm × 11 mm (4 solder pads for wire attachment)	4.5 节

2 System Overview

Heat Meters are typically powered by one Lithium primary battery cell and must operate for at least 6 years or longer, depending on the ambient temperature conditions and the number of wireless communication packets transmitted during a specific time period. Therefore, a key product design consideration is the lowest possible power consumption.

Heat and *Cooling Meters* use a DTM subsystem to measure the temperature every few seconds (or less frequently) of two flows of an opposite direction, which allows to power off the DTM circuitry for most of the measurement cycle. Besides the highly-accurate temperature measurement, the energy consumption of these meters is minimized by the ability to quickly wake from power-down mode, measure the temperature of two RTDs and return to power-down mode as quickly as possible.

The TMP116 device features a very short power-up or reset period of only 1.5 ms typical, a conversion measurement cycle of 15.5 ms, a highly-accurate 0.0078125ºC temperature resolution, and a Fast-Mode (400 kHz) I2C-bus communications interface. All of these enable the power on-off cycling of the TIDA-010002 between measurement cycles.

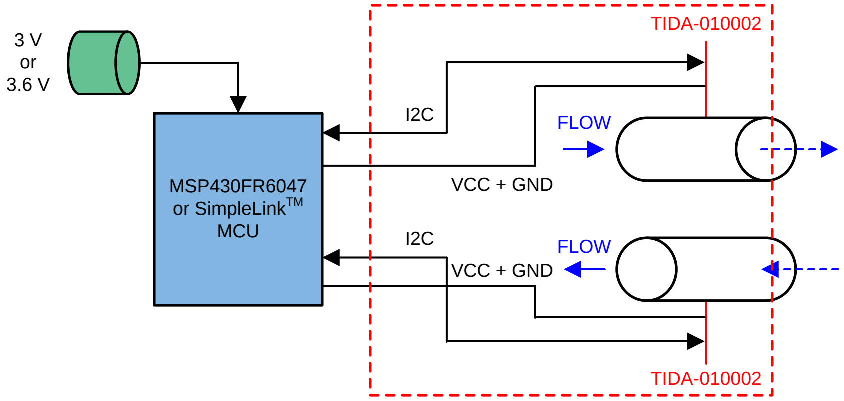
This Digital RTD solution saves processing time on the host MCU, as the linearization of the measurement result and conversion to a temperature value is done inside the TMP116 device.

2.1 Block Diagram

Heat and *Cooling Meters* are becoming more and more popular in EMEA, Russia, and China markets, as the requirements for billing thermal energy (heat and cold) are steadily increasing. As the measurement cycle of these devices is configurable and is typically less frequent than once in a few seconds, the complete DTM subsystem is powered-off between the measurements. Such an approach is highly beneficial not only in all battery-powered products but also for any application with limited available power, such as M-Bus wired or 4- to 20-mA industrial sensors.

The TIDA-010002 can be placed into the standard 5.2-mm diameter metal sheath for RTDs as used in *Heat Meters*, and assembled with a 4-wire cable as a DRTD sensor. The DRTD is then immersed into the inlet and outlet flow, as shown in red in 图 1.

图 1. TIDA-010002 Block Diagram



2.2 Design Considerations

Typical thermal energy meters use a pair of PT100, PT500, or PT1000 sensors, which are connected to a precision delta-sigma device, such as TI's ADS1220 family, or to an MCU or an analog front end (AFE) device, utilizing the ADC slope conversion approach based on a precision comparator and a digital timer. In the EU countries, the EN1434(2) specification series define the requirements for these meters.

The *High Precision Temperature Measurement for Heat and Cold Meters Reference Design* (TIDA-01526) implements a differential temperature measurement (DTM) subsystem using a 24-bit, low-power, delta-sigma ADC such as the ADS122U04 or ADS122C04 devices (but also applies to the ADS1220 device with an SPI interface). The TIDA-01526 is a low-cost, high-precision DTM subsystem, which can be combined with TI's ultra-sonic or rotation detection flow measurement subsystems, based on the MSP430FR6047 or MSP430FR6989, or TI's CC13xx and CC26xx wireless MCUs.

The TIDA-010002 reference design shows an alternative DTM system solution to TIDA-01526 by having the complete signal chain of a delta-sigma device together with the external RTD sensor integrated into a single active precision temperature semiconductor component, the TMP116 device.

The newly-introduced digital RTD approach in the TIDA-010002 represents an alternative to the traditional thin-film RTD sensors and brings multiple advantages, such as unique calibration parameters being programmed inside each DRTD and available to the host MCU for read out at any time.

Because of the better linearity compared to the Platinum RTD sensors, a reduced effort for the calibration and pairing process can be expected.

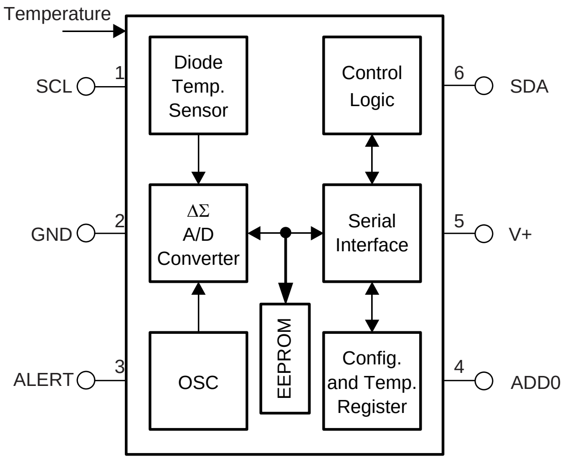
2.3 Highlighted Products

2.3.1 TMP116

The TMP116 (TMP116, TMP116N) device is a family of low-power, high-precision temperature sensors with integrated EEPROM memory. The TMP116 device provides a 16-bit temperature result with a resolution of 0.0078125°C and an accuracy of up to ±0.2°C with no calibration. The TMP116 is I2C- and SMBus-interface compatible, has programmable alert functionality, and can support up to four devices on a single bus.

The TMP116 device consumes minimal current that, in addition to providing power savings, minimizes the self-heating effect while measuring temperature and improves measurement accuracy. The TMP116 operates from 1.9 V to 5.5 V and typically consumes 3.5 µA in average. Across its full operating temperature range the TMP116 device achieves the accuracy of a Class A RTD without calibration and requires significantly less processing software by dropping the need for the voltage to temperature measurement conversion and subsequent offset and gain result adjustment. In addition, the extern-al analog signal chain circuitry, with the precision reference resistor, analog input matched RC-filters and the impedance matched traces on the PCB are completely eliminated.

图 2. TMP116 Internal Block Diagram



The TMP116 units are 100% tested on a production setup that is NIST traceable and verified with equipment that is calibrated to ISO/IEC 17025 accredited standards.

2.3.2 ESD351, TPD1E04U04

The ESD351 device is a unidirectional TVS ESD protection diode featuring low dynamic resistance RDYN and low clamping voltage. The ESD351 is rated to dissipate ESD strikes up to the 30 kV (contact and air) level per the IEC 61000-4-2 standard. The ultra-low dynamic resistance (0.1 Ω) and extremely low clamping voltage (6.5 V at 16-A TLP) ensure system-level protection against transient events. This device has a capacitance of 1.8 pF (typical) making it ideal for protecting interfaces. The ESD351 is offered in the industry-standard 0402 (DPY) package and is convenient for component placement in space-saving applications. The small package size has been a key decision factor for selecting ESD351 in this extremely space constraint application.

图 3. ESD351 Functional Block Diagram

The ESD351 is a diode-type TVS which is used to provide a path to ground for dissipating ESD events on high-speed signal lines between a human interface connector and a system. As the current from ESD passes through the TVS, only a small voltage drop is present across the diode and is the voltage presented to the protected IC.

The ESD351 device supports the industrial temperature range: –40°C to +125°C, the recommended input voltage V_{IN} is between 0 and 3.6 V.

The TPD1E04U04 device is a unidirectional TVS ESD protection diode rated to dissipate ESD strikes above the maximum level specified in the IEC 61000-4-2 international standard (Level 4). The low dynamic resistance and ultra-low clamping voltage ensure system level protection against transient events for sensitive SoC. The TPD1E04U04 is offered in the industry standard 0402 (DPY) and 0201 (DPL) packages and also supports the industrial temperature range: –40°C to +125°C.

2.4 System Design Theory

Chapter 4.1 of the *Heat Meter* specification EN1434-2(2) states that all temperature pairs must consist of suitably selected PT sensors elements. Pre-calibrate and pair the PT sensors before they are built into the *Heat Meter* or alternatively, firmly mount (for example, soldered) them onto the *Heat Meter* PCB and calibrated afterwards to minimize the temperature offset between these two PT sensors.

Next, EN1434-2(2) also states that other types of temperature sensors may be used. If they are, they cannot be separated from the *Heat Meter* or *Heat Calculator* device.

Another important fact to consider is the EN60751(1) requirement in Chapter 5.4. Construct all industrial platinum resistance thermometers with an accuracy higher than Class B, or equal to Class A or Class AA in 3- or 4-wire configuration.

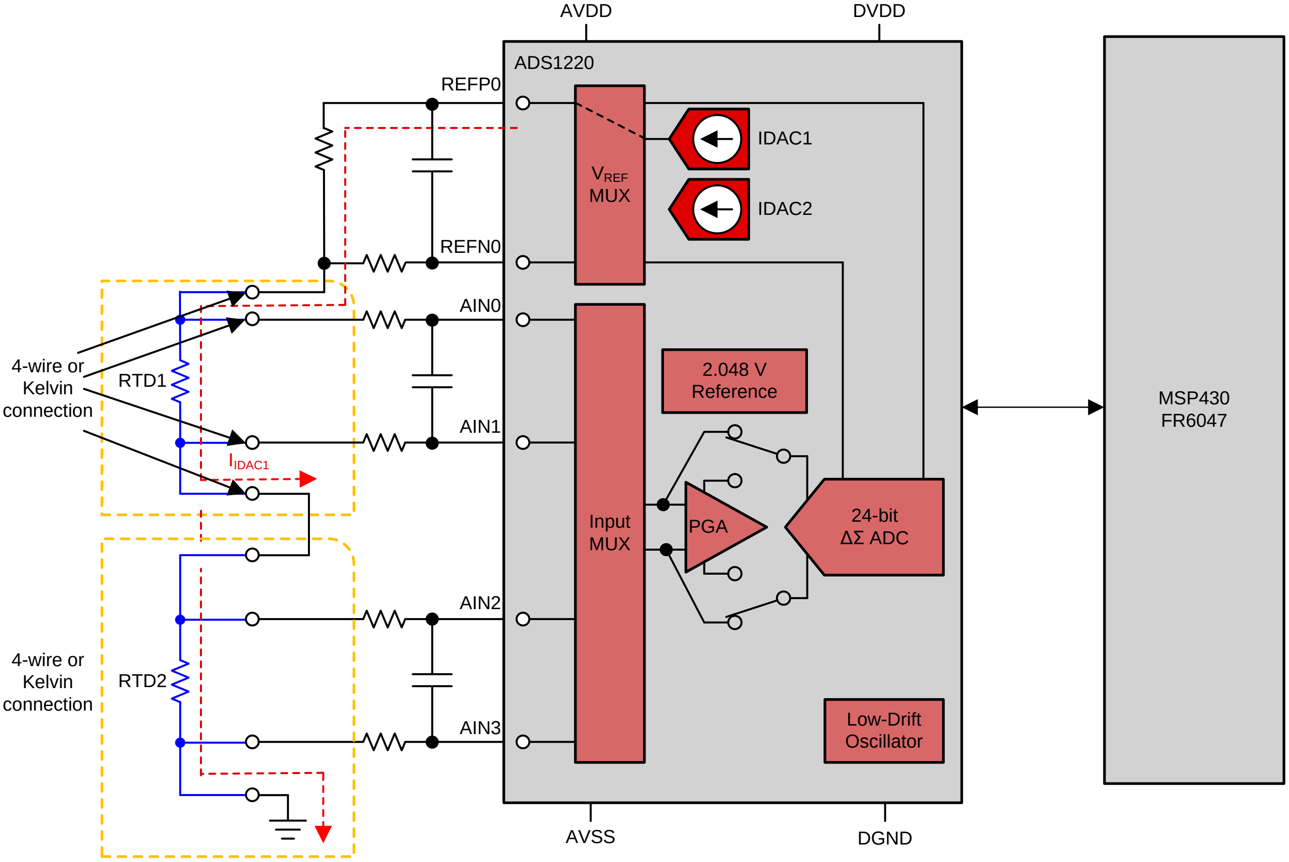
These two previous statements do not forbid the use of the TIDA-010002 as a digital temperature sensor (or DRTD) with a 4-wire interface when firmly mounted onto a *Heat* or *Cooling Meter* device.

With the TIDA-010002, the Host MCU, such as TI's UltraSonic MSP430FR6047 device, can simply read out the DRTD sensor calibration parameters stored in the 64-bit EEPROM area over a I2C-bus and use the this data to achieve the accuracy of a Class AA thermometer. The TIDA-010002 design is an alternative solution to the RTD Precision Temperature measurement subsystem, described in TIDA-01526 and delivers similar resolution and temperature accuracy but only in the –55 to +125°C range, due to its nature of an active semiconductor device.

2.4.1 PT100, PT500, PT1000 Sensors in Heat Meters

In 图 4 the ADS1220 Delta-Sigma device is used to measure the resistance of two 4-wire PT sensors in series and passes the data to the MSP430 host MCU for conversion from a resistance value to a temperature value, as implemented in the TIDA-01526. There the 4-wire interface is part of the Kelvin connection, where two outer leads on RTD1 and RTD2 carry the measurement current I_{IDAC1} and the two inner leads are connected to AIN0-1 and AIN2-3 analog inputs of the ADS1220 to measure the voltage across RTD1 and RTD2 and thus their respective resistance values.

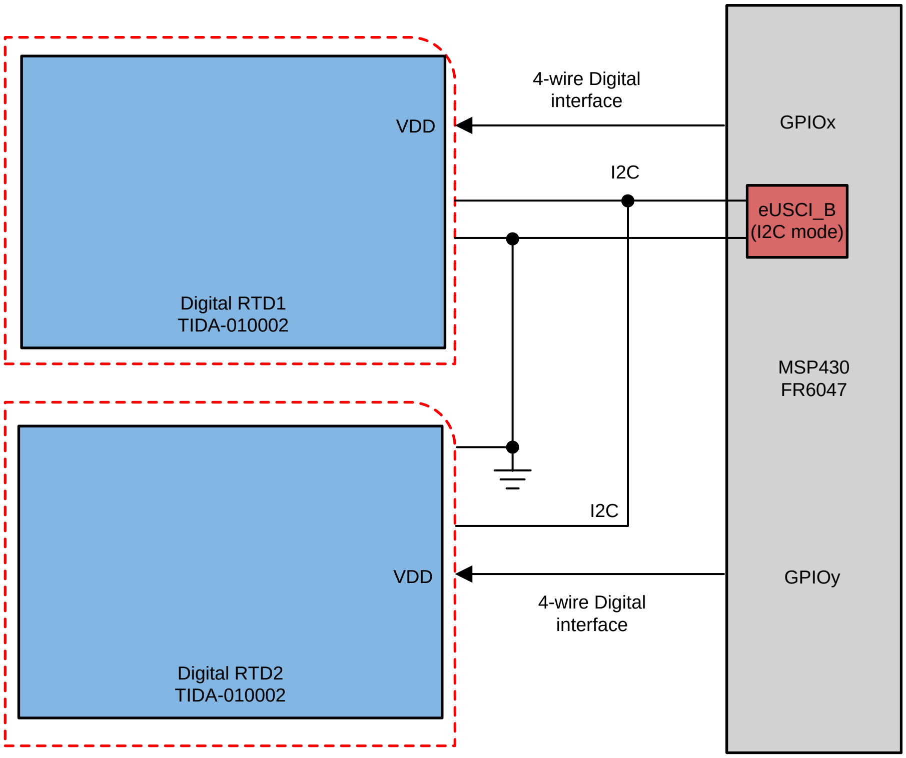
图 4. DTM Subsystem With a 24-bit Delta-Sigma Device and a Pair of 4-Wire RTDs



2.4.2 Digital RTD Solution With TMP116

The TIDA-010002 integrates the entire DTM subsystem into a single device by combining the Delta-Sigma core and the RTD into a highly accurate digital temperature sensor (see 图 5). Note that the 4-wire *digital* interface of the TIDA-010002 is *not* electrically compatible to the standard analog 4-wire RTD sensor, measured with the help of the Kelvin connection as 图 4 shows.

图 5. Integration of the Analog Measurement Chain Into a Semiconductor Temperature Sensors TMP116 With Digital I2C Interface



The 4-wire digital interface requires the supply voltage VDD, which can be provided by a GPIO pin of the host MCU, such as GPIOx in 图 5. An additional GPIO pin, called GPIOy, can be used to power on and off the second DRTD sensor, and a 3rd GPIO and 4th pin can be added, in case more than two DRTD sensors have to be used. Using a dedicated GPIO pin to power each connected DRTD has the advantage, that all of those can be used on the same I2C-bus and still have the same I2C-address. The user has to ensure that only one GPIO pin of the host MCU is active (or HIGH), while all the others on the same I2C-bus lines having the same I2C address are inactive (or LOW).

As TMP116 integrates the complete temperature measurement subsystem using a diode temperature sensor and a 16-bit Delta-Sigma core into a fully digital solution, there is no extra temperature conversion effort to be done by the host MCU. The latter reads out the value and applies an offset (if needed), based on the parameters in the NV memory of the TMP116 device. It is more energy efficient to read out the NV memory content once at the beginning and apply the offset or any other adjustments to the result, each time the temperature is measured. The calibration offset data is stored into the NV memory as part of the DRTD manufacturing process or during end system calibration.

An important benefit of the DRTD approach, introduced here, is the elimination of offset and gain calibration steps for the analog signal chain, required with traditional analog signal measurements in 2-, 3-, or 4-wire configurations.

The high precision Reference resistor, typically with accuracy better than 0.1% and ±25 ppm/C, and the matched RC-filters are not needed anymore. This represents a cost reduction in terms of Bill of materials as well as in PCB space and a much simplified layout on the host MCU side.

Last but not least, for all Heat and Cooling meters with precision temperature measurement in the –55°C to 125°C range, TIDA-010002 is expected to enable significantly lower cost in manufacturing by reducing the three temperature points calibration as in EN 1434 to a single point temperature offset calibration.

A major advantage of the DRTD approach, based upon the TIDA-010002, is the capability to store user defined calibration parameters in the 8 Bytes EEPROM memory area of each TMP116 device. This significantly simplifies and can even completely eliminate the paperwork and calibration data handling efforts when compared to traditional analog RTD sensors, where labels with an ID number have to be attached to the RTD cable and the calibration data is passed over to the Meter vendor by the RTD sensor vendor by some off-line means, for example, in an electronic data format.

A 1-point offset calibration at 0°C or at room temperature may be required to achieve Class AA accuracy; this calibration step will narrow the 3-sigma accuracy spread of the TMP116 devices down to the average curve shown on *TMP116x High-Accuracy, Low-Power, Digital Temperature Sensor With SMBus- and I2C-Compatible Interface*.

2.4.3 Ambient Temperature Considerations

The TIDA-010002 is proposed as a replacement of standard analog RTD sensors, which use thin-film passive components and are popular in *Heat* and *Cooling Meters*. The design is expected to operate at high ambient temperature and experience multiple cycles of changing from "hot" to "cold" and vice versa over its lifetime. Note that TMP116 datasheet specifies that the long-term stability and drift are tested at 300 hours at 150°C and are typically in the range of ±0.05°C.

Furthermore, the datasheet specifies the temperature cycling and hysteresis accuracy of ±1 LSB with 8 averages. Such cycling is defined as the ability to reproduce a temperature reading as the temperature varies from room → hot → room → cold → room. The temperatures used for this TMP116 test are –40°C, 25°C, and 125°C as per the datasheet.

To take full advantage of the industrial temperature range of the TMP116 device, the supply voltage capacitor C1, the optional VDD filter resistor (not present in the TIDA-010002), and any resistors used for I2C address configuration (see R3 and R4 in 4.1 节) should also cover the wide temperature range of –55°C to 125°C, as well as the PCB material used.

For volume production with a fixed I2C slave address, the TIDA-010002 reference design can be modified and the ADD0 pin can be hard-wired to GND, VDD, SDA or SCL lines. Thus R3 and R4 will be removed for further cost saving and improved system reliability.

Class AA and Class A resistance thermometers are defined in EN 60751:2008 within the temperature ranges of 0°C to 150°C and –30°C to 300°C respectively. The TIDA-010002 has a recommended operating free-air temperature down to –55°C, exceeding the minimum temperature limits of both Class A and AA.

The maximum operating temperature is 125°C with TMP116 as used in this Reference Design and is suitable for multiple industrial applications, not only metering.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

A combination of existing and available TI hardware and software tools is required to evaluate the performance of the TIDA-010002.

3.1.1 Hardware

The TIDA-010002 board was initially tested for proper operation using the *USB2ANY Interface Adapter*, which features I2C-bus protocol support. Both read and write slave access to the TMP116 was verified after correct wiring of the VDD, GND, SDA, and SCL lines between the TIDA-0100012 design and USB2ANY tool.

The fully assembled probes with TIDA-010002 inside, as shown in 图 6, were used for testing. These digital temperature probes (see the 4-wire white cable with 6 m length as an example) were produced by JUMO GmbH & Co. KG in Germany. JUMO is a market leader in the development of industrial temperature probes for a variety of applications, including residential and commercial heat meters. JUMO can be contacted with inquiries about digital temperature probes based upon TIDA-010002 at *HeatMeter@jumo.net*.

In addition, the I2C-bus data transfer to and from the TMP116 device was proven using the Logic Pro 16 tool, which integrates an I2C protocol decoder software.

Next, the full TIDA-010002 based digital probe was attached to the *MSP430FR6047 Ultrasonic Sensing Evaluation Module* using the BoosterPack™ Plug-in Module extension connectors J5 and J6. 表 2 shows the four connections required, where the VDD of the TMP116 device can be provided continuously or by a GPIO pin for easy power-on and off.

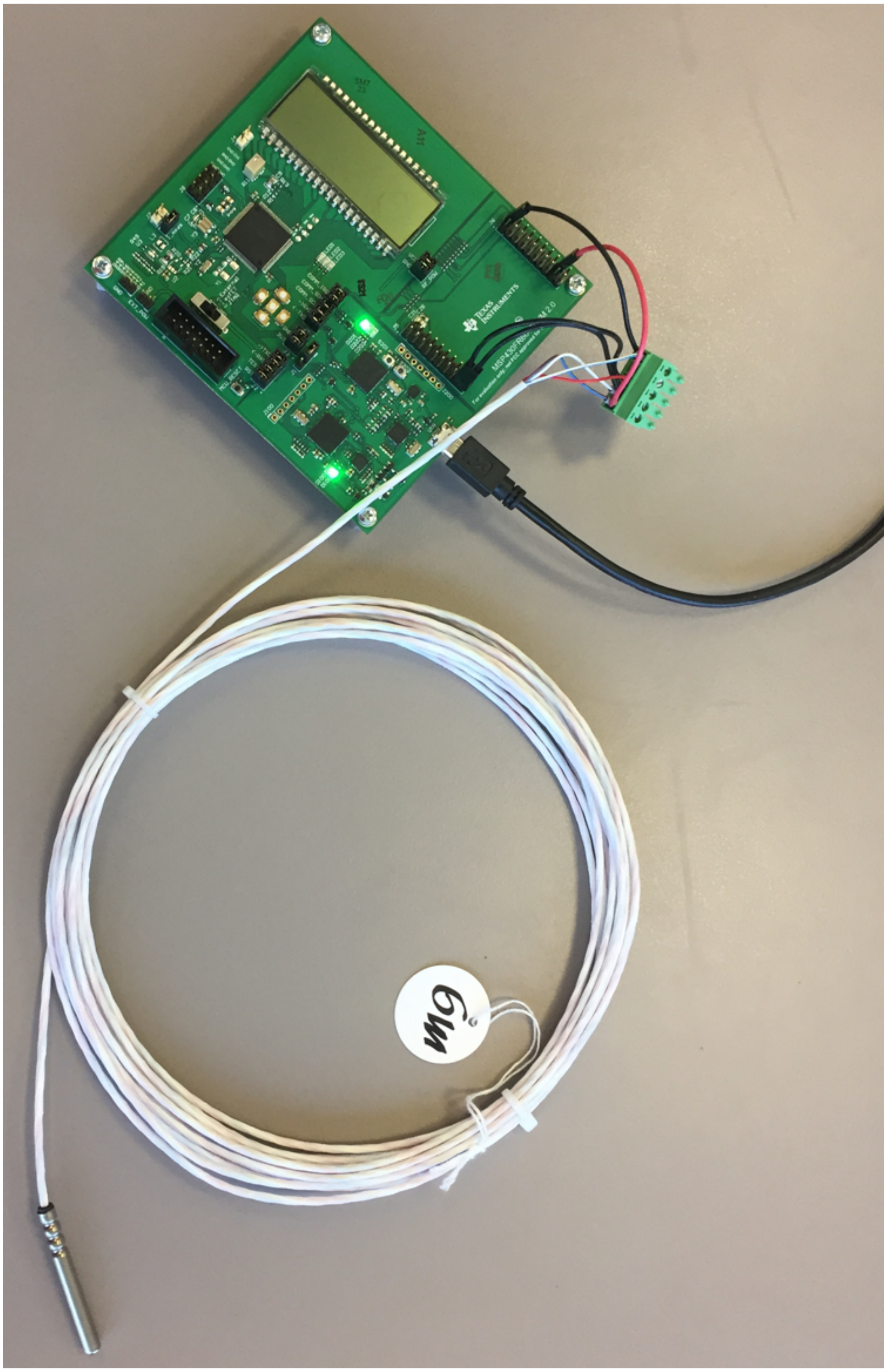
表 2. Wiring Scheme for MSP430FR6047EVM and TIDA-010002

MSP430FR6047EVM	TIDA-010002	COMMENT
SCL (J5.17)	SCL	I2C from eUSCI_B0
SDA (J5.19)	SDA	I2C from eUSCI_B0
GND (J6.2)	GND	
GPIO P8.0 (J6.18)	VDD on/off	used for power cycling of the first DRTD
GPIO P7.5 (J6.20)	VDD on/off	used for power cycling of the second DRTD
VDD (J5.1)	VDD	alternative to GPIO8.0; used for continuous powering of DRTD

3.1.2 Software

The TIDA-010002 has been tested together with the *EVM430-FR6047*, a reference development platform used to evaluate the performance of the MSP430FR6047 for ultrasonic sensing applications, such as smart water or *Heat Meters*. The highly-accurate flow measurement of the MSP430FR6047 MCU in combination with the Class AA sensor temperature accuracy delivers a cost-optimized, ultra-low-power hardware platform for designing *Heat* and *Cooling Meters* or *Heat Calculators*.

图 **6. EVM430-FR6047 With a 6-m DRTD (TIDA-010002 is Sealed Inside the Metal Body)**



The MSP430FR6047 application software is called *Ultrasonic Sensing (USS) Design Center*. To download the software, visit *MSP430 MCUs Ultrasonic Sensing Design Center*. The MSP-USSSWLIB free software is the basis for the example code provided with the TIDA-010002 design. The MSP-USSSWLIB has three parts, the USSSWLib, the USS Design Center GUI and the Demo Application. As of August, 2018 the latest revision on TI.com is the "UltrasonicWaterFR6047_02_10_00_05_windows_installer.exe" and contains the "MSP430FR6047EVM_USS_Water_Demo" Code Composer Studio project, which is the one used here.

The "hal_system.c" file was modified to enable MSP430FR6047's eUSCI_B0 as the I2C-master for the TIDA-010002 as the slave. The "main.c" file in "Water_Demo" software project has been modified; both read and write access to the TMP116 device is implemented, including the TMP116 EEPROM write function.

The USCI_A1 module of the MSP430FR6047 has been set to operate as the communication interface to the PC (using the back-channel UART of the MSP430 debugger, integrated onto the EVM). The UART settings are 57600,8N1 and the data being output can be monitored inside the Code Composer Studio CCSv8.1.0 by opening a Terminal window; alternatively the user can run his favorite UART terminal program.

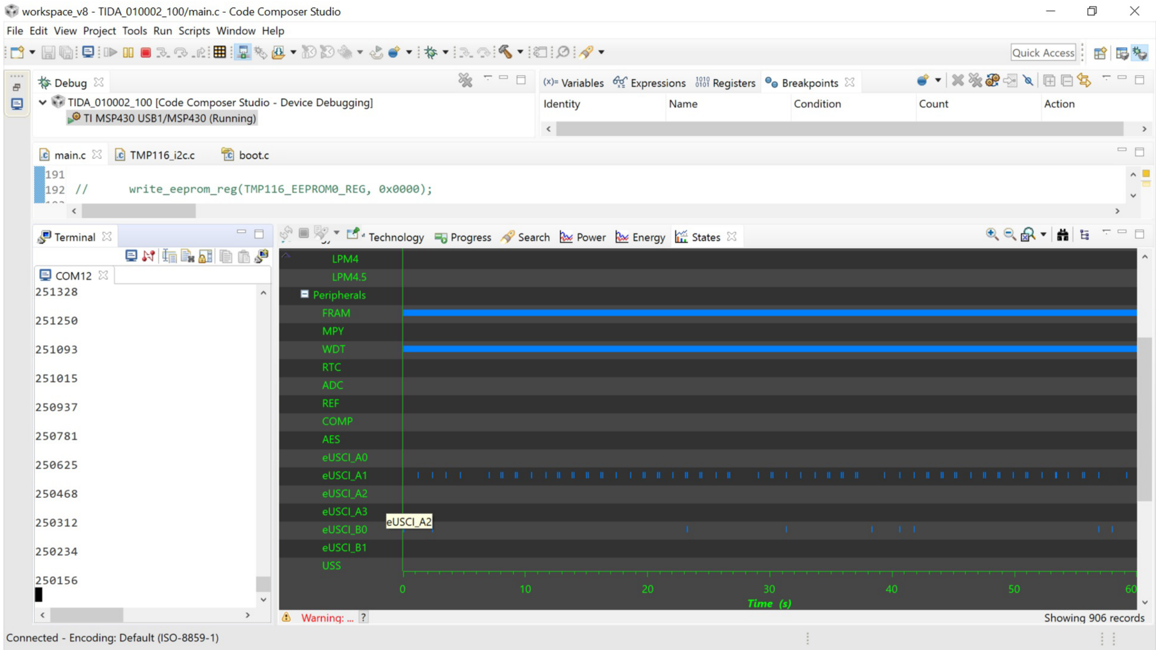
The I2C driver for communication with the TMP116 has been developed, utilizing the existing Hardware Abstraction Layer (HAL) driver for the MSP430FR6047 EVM. The I2C-Address of the TIDA-010002 is hard-wired 0x48 hex, with R3 mounted on the TIDA-010002 PCB (see 图 6).

The complete modified Demo Application software is available under BSD Clause 3 license as an open source example in 5 节. When using this code project under CCSv8.3 or later the actual temperature reading is printed into the Terminal window, which is displayed in the bottom left in 图 7. The number format in the terminal is two digits before and 4 digits after the decimal point. Thus the string "251328", which is the first data in the COM12 Terminal window, means +25.1328°C.

Note that below 0°C temperature conversion has not been implemented in the text code and must be added by the user.

The code example uses 8 samples averaging with a cycle of 1 second as the default settings for TMP116 to demonstrate the operation of the complete system. The user should adjust the TMP116 settings as appropriate for his specific application.

图 7. TIDA-010002 Code Example With Terminal Output in COM12 and EnergyTrace++



```
//      write_eeprom_reg(TMP116_EEPROM0_REG, 0x0000);
```

```
251328

251250

251093

251015

250937

250781

250625

250468

250312

250234

250156
```

The EnergyTrace++图 7 window on the bottom right shows the activity of the MSP430 peripherals - see vertical blue stripes in the lines eUSCI_A1 and eUSCI_B0.

3.2 Testing and Results

For testing the temperature measurement accuracy, several TIDA-010002 PCBs were assembled by JUMO into a fully digital RTD using a 4-wire cable and a 5.2-mm outer diameter metal sheath as common in *Heat Meters*.

3.2.1 Test Setup

The *TMP116 High-Precision Digital Temperature Sensor Evaluation Module* was used to connect the DRTDs and capture all measurement data; all tests were done at 3.3 V.

One DRTD sensor has been placed as the DUT (Device Under Test) in a stirred oil bath with controlled temperature for measuring the temperature offset accuracy and response time.

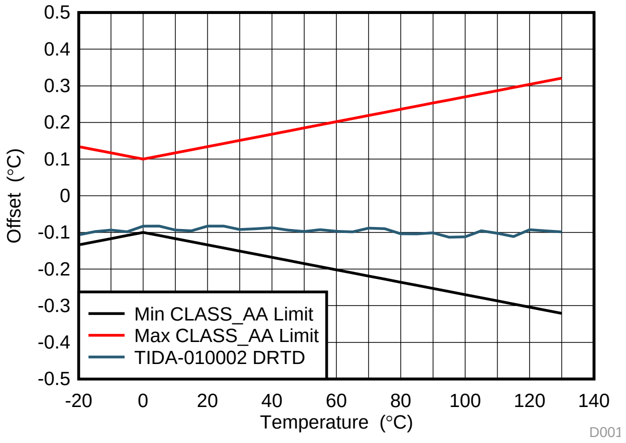
Two DRTDs were tested for still air response time and compared to other TI boards with the TMP116 device. Several items of precision measurement equipment were used during the tests documented in this chapter:

- Oil bath Fluke 7320 or 7340 with Galden HT200 fluid
- Fluke 1502A meter with accuracy up to ±0.006°C
- Secondary standard PRT probe Fluke 5628 with calibrated accuracy of ±0.006°C at 0°C

3.2.2 Test Results

One DRTD probe was immersed into the precision Fluke oil bath with Galden HT200 oil and ten read out values for each temperature point were collected. The measured range is from –20°C to 130°C in steps of 5 degrees C; the worst (largest) deviation from each of these ten values per step has been plotted for the respective temperature measurement point in 图 8.

图 8. TIDA-010002 Board Meets Class AA Thermometer Limits Without Calibration



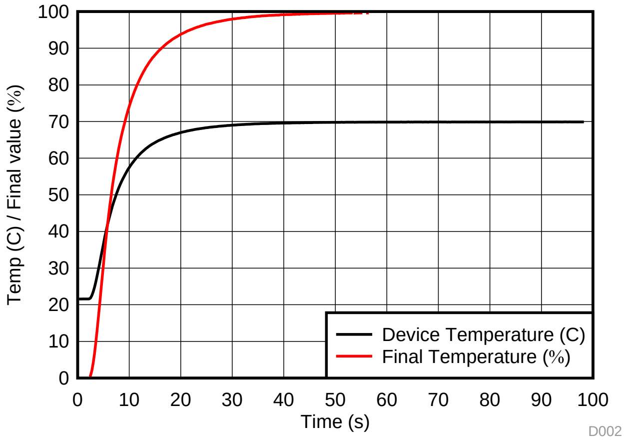
Note that the Class AA accuracy achieved with this TIDA-010002 DRTD unit without calibration is *not* guaranteed for all TMP116 devices by default.

Due to the average ±3σ spread of the devices (see *TMP116x High-Accuracy, Low-Power, Digital Temperature Sensor With SMBus- and I2C-Compatible Interface*), a single-point calibration is needed to minimize the temperature offset, either at 0°C using an ice bath or at room temperature, for example. 图 8 shows that a DRTD probe with the TIDA-010002 inside, *can* meet the Class AA limits for temperature offset without calibration, if the specific device performs close to the average curve shown in the data sheet.

EN60751:2008 requires that all RTDs are checked at one temperature point between –5°C and 30°C at least, preferably at 0°C. Class A and Class AA thermometers, which utilizes the TIDA-010002, will require a second check, at a temperature of 90°C above the first one; this could be 0°C and 90°C or 3°C and 93°C, for example.

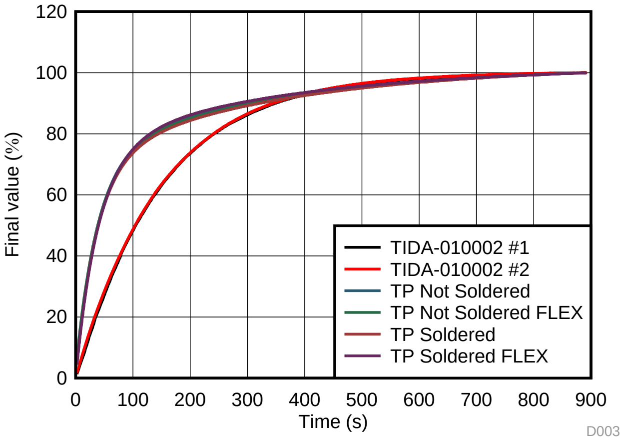
As the response time of the temperature sensor is an important parameter for standard RTDs, the TIDA-010002 performance was measured in stirred oil and still air for comparison. Stirred oil result is relevant for applications where the DRTD has direct contact with the fluid, as is the case with *Heat* and *Cooling Meters*. In 图 9 the DUT has initial temperature of 20.5°C and is inserted into a 70°C hot oil bath and the DUT reported temperature has been logged.

图 9. TIDA-010002 DRTD Response Time in Stirred Oil Bath



The still air response time of two DRTD probes, named DUT1 and DUT2, is shown in 图 10 and also compared to other TI test boards with the TMP116 thermal pad either soldered or not soldered. Obviously, the DRTD probes with their metal sheath and much larger thermal mass have a longer response time but after a delay of approximately 400 seconds they are equal to a bare PCB with TMP116. TP means *Thermal Pad* and tests have been made to compare the performance with and without soldering the thermal pad (for details see *Precise Temperature Measurements with TMP116*).

图 **10. TIDA-010002 DRTD Response Time in Still Air**



3.2.3 I2C-bus Cable Length Considerations

The 4-wire digital interface with I2C-bus operation has been verified with multiple DRTD probes of 2, 4, 6, 8 and 10-m cable length. An external 4.7-kΩ pullup resistors for the SCL line has been used.

Note that the I2C-bus specification defines maximum bus capacity which limits the possible cable length. The distance achieved (10 m was the maximum cable length DRTD probe available) depends on the parameters of the 4-wire cable used as well as from the driving capability of the I2C-master device (here a MSP430FR6047 MCU). Multiple oscilloscope plots of data transfer taken for cable lengths of 6 m, 8 m, and 10 m show that for longer cable distances bit errors probability increases as the signal rise and fall times get longer and the total capacitance of each wire goes beyond the I2C-bus limit of 400-pF maximum due to its cable length.

Nevertheless, the I2C specification mentions that using higher driver strength device than 3 mA for Fast mode with 400 kHz clock frequency can help overcome this limitation. The MSP430FR6047 Digital IO pins can drive up about 10-mA low-level output current at about 0.6-V output voltage, when the MSP430 supply voltage VCC = 2.2 V.

It is user's responsibility to verify which is the maximum achievable cable length for worst case conditions of both VDD supply voltage levels (for example, a primary battery LiMnO2, discharged down to 2.5 V) and the ambient operating temperature of the application (for example, *Heat Meter*).

The peak case ± 11.13 mK inaccuracy of the TIDA-010002 DRTD probe is significantly better than the limit of ±700 mK, set in prEN1434- 5:2014, when comparing each RTD sensor behavior with the ideal RTD plot using the EN 60751 Callender-Van-Dusen (CVD) reference equation. The compliance with this limit has to occur for 3 typical temperature points, for example at 10ºC, 30ºC, and 50ºC, which is verified in 图 8.

3.2.4 Power Supply

Heat and *Cooling Meters* are typically battery power devices, thus a key design criteria is the implementation of a temperature measurement sub-system with ultra-low-power consumption.

The lowest operating voltage of 1.9 V for TMP116 reduces the total power consumption and enables maximum utilization of the available battery capacity down to 1.9 V, which is an excellent fit for LiMnO2 3.0-V primary cells with typical "cutoff" voltage of 2.0 V.

The TIDA-010002 works well also with 3.6 V LiSoCl2 cells, the latter usually have their cutoff voltage around 3.1 or 3.2 V, depending on the application.

The EVM430FR6047 together with DRTD probe was tested successfully down to 2.05 V by powering the complete setup thru an external E3631A Agilent DC power supply.

3.2.5 ESD Test Results

Using industry standard ESD test generators calibrated to the IEC/EN test waveforms, TIDA-010002 PCB has been tested for ESD compliance as shown in 表 3. For more details on the ESD test setup used, see *IEC 61000-4-x Tests for TI's Protection Devices*.

As per the EN1434-4 requirements, EN 61000-4-5 testing is only applicable if the cable length for the RTD sensor is longer than 10 m, which is quite challenging for I2C-bus connection. Nevertheless, a surge test has been run with an actual pulse voltage of 29 V through a 2-Ω load plus the 2.83-Ω dynamic resistance of the ESD device and the TMP116 downstream device.

For a surge test with a 42-Ω load (2 Ω is the CWG source impedance and 40 Ω from the coupling network) plus the ESD351 + TMP116 dynamic resistance of 2.83 Ω the result is 44.83 times the amount of current 6 A or approximately 269 V.

The 269 V are almost half of the 500 V, required for signal cables longer than 10 m.

表 3. ESD Testing of TIDA-010002

EN 61000-4-2 ESD TEST LEVEL	CONTACT DISCHARGE TEST VOLTAGE (± kV)	AIR DISCHARGE TEST VOLTAGE (± kV)	TIDA-010002 WITH ESD351
4	8	15	passed

The ESD compliance achieved and listed in 表 3 is nearly double of the required (as per EN 1434-4:2014-04) limits for contact discharge of 4 kV and air discharge of 8 kV.

Here the TPD1E04U04 device can be an alternative, as it is specified for ±16 kV IEC 61000-4-2 level 4 ESD protection, which is also above the required minimum.

Either of the ESD351 or TPD1E04U04 protection devices can be populated as they share a single 0402 footprint on the TIDA-010002 PCB, providing alternatives based on price or performance.

3.2.6 Summary

The test results for the TIDA-010002 reference design mounted into a metal body with a 4-wire cabling prove that the measurement accuracy meets Class AA thermometer requirements as per *DIN EN* 60751:2008 (German and EU norm) .

A single (1-point) offset adjustment is necessary to achieve Class AA accuracy over the full temperature range of the TIDA-010002 from –55°C to +125°C; no TMP116 calibration is necessary if Class A accuracy is sufficient for the user application.

Overall, DRTDs offer the highest accuracy of Class A or Class AA RTD sensors in combination with the unique feature of EEPROM on-chip memory for storing user defined calibration data.

The storage of calibration data per DRTD sensor is a major advantage versus standard platinum RTDs and enables significant cost savings for the sensor manufacturer and sensor end customers by reducing the paperwork and calibration data handling effort.

The lower operating temperature limit of –55ºC enables higher precision in multiple applications beyond metering.

ESD61000-4-2 level 4 compliance for contact discharge test voltage of ± 8 kV and air discharge test voltage of ±15 kV has been verified.

If no backwards compatibility to the PT sensors interface is required, as is the case for many *Heat* and *Cooling Meters*, where the PT sensors and the flow meter subsystem build a single unit and can only be replaced altogether, the introduced TIDA-010002 DRTD can deliver system cost savings, due to simplified handling of calibration data, the removal of multiple passive components and simplified PCB design due to the elimination of matched signal PCB traces. Also, the complicated resistance to temperature conversion calculations compared to traditional industrial thin-film RTD sensors are completely redundant, making the user application code development much simpler and saving some extra power due to less MCU operation cycles.

If the temperature to be measured in the *Heat* or *Cooling Meter* or *Heat Calculator* application is lower than –55ºC or higher than 125ºC or if backwards compatibility with standard PT sensors is mandatory, then the TIDA-01526 reference design with support for PT100, PT500 or PT1000 sensors is the recommended system solution.

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-010002.

Note that the resistors R3 and R4 for the I2C-bus address configuration were added for testing purposes such as having two TIDA-010002 on the same I2C-bus with address of 0x48 and 0x49 respectively. In a final product these two resistors can be removed and the I2C-address configuration done by wiring directly to the VDD, GND, SDA or SCL lines. Such cost-optimization step will also allow for further reduction of the PCB size and will have a positive effect on the response time of the DRTD.

As R3 has been populated on the PCB, the I2C-bus slave address of the DRTD is 0x48hex.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-010002.

4.3 PCB Layout Recommendations

To fit the PCB into the smallest possible sheath body, the PCB size is only 4 mm × 11 mm. Two signal PCB layers, single side components placement and a 20 mil PCB Stack have been selected for minimizing both the thermal mass and the cost of the PCB. There are no copper planes in use, the TMP116 thermal pad and the copper area below the thermal pad on the bottom layer are used for improving the temperature response time, as described in *Wearable Temperature Sensing Layout Considerations Optimized for Thermal Response*.

The thermal pad of TMP116 itself is *not* soldered to the PCB to improve accuracy of the measurement, as recommended in *Precise Temperature Measurements with TMP116*.

Both ESD351 and TPD1E04U04 devices are available in 0402 standard package; thus only one footprint per signal line is available on the PCB.

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-010002.

4.4 Altium Project

To download the Altium Designer® project files, see the design files at TIDA-010002.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-010002.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-010002.

5 Software Files

To download the software files, see the design files at TIDA-010002.

6 Related Documentation

1. DIN EN 60751:2008 (German and EU norm)
2. Beuth, *EN1434-1 through -6*
3. Texas Instruments, *3-Wire RTD Measurement System Reference Design, –200°C to 850°C*
4. Directive 2014/32/EU of the EUROPEAN PARLIAMENT and of COUNCIL of 26 February 2014
5. Texas Instruments, *TMP116 High-Precision Digital Temperature Sensor Evaluation Module*
6. Texas Instruments, *TMP116EVM GUI Software*
7. Texas Instruments, *Wearable Temperature Sensing Layout Considerations Optimized for Thermal Response Application Report*
8. Texas Instruments, *Precise Temperature Measurements with TMP116 Application Report*
9. Texas Instruments, *USB2ANY Interface Adapter*
10. Texas Instruments, *IEC 61000-4-x Tests for TI’s Protection Devices*
11. NXP Semiconductors, *I2C-bus specification and user manual*, UM10204, Rev.6
12. JUMO GmbH & Co. KG

6.1 商标

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7 Terminology

- Class C, B, A or AA - accuracy of RTD sensors as defined in *DIN EN* 60751:2008
- RTD - Resistance Temperature Detector
- PT sensor - Platinum sensor (or Platinum RTD), such as PT100 or PT500 or PT1000
- DRTD - Digital RTD (using TMP116 digital Temperature Sensor With NV Memory)
- DTM - Differential Temperature Measurement subsystem, often implemented with a delta-sigma ADC and a PT100/500/1000 sensor

8 About the Author

MILEN STEFANOV (M.Sc.E.E) is a system engineer at TI, working in the Grid Infrastructure field and an expert in RF communication technologies and metering applications. After graduating there, he spent 5 more years as a research assistant at the University of Chemnitz (TUC) and the following 3.5 years as a system engineer in the semiconductor industry with focus on high-speed optical and wired communications. He joined TI in 2003 to become a Wi-Fi® expert and support TI’s Wi-Fi products at major OEMs. Since 2010, he has focused on metering and Sub-1 GHz RF solutions for the European Grid Infrastructure market. Mr. Stefanov has published multiple articles on wM-Bus technology in several European magazines and presented technical papers at the Wireless Congress and Smart Home & Metering summits in Munich.

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