

TI Designs

Wireless pH Sensor Transmitter (DevPack for SensorTag)



TI Designs

This reference design shows how to build an isolated pH sensor thanks to a wireless link. The selected wireless technology is Bluetooth® Smart because of its integration in most modern consumer equipment, making testing and demonstration easier. The form factor and electrical connections being compatible with TI SensorTag ecosystem allows for easy prototyping with other wireless technology (Zigbee, WiFi, sub 1GHz, and so on) while the selected pH front-end allows industrial grade accuracy and resolution.

Design Resources

TIDA-00561	Design Folder
LMP91200	Product Folder
ADS1120	Product Folder
REF3220	Product Folder
TS5A3159	Product Folder
SensorTag	Tools Folder

Design Features

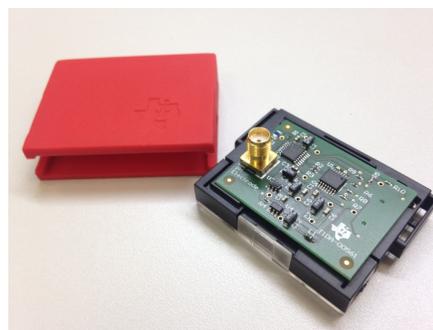
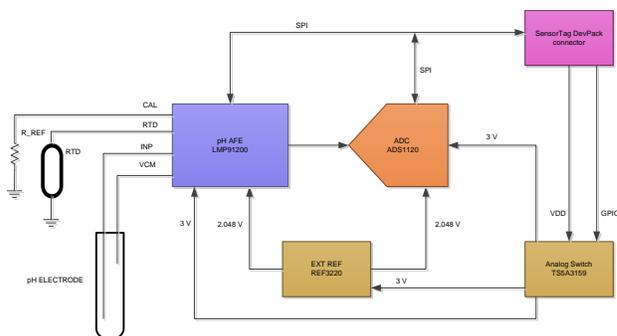
- Isolated (Wireless) pH Sensor Transmitter
- Bluetooth Smart Interface
- pH Input Bias Current < 7 pA
- Less Than 200 μ A in Advertising Mode
- Include PT100 for Temperature Compensation
- Accuracy: 25°C \pm 0.01 pH
- Repeatability: 25°C \pm 0.01 pH
- Temperature Range: -40°C to 125°C

Featured Applications

- Isolated Field Transmitters
- Wireless Field Transmitter



[ASK Our E2E Experts](#)
[WEBENCH® Calculator Tools](#)



An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

1 System Overview

1.1 System Introduction

pH measurement is a generic area of measurement that spans from process control (the shift in pH can be an indication of a process drift) to recycling plants as well as in non-industrial areas. pH measurement could also be mentioned in test and measurement equipment for laboratories, home automation equipment like swimming pool monitoring, grid infrastructure monitoring like drinking water quality monitoring, and so on.

This reference design targets especially the needs of process control application with high accuracy, temperature compensation, and electrical isolation between the PLC/DCS/PAC and the sensing element itself.

The system described in this TI Design aims at solving the following challenges:

Table 1. TIDA-00561 Industry Solutions

INDUSTRY CHALLENGE	TIDA-00561 SOLUTION
Ground loop potential differences	Ground loop isolation through wireless communication
Wireless communication standard fragmentation	Bluetooth Smart interface compatible with majority of portable electronics
pH probe high impedance	Analog front-end with <7-pA input bias current
pH sensing sensitive to ambient noise	Triax probes (with shield around signal lines) supported by the hardware

1.2 Key System Specification

[Table 2](#) only specifies the performances of pH sensor board and temperature restrictions specific to the SensorTag applied when used in the full system.

Table 2. Key Systems Specification

PARAMETER	SPECIFICATION	VALUE	DETAILS
Input bias current	85°C	< 6.5 pA	See Section 3.1.4
Accuracy		< 0.02 pH	See Section 4.2 and Section 6
Temperature range	T_A	–40°C to 125°C	See Section 3.1.4 , Section 3.1.5 , Section 3.1.6 , Section 3.1.7

2 Theory of Operation

This section is intended as a general introduction to the topic of pH measurement, starting from the international standard definition of pH and helping the reader to understand the design decisions made in subsequent sections.

2.1 pH

This section covers the definition of pH, how pH is measured from both a chemical standpoint and electronic standpoint, what accuracies can be reached, and under which conditions.

2.1.1 pH Definition

The concept of pH is unique among the commonly encountered physicochemical quantities in that its definition is:

$$\text{pH} = -\lg a_{\text{H}} = -\lg \left(\frac{m_{\text{H}} \gamma_{\text{H}}}{m^{\circ}} \right) \quad (1)$$

where

- a_{H} is the relative (molality basis) activity
- γ_{H} is the molal activity coefficient of the hydrogen ion H^+ at the molality m_{H}
- m° is the standard molality

pH involves a single ion activity (the hydrogen ion), which by definition is a purely theoretical definition and cannot be measured by any valid method. [1]

This led to multiple international conventions until an operational method of measure was commonly agreed and formalized in *DEFINITION OF pH SCALES, STANDARD REFERENCE VALUES, MEASUREMENT OF pH AND RELATED TERMINOLOGY* [2] by means of a cell named the Harned cell, which is used as a primary method for absolute measurement of pH.

The Harned cell is defined by: $\text{Pt} \mid \text{H}_2 \mid \text{buffer S, Cl}^- \mid \text{AgCl} \mid \text{Ag}$

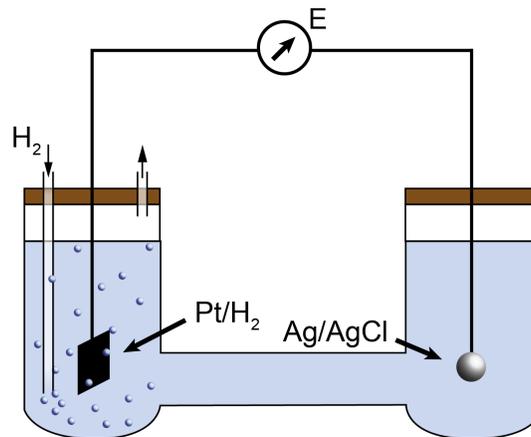


Figure 1. Harned Cell for Primary pH Measurements

NOTE: According to IUPAC recommendations on nomenclature and symbols [3], a single vertical bar (|) is used to represent a phase boundary, a dashed vertical bar (- -) represents a liquid–liquid junction between two electrolyte solutions (across which a potential difference will occur), and a double dashed vertical bar (||) represents a similar liquid junction, in which the LJP is assumed to be effectively zero (~1 % of cell potential difference).

Substances that do not fulfill all the criteria for primary standards but to which pH values can be assigned using a primary cell are considered secondary standards. Some illustrative pH(SS) values for secondary standard materials are given in [Table 3](#).

Table 3. pH(SS) Secondary Standards References [3]

SECONDARY STANDARDS	TEMPERATURE (°C)									
	0	5	10	15	20	25	30	37	40	50
0.05 mol kg ⁻¹ potassium tetroxalate ⁽¹⁾		1.67	1.67	1.67	1.68	1.68	1.68	1.69	1.69	1.71
0.05 mol kg ⁻¹ sodium hydrogen diglycolate ⁽²⁾		3.47	3.47	3.48	3.48	3.49	3.50	3.52	3.53	3.56
0.1 mol dm ⁻³ acetic acid + 0.1 mol dm ⁻³ sodium acetate	4.68	4.67	4.67	4.66	4.66	4.65	4.65	4.66	4.66	4.68
0.1 mol dm ⁻³ acetic acid + 0.1 mol dm ⁻³ sodium acetate	4.74	4.73	4.73	4.72	4.72	4.72	4.72	4.73	4.73	4.75
0.02 mol kg ⁻¹ piperazine phosphate ⁽³⁾	6.58	6.51	6.45	6.39	6.34	6.29	6.24	6.16	6.14	6.06
0.05 mol kg ⁻¹ tris hydrochloride + 0.0167 mol kg ⁻¹ tris ⁽³⁾	8.47	8.30	8.14	7.99	7.84	7.70	7.56	7.38	7.31	7.07
0.05 mol kg ⁻¹ disodium tetroxalate	9.51	9.43	9.36	9.30	9.25	9.19	9.15	9.09	9.07	9.01
Saturate (at 25°C) calcium hydroxide	13.42	13.21	13.00	12.81	12.63	12.45	12.29	12.07	11.98	11.71

⁽¹⁾ potassium trihydrogen dioxalate (KH₃C₄O₈)

⁽²⁾ sodium hydrogen 2,2'-oxydiacetate

⁽³⁾ 2-amino-2-(hydroxymethyl)-1,3 propanediol or tris(hydroxymethyl)aminomethane

Beyond the secondary standard for pH, the most common way to measure pH in laboratories and on industrial sites is with a glass electrode (see [Section 2.1.4](#) for further details).

2.1.2 pH Scale

Despite the relatively common misconception, the pH value scale is not limited to 0 through 14. Negative pH values can be found in nature (for example, in extremely acidic mine waters) [3].

The reason for this misconception beyond the broad set of textbooks propagating this notion is also related to lack of suitable buffer standards for $\text{pH} < 1$ and experimental challenges. A proposed pH scale representation adopted for this design guide is given by Figure 2:

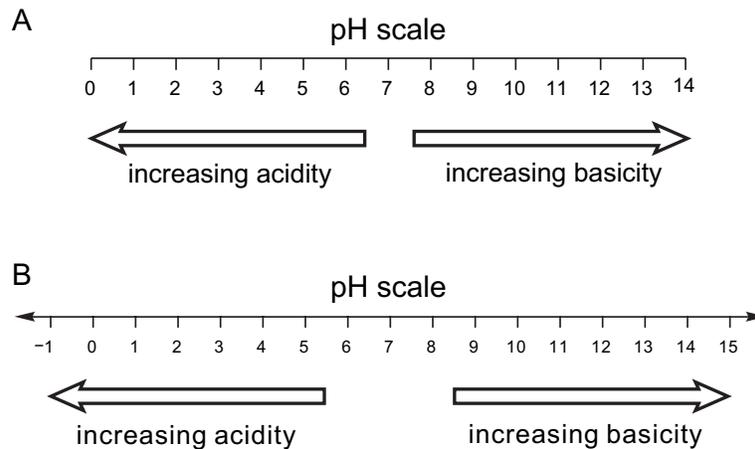


Figure 2. Two pH Scales: A) Typical Textbook Diagram, B) More Generic Diagram Showing an Open-Ended Scale

On a practical aspect, a literature review yields the following practical examples:

- Hot springs near Ebeko volcano have estimated pH values as low as -1.7 [5] [6].
- Waters from the Richmond Mine at Iron Mountain, CA have $\text{pH} = -3.6$ [9].
- Industrial products with pH ranges -2 to 16 [10]
- Other industrial mentioning that "solutions containing non-water solvents can have pH value outside the $[0 \text{ to } 14]$ range" [11]

2.1.3 pH Accuracies

Primary pH cell uncertainty is of the order of 0.004 [2]. For an industrial sensor, an uncertainty better than 0.02 pH would not make any sense as Figure 3 shows the metrological traceability that better explains it.

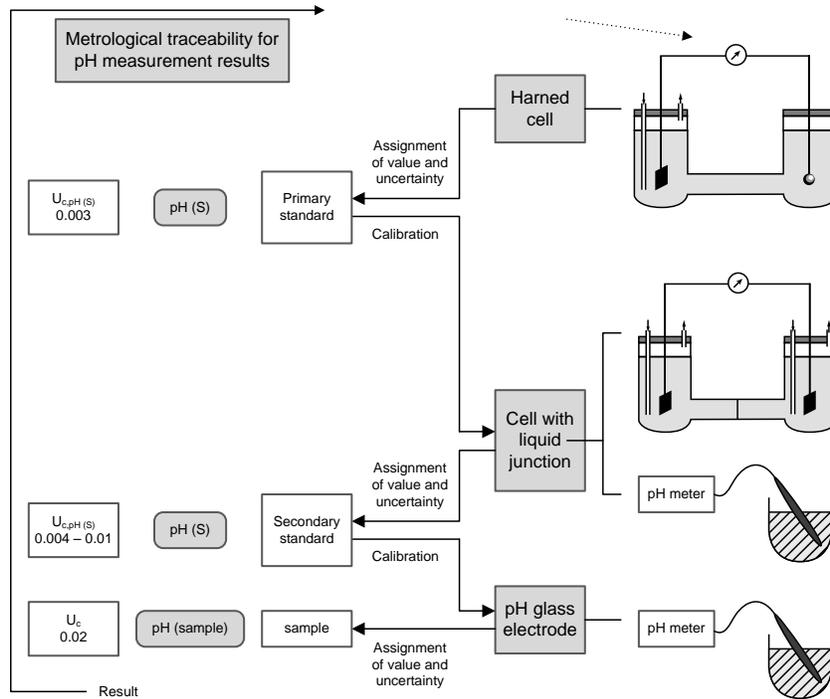


Figure 3. Metrological Traceability Scheme for pH

Beyond the primary references, in order to keep relevant uncertainties for pH measurement when designing an electronic system, [Table 4](#) (extracted from *DEFINITION OF pH SCALES, STANDARD REFERENCE VALUES, MEASUREMENT OF pH AND RELATED TERMINOLOGY*, Table 4 [2]) gives physicochemical related uncertainties, which limit a measurement system's accuracy:

Table 4. pH Uncertainty for System Design Target Accuracies

	U(pH) FOR COVERAGE FACTOR 2	COMMENTS
PRIMARY STANDARDS (PS)		
Uncertainty of PS measured (by an NMI) with Harned Cell I	0.004	
Repeatability of PS measured (by an NMI) with Harned Cell I	0.0015	
Reproducibility of measurements in comparisons with Harned Cell I	0.003	EIROMET comparisons
Typical variations between batches of PS buffers	0.003	
SECONDARY STANDARDS (SS)		
Value of SS compared with same PS measured in Harned Cell I	0.004	Increase in uncertainty is negligible relative to PS used
Value of SS measured in Harned Cell I	0.01	For example, biological buffers
Value of SS labeled against different PS with Cell II or IV	0.015	
Value of SS (not compatible with Pt H ₂) measured with Cell V	0.02	Example based on phthalate
ELECTRODE CALIBRATION		
Multipoint (5-point) calibration	0.01 to 0.03	
Calibration (2-point) by bracketing	0.02 to 0.03	
Calibration (1-point), ΔpH = 3, and assumed slope	0.3	

[Table 4](#) mentions the different calibration methods and their relative uncertainty. However, this design guide does not detail the laboratory procedures; the following sections give a high-level overview of those procedures and their ranges of validity.

2.1.3.1 *pH Accuracies — 5-Point Calibration*

Multipoint calibration is carried out using up to five standard buffers. The use of more than five points does not yield any significant improvement in the statistical information obtainable.

The calibration function is given by the linear regression of the measured potential differences.

2.1.3.2 *pH Accuracies — 2-Point Calibration*

In the majority of practical applications, glass electrodes cells are calibrated by two-point calibration, or bracketing, procedure using two standard buffer solutions with pH values pH(S1) and pH(S2) bracketing the unknown pH(X).

Bracketing is often taken to mean that the pH(S1) and pH(S2) buffers selected should be those that are immediately above and below pH(X); however, IUPAC does not judge this mandatory.

2.1.3.3 *pH Accuracies — 1-Point Calibration*

Given that a single-point calibration is insufficient to determine both slope offsets, the theoretical value for the slope is more often the one which is assumed (but the practical slope may be up to 5% lower).

The one-point calibration, therefore, yields the highest uncertainty of pH(X), since both slope and offset may change with age of the electrodes, this is the least reliable procedure.

2.1.3.4 *pH Accuracies — Below 1 and Above 13*

Even today, the primary standard is only defined as low as 3 (and the secondary pH standard only as low as 1.67). So, it should not be surprising that for pH values below 1.0 pH, the glass electrode may be subject to a chemical attack and lead to errors in the reported acid values.

Similarly, the accuracy of the measure for pH above 11 with standard glass electrode is subject to cautious review of the medium being tested before using the voltage generated and sampled by the system.

Alternative measurements such as toroidal conductivity measurements might be considered for those extreme pH values.

2.1.3.5 *Processes With Mixed Solvents*

Given that the glass electrodes are mostly designed to measure pH in water solutions, when a non-water solvent is being measured, the pH reading will have an offset from the expected values.

In those situations, study the pH measurement of the mixed solvent solution in the laboratory and correlate the measures with the glass cell measure before going online. Additionally, consider the deterioration of the O-ring of the electrode before going to field measures.

2.1.4 pH Glass Electrode

The modern pH electrode is a combination electrode composed of two main parts: a glass electrode and a reference electrode as shown in Figure 4. pH is determined essentially by measuring the voltage difference between these two electrodes. At the tip of the electrode is the thin membrane that is a specific type of glass that is capable of ion exchange. It is this element that senses the hydrogen ion concentration of the test solution. The reference electrode potential is constant and is produced by the reference electrode internal element in contact with the reference-fill solution that is kept at a pH of seven.

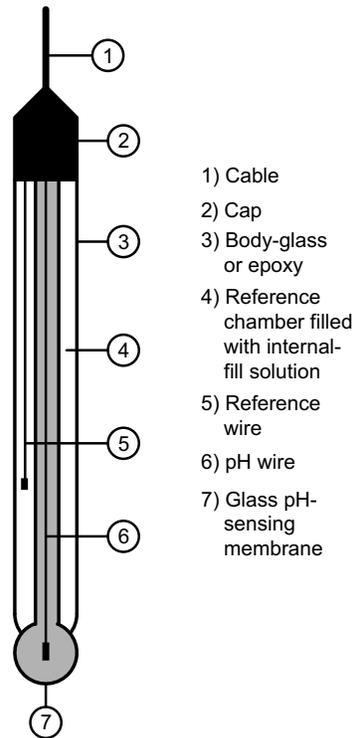


Figure 4. Typical pH Glass Electrode

The slope of the voltage as a function of the pH is called the Nernst potential.

2.1.4.1 pH Electrode Characteristics

When designing with a pH electrode, as with any sensor, it is important to understand the sensor characteristics and how they affect a specific application. These characteristics include whether the sensor is active or passive, unipolar or bipolar, and whether it has a voltage or current output. Sensor sensitivity, linearity, full scale range, and source impedance should also be considered.

The pH electrode is a passive sensor, which means no excitation source (voltage or current) is required. Because the electrode's output can swing above and below the reference point, it is classified as a bipolar sensor. It produces a voltage output that is linearly dependent upon the pH of the solution being measured.

The source impedance of a pH electrode is very high because the thin glass bulb has a large resistance that is typically in the range of 10 to 1000 MΩ. This means that the electrode can only be monitored by a high-impedance measuring device.

The transfer function of the pH electrode is:

$$pH(X) = pH(S) + \frac{(E_s - E_x)F}{RT \ln(10)} \tag{2}$$

where

- pH(X) = pH of unknown solution(X)
- pH(S) = pH of standard solution = 7
- E_s = Electric potential at reference or standard electrode
- E_x = Electric potential at pH-measuring electrode
- F is the Faraday constant = 9.6485309 × 10⁴ C mol⁻¹,
- R is the universal gas constant = 8.314510 J K⁻¹ mol⁻¹
- T is the temperature in Kelvin

The transfer function in [Figure 5](#) and [Figure 6](#) shows that as the pH of the solution increases, the voltage produced by the pH-measuring electrode decreases.

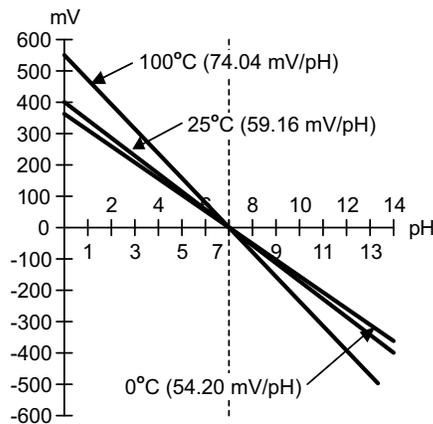


Figure 5. pH-Electrode Transfer Function

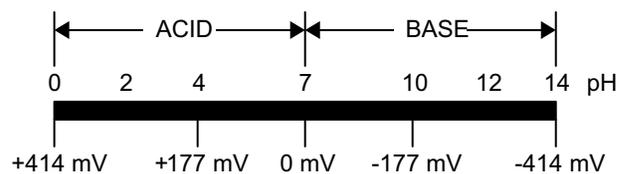


Figure 6. pH Scale

Note that a pH electrode's sensitivity varies over temperature. Looking at the pH-electrode transfer function shows that the sensitivity linearly increases with temperature according to [Equation 3](#):

$$\frac{RT \ln(10)}{F} \text{ or } 0.000198T \text{ V / pH} \tag{3}$$

This results in a sensor output full-scale range that is dependent on the temperature. For example, at 25°C, electrode sensitivity is 59.16 mV/pH and the output of the electrode will swing from $-7 \text{ pH} \times -59.16 \text{ mV/pH} = 414.12 \text{ mV}$ (pH 0 strong acid) to $7 \text{ pH} \times -59.16 \text{ mV/pH} = -414.12 \text{ mV}$ (pH 14 strong base). However, if the measured solution temperature is increased to 100°C, the output will swing from $-7 \text{ pH} \times -74.04 \text{ mV/pH} = 518.29 \text{ mV}$ down to $7 \text{ pH} \times -74.04 \text{ mV/pH} = -518.29 \text{ mV}$. Due to this behavior, it is critical to know the temperature of the solution being measured and compensate the measurement accordingly.

An ideal electrode at 25°C will produce 0 mV when placed in a solution with a pH of seven. Of course, real-world electrodes are not ideal and will have an actual reading that varies from 0 mV. This variation is called the electrode's off set error. As stated previously, the sensitivity of an ideal electrode at 25°C is 59.16 mV per pH unit. Any variation from this ideal value is specified as the electrode's span error. These errors will need to be accounted for through calibration if high system accuracy is required.

2.1.5 Electrical Noise

Given the high output impedance, the most classical approach is to design an active input circuitry with a high input impedance to avoid the voltage readings to be biased because of Ohm's law.

The consequence of this high input impedance circuitry is that in noisy environment, the noise picked up by the pH probe cable can be significant (that is, higher than the stated system accuracy).

To this effect, multiple possibilities exist:

- Analog domain filtering (any way needed for rejection of aliasing noise at the ADC stage)
- Digital domain filtering (which allows having a running average and standard deviation with the extra benefit of rejecting outliers)
- Usage of triax electrode cables (which will shield the signal from the noise)

3 Design Methodology

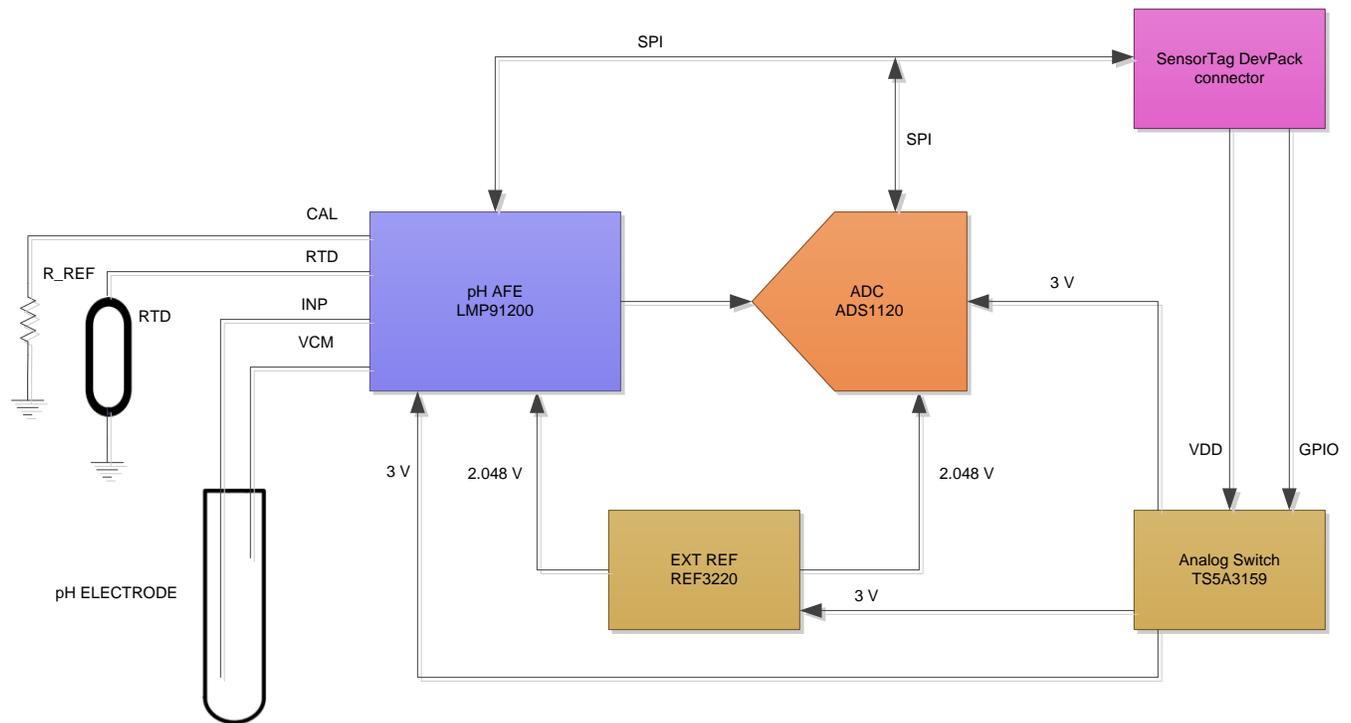


Figure 7. pH Sensor Electronics as Extension Board for Wireless Sensor Tag

A wireless system for pH measurement needs to address multiple functional needs:

- High input impedance for the pH electrode voltage sampling
- Temperature measurement for pH temperature dependency compensation
- Low power to maximize the battery run time
- Noise rejection to minimize the measurement uncertainty

The following sections cover how to solve those design challenges.

3.1 High-Level Design Concepts

3.1.1 Signal Chain

Interfacing a sensor involves a complete signal chain. This design is built around the AFE LMP91200 that represents the first interface to the external probes, the pH electrode, and the RTD sensor (pt100 or pt1000). It sets the voltage common mode (V_{CM}) of the electrode, injects current in the RTD, multiplexes the inputs, and output a differential signal that will be sampled by the analog-to-digital converter (ADC). The low-input bias current of the LMP91200 allows the voltage error produced by the input bias current and electrode resistance to be minimal. In fact, the output impedance of a pH electrode is extremely high, ranging from 10 to 1000 M Ω . For example, assuming that the impedance of the pH electrode used is 10 M Ω and an op-amp with 3 nA of bias current is used, instead of a LMP91200, the error caused due to this amplifier's input bias current and the source resistance of the pH electrode is 30 mV. Using the LMP91200, the error can be reduced to 1.25 μ V with a 125-fA input bias current

3.1.2 ADC

The ADS1120, a precision, sigma-delta 16-bit, ADC, is used to achieve maximum accuracy. Typically, a good pH probe has ± 0.01 -pH resolution and a voltage range from -0.4 to 0.4 V for a pH range between 0 and 14. To detect a 0.01-pH variation, a resolution smaller than 0.51 mV is needed. Considering that the circuitry has 14 effective number of bits (ENOBs), the ADC offers a resolution of 0.125 mV per bit for a 2.048-V reference, which satisfies the best pH probe needs. To benefit from the ADC's full scale of the differential input, a PGA of 4 is used when reading pH data.

3.1.3 PT100 Calibration

A 100- Ω reference resistor with a 0.1% accuracy is used for internal calibration and error compensation. If a PT1000 RTD is used, the 100- Ω reference resistor should be replaced with a 1000- Ω reference resistor. Both the LMP91200 and ADS1120 get the same reference voltage from the REF3220, and both are connected on the same SPI bus.

3.1.4 LMP91200 – pH Front-End

Features:

- Programmable output current in temperature measurement
- Programmable output common mode voltage
- Active guarding
- Onboard sensor test
- Supported by Webench sensor AFE designer
- Supported by Webench sensor designer tools

Key Specifications:

- Unless otherwise noted, typical values at $T_A = 25^\circ\text{C}$, $V_S = (V_{DD} - GND) = 3.3\text{ V}$
- pH buffer input bias current ($0 < V_{INP} < 3.3\text{ V}$)
 - Max @ 25°C : $\pm 125\text{ fA}$
 - Max @ 85°C : $\pm 445\text{ fA}$
- pH buffer input bias current ($-500\text{ mV} < V_{INP} - V_{CM} < 500\text{ mV}$), $V_S = (V_{DD} - GND) = 0\text{ V}$
 - Max @ 25°C : $\pm 600\text{ fA}$
 - Max @ 85°C : $\pm 6.5\text{ pA}$
- pH buffer input offset voltage: $\pm 200\text{ }\mu\text{V}$
- pH buffer input offset voltage drift: $\pm 2.5\text{ }\mu\text{V}/^\circ\text{C}$
- Supply current (pH mode): $50\text{ }\mu\text{A}$
- Supply voltage: $1.8\text{ to }5.5\text{ V}$
- Operating temperature range: -40°C to 125°C
- Package: 16-Pin TSSOP

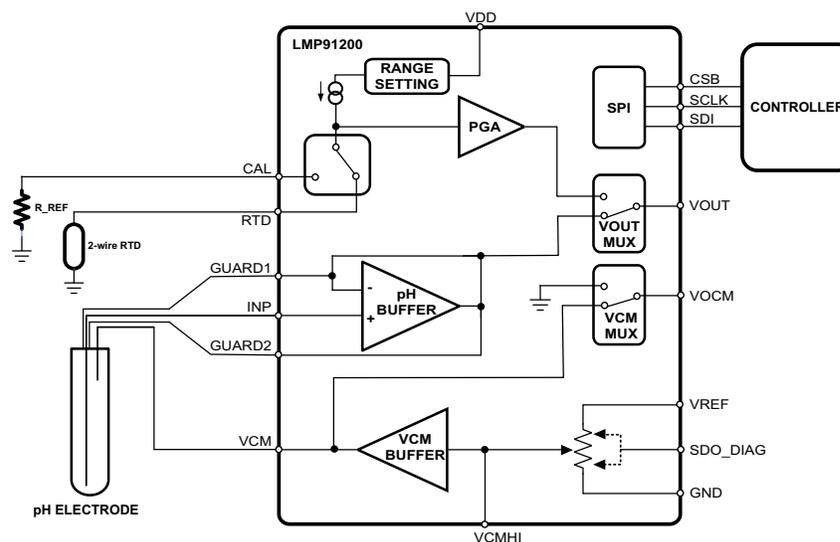


Figure 8. LMP91200 Typical Application

The pH buffer is a unity gain buffer with a low-input bias current. The common mode selector allows to set seven different values of common mode voltage (from $1/8$ to $7/8$ V_{REF} with a $1/8 \cdot V_{REF}$ step) according to the applied voltage reference at the V_{REF} pin.

As described previously, the LMP91200 also supports RTD. The internal current source is a programmable current generator that is able to source four different current values ($100\text{ }\mu\text{A}$, $200\text{ }\mu\text{A}$, 1 mA , 2 mA) to well stimulate PT100 and PT1000 thermal resistors. The selected current is sourced from either the RTD pin (for thermal resistor connection) or CAL pin (for reference resistor connection). The voltage across either the thermal resistor or the reference resistor is amplified by the PGA (5 V/V , 10 V/V) and provided at the VOUT pin when the LMP91200 is set in Temperature Measurement mode.

3.1.5 ADS1120 — Low-Power ADC

Features:

- Low current consumption: As low as 120 μA (typ) in Duty Cycle mode
- Wide supply range: 2.3 to 5.5 V
- Programmable gain: 1 to 128 V/V
- Programmable data rates: Up to 2 kSPS
- 16-bit noise-free resolution at 20 SPS
- Simultaneous 50-Hz and 60-Hz rejection at 20 SPS with single-cycle settling digital filter
- Two differential or four single-ended inputs
- Dual-matched programmable current sources: 50 μA to 1.5 mA
- Internal 2.048-V reference: 5 ppm/ $^{\circ}\text{C}$ (typ) drift
- Internal 2% accurate oscillator
- Internal temperature sensor: 0.5 $^{\circ}\text{C}$ (typ) accuracy
- SPI-compatible interface (Mode 1)
- Package: 3.5x3.5x0.9-mm VQFN

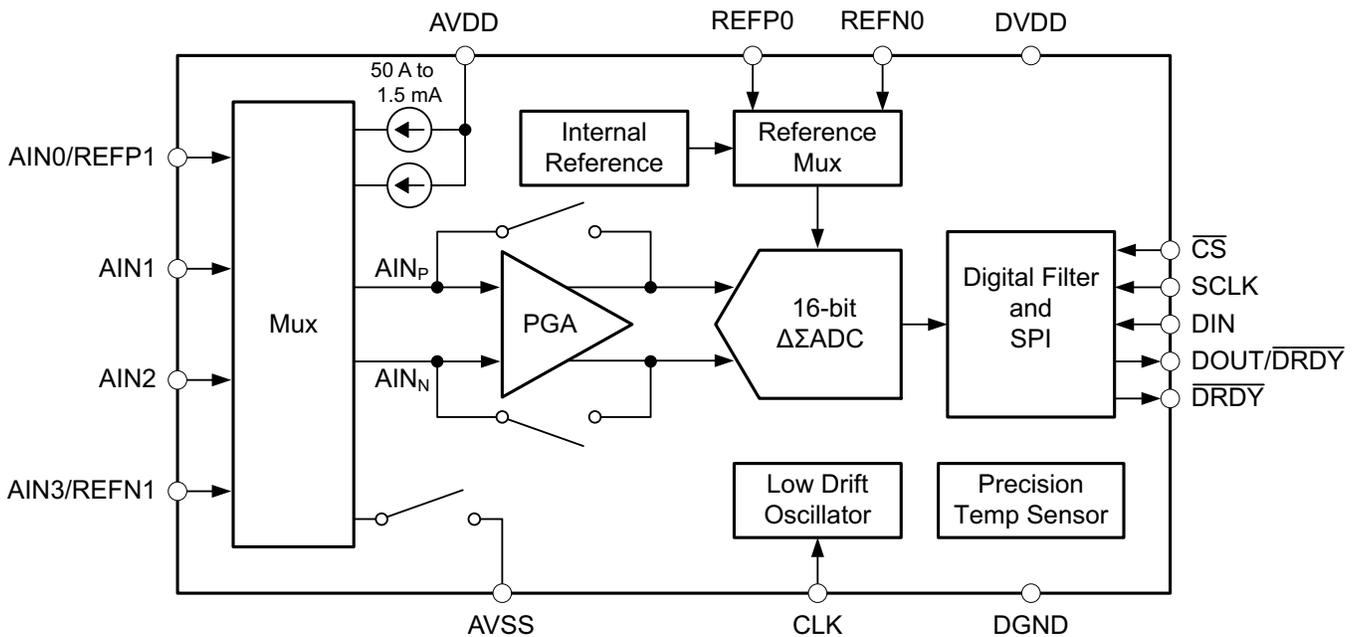


Figure 9. ADS1120 Functional Block Diagram

3.1.6 REF3220 — Voltage Reference

Features:

- Excellent specified drift performance:
 - 7 ppm/°C (max) at 0°C to 125°C
 - 20 ppm/°C (max) at –40°C to 125°C
- Microsize package: SOT23-6
- High output current: ± 10 mA
- High accuracy: 0.01%
- Low quiescent current: 100 μ A
- Low dropout: 5 mV

3.1.7 TS5A3159 — Load Switch for Power Efficiency

Features:

- Specified break-before-make switching
- Low ON-state resistance (1 Ω)
- Control inputs are 5-V tolerant
- Low charge injection
- Excellent ON-resistance matching
- Low total harmonic distortion
- 1.65-V to 5.5-V single-supply operation
- Latch-up performance exceeds 100 mA per JESD 78, Class II
- ESD performance tested per JESD 22
 - 2000-V human-body model (A114-B, Class II)
 - 1000-V charged-device model (C101)

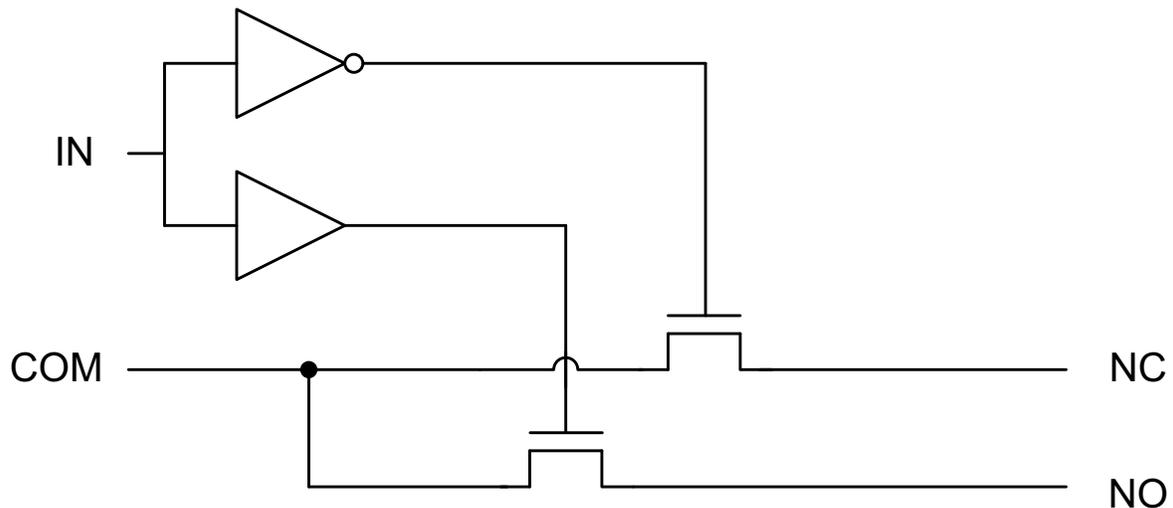


Figure 10. TS5A3159 Block Diagram

4 Design Calculations

This section covers the different key parameters of the datasheets needed to complete the electronic design.

4.1 Signal Conditioning

The V_{OUT} and V_{OCM} provided by the LMP91200 to the inputs of the ADS1120 are not within the linear operating range of the PGA. The requirements for the input common-mode voltage range are given by the following equations:

$$V_{CM(MIN)} \geq AVSS + 0.2 + \frac{V_{IN} \times PGA}{2} \quad (4)$$

$$V_{CM(MIN)} \geq AVDD - 0.2 - \frac{V_{IN} \times PGA}{2} \quad (5)$$

In addition to these equations, the minimum V_{CM} must also meet [Equation 6](#) because of the specific design implementation of the PGA:

$$V_{CM(MIN)} \geq AVSS + \frac{AVDD - AVSS}{2} \quad (6)$$

In order to calculate the minimum and maximum common-mode voltage limits, the maximum differential input voltage ($V_{IN(MAX)}$) that occurs in the application must be used.

In this design, $A_{INn} = V_{REF} / 2 = 1.024$ and $A_{INp} = 1.024 \pm 415$ mV, which is the measured pH value. The common mode voltage injected to the pH electrode is equal to 1.024 V. To get the highest resolution, the maximum settable gain is equal to 4, so the PGA does not saturate. However, with the gain equal to 4 and powering up the ADS1120 with $AVDD = 3.3$ V, this design does not respect the requirements for the input common-mode voltage range of the PGA. Considering $V_{IN(MAX)} = A_{INn} - A_{INp(MIN)} = 1.024 - 0.609 = 0.415$ V, the lower limit of V_{CM} has to be equal to 1.03 V and the higher one equal to 2.27 V. In this case, $V_{CM} = (A_{INp} + A_{INn}) / 2$ is equal to 0.8165 V, violating the lower limit.

Due to that, the ADS1120 was configured to bypass the internal PGA while still providing high input impedance and a gain of 4 V/V.

4.2 Accuracy

From a pure electronic standpoint, the accuracy and repeatability of the measurement will be determined by:

- The input referred noise of the LMP91200: $E_{n_RMSpH} = 4$ μ V
- The input referred noise of the ADS1120: $N_{ADS1120} = 3.71$ μ V_{RMS}
- The offset of the LMP91200: 200 μ V
- The offset of the ADS1120: $V_{IO} = \pm 30$ μ V
- The cut-off frequency of the anti-aliasing filter at the input of the ADS1120
- The amplification of the PGA in the ADS1120

After calibrating to remove offset and gain errors:

$$\text{Total Error Budget} = \sqrt{((E_{n_RMSpH} + N_{ADS1120}) \times 4)^2} = 30 \mu\text{V}_{RMS} \quad (7)$$

Considering the ADS1120 $LSB = V_{REF} / 2^N = 2.048 / 2^{16} = 31$ μ V leads to the electronic noise contribution to the system.

5 Layout Consideration

This section covers mechanical needs for SensorTag and layout considerations for low-noise pickup from the pH.

The designed board has to be mechanically stacked with the SensorTag board, and then both have to fit inside a red rubber case to have a portable system. In this sense, the dimension of the board and the position of the skin connector play a crucial role.

In order to connect the two boards properly, it is important that the bottom layer of the designed board is without components apart from the skin connector. Also, all the components placed on the top layer have to be SMD because the through hole ones could cause connectivity problems due to their leads that protrude through a PCB.

In pH measurement, due to the high impedance of the pH electrode, careful circuit layout is required. Guarding techniques are highly recommended to reduce parasitic leakage current by isolating the LMP91200's input from large voltage gradients across the PCB. A guard is a low impedance conductor that surrounds an input line and its potential is raised to the input line's voltage. The input pin should be fully guarded as shown in the layout. The guard traces should completely encircle the input connections. In addition, they should be located on both sides of the PCB and be connected together. The LMP91200 makes the guard ring easy to be implemented without any other external op-amp. The ring needs to be connected to the guard pins (GUARD1 and GUARD2), which are at the same potential of the INP pin. The solder mask should not cover the input and the guard area including guard traces on either side of the PCB.

Also for wireless designs, the RF transceiver should be located as far as possible from the pH probe.

6 Verification and Characterization

This section covers how the TI Design was tested and the results of the characterization.

The tests were performed using the MSP430FR5969 LaunchPad connected to the TIDA-00561 through a pin header to hermaphroditic strip connector, and then a pH electrode is connected to the TIDA-00561. Energia code was implemented to configure the ADS1120 and LMP91200, acquire the data through SPI, and show them to the serial monitor of the PC.

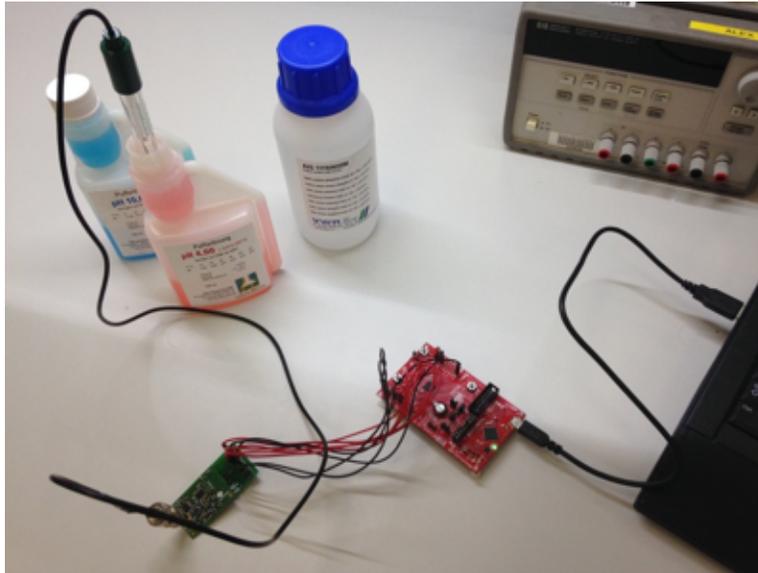


Figure 11. Test Setup

Two different tests were carried out, one measuring different pH values with a pH probe from EXTECH INSTRUMENTS (601500) and three pH buffers solutions (4, 10, and 7) and another one shorting the input of the TIDA-00561 with a 50-Ω SMA connector, measuring the V_{OUT} over temperature. The pH probe has a pH range from 0 to 14 and an accuracy of 0.02 pH. The pH value depends on the temperature according to this formula:

$$E = E_0 + \left(2.3 \frac{RT}{nF} \right) \log aH^+ \quad (8)$$

where

- E is the measured potential from the sensing electrode
- E_0 is related to the potential of the reference electrode
- $(2.3 RT/nF)$ is the Nernst factor
- $\log aH^+$ is the pH (aH^+ = activity of Hydrogen ions)

$2.3 RT/nF$ includes the Gas Law constant (R), Faraday's constant (F), the temperature in Kelvin (T), and the stoichiometric number of ions involved in the process (n). For pH, where $n = 1$, the Nernst factor is $2.3 RT/nF$. Since R and F are constants, the factor and therefore electrode behavior are dependent on temperature. The Nernst factor is equivalent to the electrode slope, which is a measure of the electrode response to the ion being detected.

When the temperature is 25°C, the theoretical Nernst slope is 59.16 mV/pH units. The temperature is measured by the RTD on the TIDA-00561. Note that the best approach would be to have the RTD directly inside the buffer solution because the temperature in there could vary from the environmental temperature.

This design has an SMD RTD on board due to space and because the SensorTag is equipped with an IR Thermopile Temperature Sensor (TMP007) able to detect the temperature in the solution. For the first test, 1000 pH values were acquired for the three different solutions at room temperature (~25°C).

First of all, the voltage value with a pH buffer equal to 7 was measured. The user should ideally obtain 0 mV; however, it is possible to see from the histogram a median value equal to 10.92 mV. Many factors introduce errors, like the buffers solution accuracy, the electrode accuracy, the error introduced by the TIDA-00561 itself, and the temperature.

The range, or the maximum minus the minimum measured voltage, is equal to 328.13 μ V, which shows that the signal is pretty noisy. This is due to the high impedance of the pH electrode that is very sensitive to external disturbances. As well the coaxial cable does not reject interference due to the fact that it does not have an extra layer of insulation and a second conducting sheath like the triax cable. Short cables are preferable to long ones for pH measurements.

However, the standard deviation equal to 61.78 μ V, which suggests that the high range issue is mainly due to outliers. Since no average was performed to the results, one can conclude that we obtained what we have expected. To calculate the pH, use Equation 9, which is derived by the previous one and considering a temperature equal to 25°C:

$$pH = 7 - \frac{V_{OUT} (mV)}{59.16 \left(\frac{mV}{pH} \right)} \tag{9}$$

The median is equal to 6.79 pH, the range is equal to 0.005 pH, and the standard deviation is 0.001 pH—values much smaller than the accuracy of the pH electrode (0.02 pH).

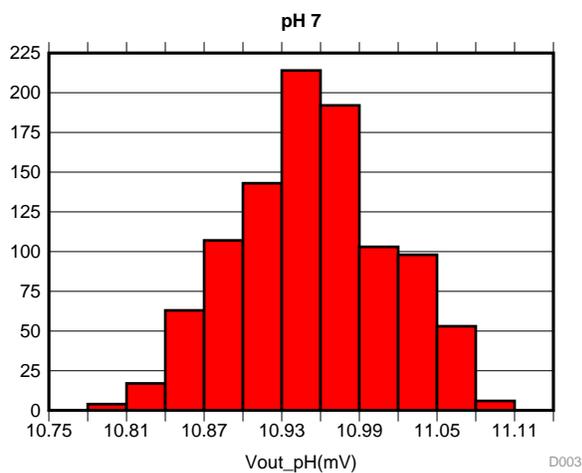


Figure 12. Measured V_{OUT} When pH Buffer Equals 7

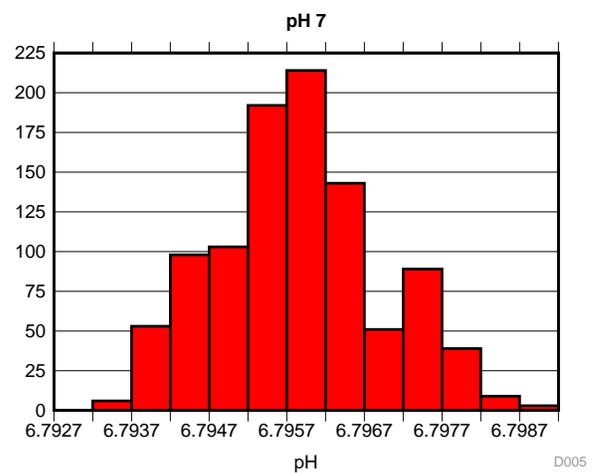


Figure 13. Measured pH When pH Buffer Equal 7

The same analysis was conducted for pH values equal to 4.01 and 9.94. The results are in the following graphs:

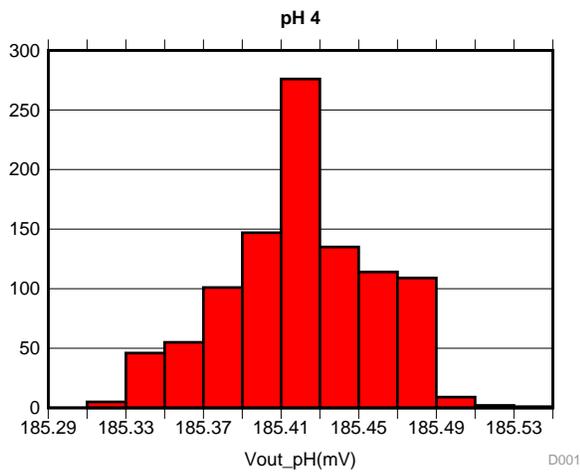


Figure 14. Measured V_{OUT} When pH Buffer Equals 4

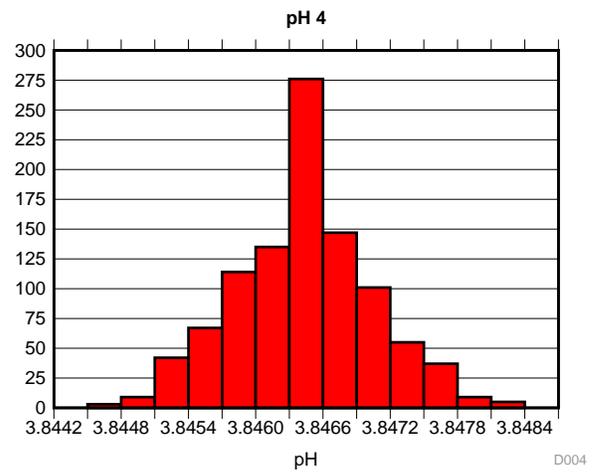


Figure 15. Measured pH When pH Buffer Equals 4

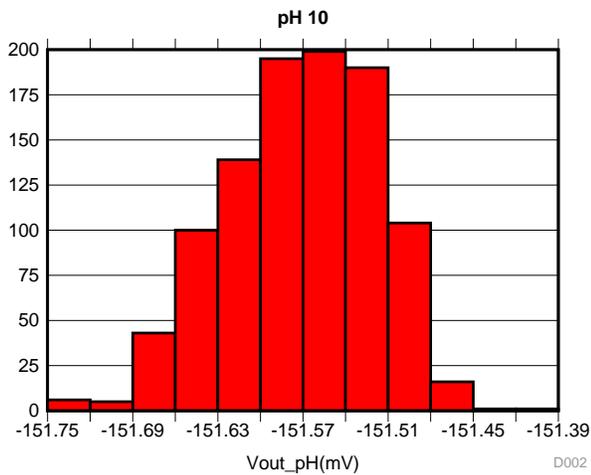


Figure 16. Measured V_{OUT} When pH Buffer Equals 10

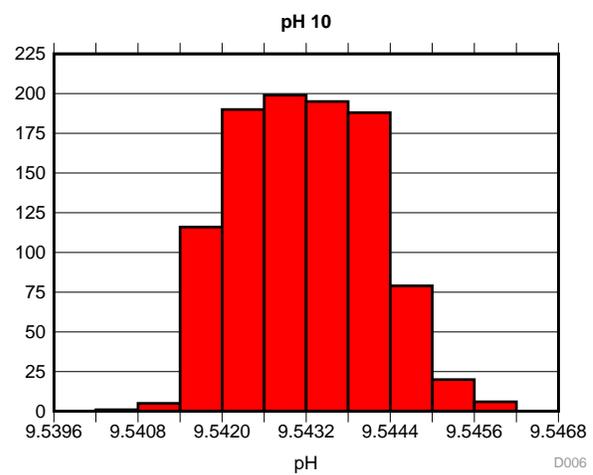


Figure 17. Measured pH When pH Buffer Equals 10

The standard deviation and range of pH 4 and pH 10 are very similar to the one calculated with pH 7, as seen in [Table 5](#).

Table 5. Test Results

pH	4	7	10
V_{std_dev}	0.04 mV	0.06 mV	0.05 mV
$V_{range(max-min)}$	0.22 mV	0.33 mV	0.34 mV
V_{median}	185.4 mV	10.9 mV	-151.6 mV
pH	4	7	10
pH_{std_dev}	0.0006 pH	0.001 pH	0.0009 pH
$pH_{range(max-min)}$	0.004 pH	0.005 pH	0.006 pH
pH_{median}	3.85 pH	6.79 pH	9.54 pH

The median values are affected by the offset and gain error and the fact that the solution or the electrode could be a bit contaminated by previous measurements or the aging of the buffer solutions that could change slightly the value of it.

As previously mentioned, the measurements over temperature were made with the input short circuited, so there were no disturbances from the pH probe. For each temperature (-40°C , 25°C , and 85°C) 1000 measurements of V_{OUT} are acquired. As seen from the histogram, the results are pretty stable varying only between two codes for each temperature.

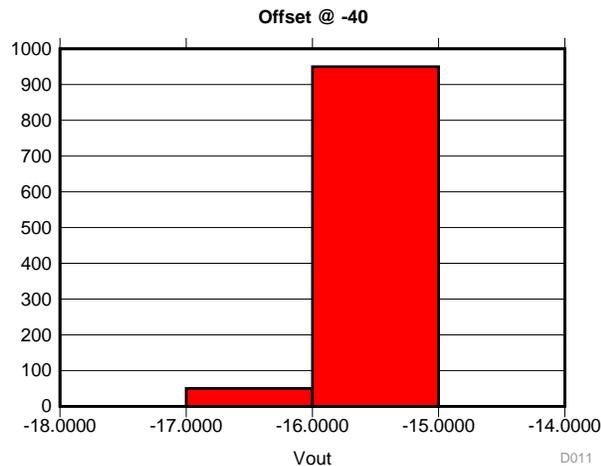


Figure 18. Measured Offset at -40°C

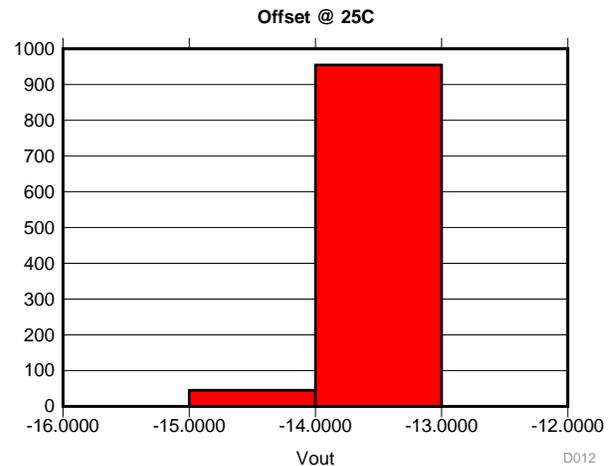


Figure 19. Measured Offset at 25°C

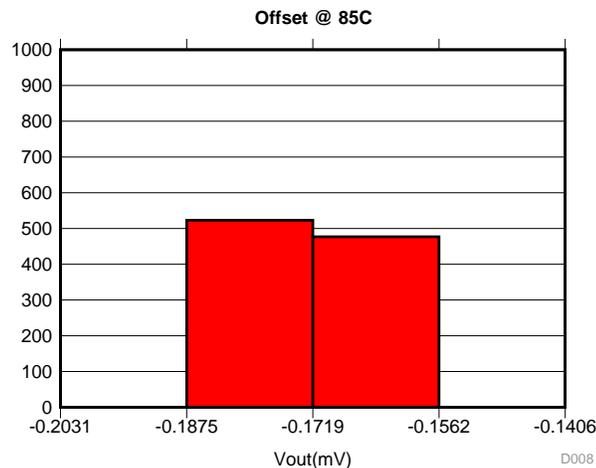


Figure 20. Measured Offset at 85°C

The results at room temperature are comparable to the noise performance shown in the datasheet of the ADS1120, where it says that the ENOB with PGA disabled, AVDD = 3 V, AVSS = 0 V, VREF = 2.048 (although in the TIDA-00561 there is an external reference), and the ADC is working in normal operation mode. Finally, in [Figure 21](#), V_{OUT} in function of the temperature shows that the offset drift is equal to $0.5 \mu\text{V}/^\circ\text{C}$.

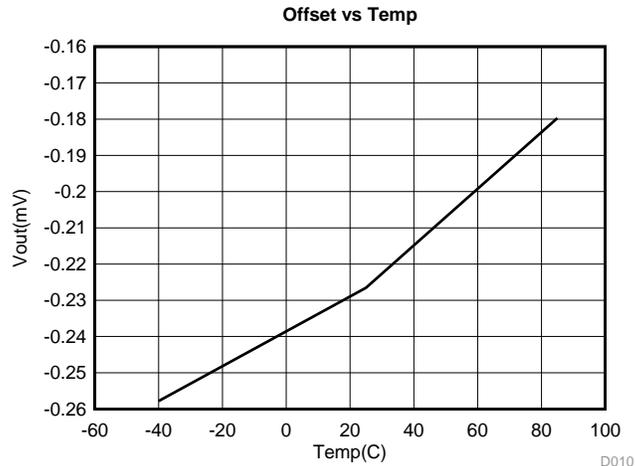


Figure 21. Offset Drift versus Temperature

7 Getting Started

For general information about SensorTag, refer to the SensorTag wiki (<http://processors.wiki.ti.com/index.php/SensorTag2015>).

To setup the wireless pH:

1. Download IAR Embedded Workbench for ARM.
2. Connect the SensorTag to the PC through the XDS200 USB Debug Probe. Do not remove the battery from the SensorTag.
3. Upload the Wireless pH Sensor Transmitter DevPack Firmware to the SensorTag. For the Wireless pH Sensor Transmitter DevPack Firmware, contact your TI representatives.
4. Upload the Wireless pH Sensor Transmitter DevPack Android™ App to the desired Android device. For the Wireless pH Sensor Transmitter DevPack Android App, contact your TI representatives.
5. Connect the Wireless pH to the sensor tag:
 - (a) Remove the red casing.
 - (b) Mount the Wireless pH Sensor Transmitter DevPack on the SensorTag.
 - (c) Connect the pH probe through an SMA-to-BNC adapter to the Wireless pH Sensor Transmitter DevPack.
 - (d) Immerse the pH probe in the desired medium.
6. Turn the SensorTag 'ON'.
7. Start the application on the Android device.
8. Read the pH value on the Android device.

NOTE: Take care once the pH probe is not in usage to ensure its lifetime is maximized. For more details, refer to the pH probe's manufacturer instructions.

8 Design Files

8.1 Schematics

To download the schematics, see the design files at [TIDA-00561](#).

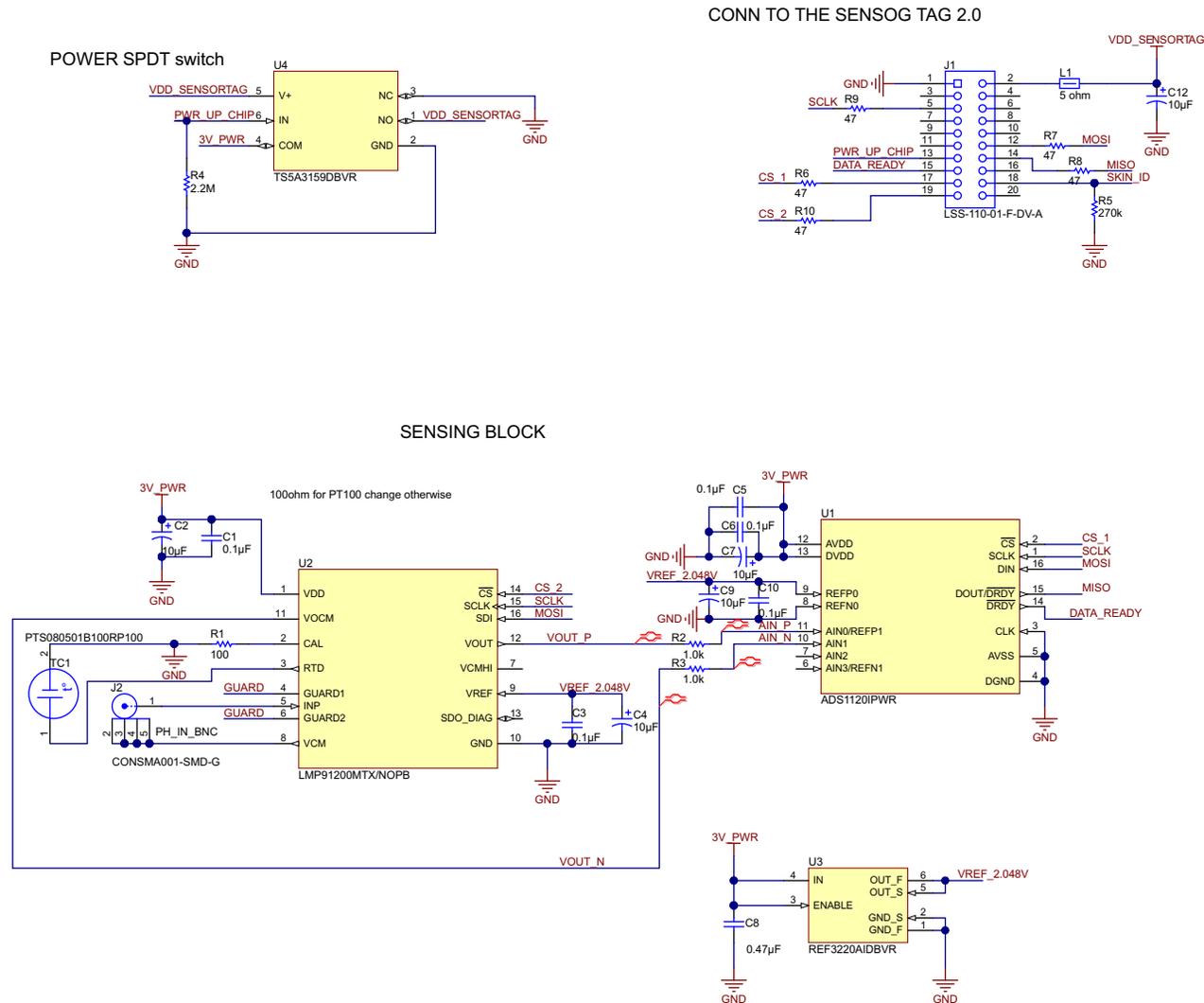


Figure 22. Wireless pH Sensor Schematic

8.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-00561](#).

8.3 Layer Plots

To download the layer plots, see the design files at [TIDA-00561](#).

8.4 Altium Project

To download the Altium project files, see the design files at [TIDA-00561](#).

8.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-00561](#).

8.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-00561](#).

9 Software Files

To download the software files, please contact your TI sales representative.

10 References

1. International Union Of Pure and Applied Chemistry, *MEASUREMENT OF pH. DEFINITION, STANDARDS, AND PROCEDURES (IUPAC Recommendations 2002)* (<http://www.iupac.org/publications/pac/2002/pdf/7411x2169.pdf>)
2. International Union Of Pure and Applied Chemistry, *DEFINITION OF pH SCALES, STANDARD REFERENCE VALUES, MEASUREMENT OF pH AND RELATED TERMINOLOGY*, (<http://pac.iupac.org/publications/pac/pdf/1983/pdf/5509x1467.pdf>)
3. Chemistry International, *A Century of pH Measurement*, Vol. 32, No. 2, March-April 2010 (http://www.iupac.org/publications/ci/2010/3202/1_mfcames.html)
4. Chemical Education Today, *Negative pH Does Exist*, (<http://pubs.acs.org/doi/pdf/10.1021/ed083p1465>)
5. Ivanov V. V., *The present hydrothermal activity of the volcano Ebeko on island of Paramshir*, Geokimiya No 1, p.63–67, 1957
6. Nikitina, L. P. Presented at Proceedings of the Water-Rock Interaction Symposium, Prague, Czechoslovakia, 1974
7. Nordstrom, Darrell Kirk; Alpers, C. N. *Proceeding National Academy Science USA*, 1999, 96, 3455
8. Nordstrom, Darrell Kirk; Alpers, C. N.; Ptacek, C. J.; Blowes, D. W. *Environ. Sci. Technol.* 2000, 34, 254
9. Nordstrom, Darrell Kirk. Geological Survey: *Negative pH and Extremely Acidic Mine Waters from Iron Mountain, California*, USGS Staff, Published Research US Geological Survey, Jan 1, 2000, *Environmental Science & Technology*, 34, p.254–258
10. Yokogawa Electric Corporation, *PH450G 4-Wire pH/ORP Analyzer*, Product Page (<http://www.yokogawa.com/an/ph-orp/an-ph450g-001en.htm>)
11. Emerson Process Management, *The Theory of pH Measurement*, Application Datasheet ([PDF](#))

11 About the Author

MATTHIEU CHEVRIER is a Systems Architect at Texas Instruments, where he is responsible for defining and developing reference design solutions for the industrial segment. Matthieu brings to this role his extensive experience in embedded system designs in both hardware (power management, mixed signal, and so on) and software (such as low level drivers, RTOS, and compilers). Matthieu earned his Master of Science in electrical engineering (MSEE) from Supélec, an Ivy League university in France. Matthieu holds patents from IPO, EPO, and USPTO.

GIOVANNI CAMPANELLA is an Industrial Systems Engineer with the Field Transmitter Team in the Factory Automation and Control organization. He earned his bachelor's degree in electronic and telecommunication engineering at the University of Bologna and his master's degree in electronic engineering at the Polytechnic of Turin in Italy. His design experience covers sensors and analog signal chain (with a focus on Fluxgate and analytics sensing technologies) and mixed-signal control of DC brushed servo drives.

AMJAD EL HILALI is a Field Application Engineer at Texas Instruments where he is responsible for technical support for industrial customers. Amjad brings to this role his experience in both hardware design (sensing and power management) and software design (RTOS, RF protocols, and signal processing). Amjad earned his master's degree in electrical engineering from INSA de Lyon University in France.

Revision B History

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

Changes from A Revision (August 2015) to B Revision	Page
• Changed location of software files.....	26

Revision A History

Changes from Original (June 2015) to A Revision	Page
• Changed from preview page.....	1

IMPORTANT NOTICE FOR TI REFERENCE DESIGNS

Texas Instruments Incorporated ("TI") reference designs are solely intended to assist designers ("Designer(s)") who are developing systems that incorporate TI products. TI has not conducted any testing other than that specifically described in the published documentation for a particular reference design.

TI's provision of reference designs and any other technical, applications or design advice, quality characterization, reliability data or other information or services does not expand or otherwise alter TI's applicable published warranties or warranty disclaimers for TI products, and no additional obligations or liabilities arise from TI providing such reference designs or other items.

TI reserves the right to make corrections, enhancements, improvements and other changes to its reference designs and other items.

Designer understands and agrees that Designer remains responsible for using its independent analysis, evaluation and judgment in designing Designer's systems and products, and has full and exclusive responsibility to assure the safety of its products and compliance of its products (and of all TI products used in or for such Designer's products) with all applicable regulations, laws and other applicable requirements. Designer represents that, with respect to its applications, it has all the necessary expertise to create and implement safeguards that (1) anticipate dangerous consequences of failures, (2) monitor failures and their consequences, and (3) lessen the likelihood of failures that might cause harm and take appropriate actions. Designer agrees that prior to using or distributing any systems that include TI products, Designer will thoroughly test such systems and the functionality of such TI products as used in such systems. Designer may not use any TI products in life-critical medical equipment unless authorized officers of the parties have executed a special contract specifically governing such use. Life-critical medical equipment is medical equipment where failure of such equipment would cause serious bodily injury or death (e.g., life support, pacemakers, defibrillators, heart pumps, neurostimulators, and implantables). Such equipment includes, without limitation, all medical devices identified by the U.S. Food and Drug Administration as Class III devices and equivalent classifications outside the U.S.

Designers are authorized to use, copy and modify any individual TI reference design only in connection with the development of end products that include the TI product(s) identified in that reference design. HOWEVER, NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT OF TI OR ANY THIRD PARTY IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of the reference design or other items described above may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI REFERENCE DESIGNS AND OTHER ITEMS DESCRIBED ABOVE ARE PROVIDED "AS IS" AND WITH ALL FAULTS. TI DISCLAIMS ALL OTHER WARRANTIES OR REPRESENTATIONS, EXPRESS OR IMPLIED, REGARDING THE REFERENCE DESIGNS OR USE OF THE REFERENCE DESIGNS, INCLUDING BUT NOT LIMITED TO ACCURACY OR COMPLETENESS, TITLE, ANY EPIDEMIC FAILURE WARRANTY AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY DESIGNERS AGAINST ANY CLAIM, INCLUDING BUT NOT LIMITED TO ANY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON ANY COMBINATION OF PRODUCTS AS DESCRIBED IN A TI REFERENCE DESIGN OR OTHERWISE. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, DIRECT, SPECIAL, COLLATERAL, INDIRECT, PUNITIVE, INCIDENTAL, CONSEQUENTIAL OR EXEMPLARY DAMAGES IN CONNECTION WITH OR ARISING OUT OF THE REFERENCE DESIGNS OR USE OF THE REFERENCE DESIGNS, AND REGARDLESS OF WHETHER TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

TI's standard terms of sale for semiconductor products (<http://www.ti.com/sc/docs/stdterms.htm>) apply to the sale of packaged integrated circuit products. Additional terms may apply to the use or sale of other types of TI products and services.

Designer will fully indemnify TI and its representatives against any damages, costs, losses, and/or liabilities arising out of Designer's non-compliance with the terms and provisions of this Notice.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2016, Texas Instruments Incorporated