TI Designs: TIDA-00854
Micropower Electrochemical Gas Sensor Amplifier Reference Design

![TEXAS INSTRUMENTS]

Description

This reference design is a micropower, two- or three-terminal electrochemical cell amplifier that uses less than 1-µA total supply current for battery-powered or energy-harvested sensor applications.

Electrochemical cells require constant bias, which requires the amplifier circuit to be powered continuously to eliminate sensor start-up and settling times.

The design is built on a PC board compatible with the TI LaunchPad™ Development Kit platform to allow testing with an MSP430™ ultra-low-power processor to utilize the LaunchPad processor analog-to digital converters (ADCs) and liquid crystal display (LCD) for stand-alone operation. A three-terminal carbon monoxide sensor is used as a electrochemical cell example.

The open source firmware has been written in Code Composer Studio™ software for easy customization.

Resources

TIDA-00854	Design Folder
MSP430FR6989	Tool Folder
LPV802[1]	Product Folder
HDC1080	Product Folder
REF1112	Product Folder

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[1] See Table 2 for more available options.

Features

- Potentiometric-Type Amplifier Adaptable for Many Electrochemical Cell Applications
- Accommodates Biased and Unbiased Sensors
- Adaptable to Many Two- and Three-Terminal Electrochemical Cell Applications
- Micropower (< 1 µA) Total Amplifier Circuit Supply Current
- Example Circuit Uses Three-Terminal Carbon Monoxide Sensor
- BoosterPack™ Plug-in Module for Use With MSP430 LaunchPad Development Platform
- Readings Display on LCD
- Timer and Multiple GPIO Pins Available for Proprietary Communications (Optional)
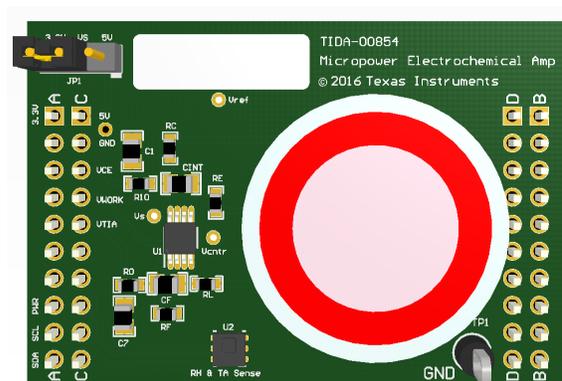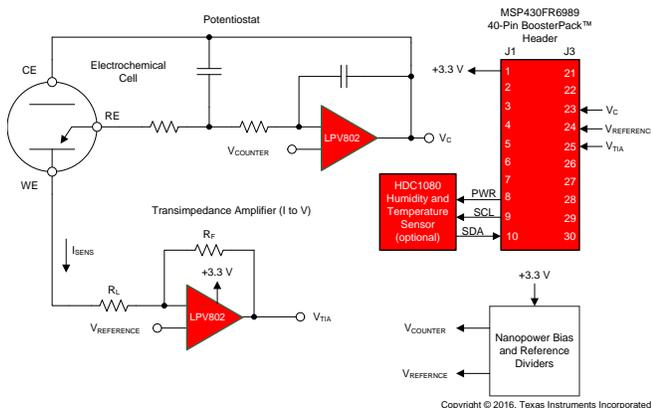- Optional Temperature and Humidity Measurement Capability

Applications

- Electrochemical Gas Detectors
- Biotransducers and Biosensors
- Electrochemistry
- Galvanostats

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 Description

At the time of this writing, electrochemical cells are being used increasingly in portable and long-life fixed monitoring devices. Such examples are glucose and other portable bio-medical devices and long-life battery powered devices, such as carbon monoxide (CO) gas and environmental monitors. Because of the nature of these sensors, they must be continuously biased to maintain proper operation. Power cycling is generally not suitable because of the long recovery time, re-zeroing requirements, or even possible sensor damage that power cycling causes. The ideal configuration is to leave the sensor continuously biased and power cycle the rest of the monitoring device.

This reference design describes the design of a nano-power, potentiostat-type electrochemical sensor circuit. While this design uses a three-terminal CO gas sensor as an example, the basic example circuit can be adapted for other types of two-, three-, even four-terminal electrochemical, potentiostatic, or amperometric cells used in the gas, industrial, and medical fields.

The design consists of a three-terminal electrochemical sensor amplifier circuit providing the sensor bias and current to voltage conversion, a selectable shunt reference or resistive divider bias voltage circuit, an MSP430 LaunchPad providing the analog-to-digital conversion, processing functions, and display functions.

Using a nano-power amplifier circuit allows the sensor circuit to function continuously and independently of the monitoring processor to keep the sensor biased continuously for immediate readings and to avoid lengthy start-up and settling times.

The LPV802 dual, micropower amplifier has been chosen for its ultra-low power (typically 320 nA per channel) so that the entire potentiostat circuit uses less than 1 µA of supply current, which allows the circuit to stay continuously powered in battery-powered applications.

The design has been implemented on a PC board compatible with the TI MSP430 LaunchPad BoosterPack specification. This configuration allows the user to leverage the MSP430 LaunchPad platform to acquire, calculate, log, and display the measurement results. The MPS430FR6989 LaunchPad board has been selected because of the multiple ADC input pins, ultra-low-power mode capability, USB connectivity, and onboard LCD.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Supply voltage	2.7 to 3.6 V	3.3-V nominal
Measurement range	0 to 300 ppm	
Baseline offset	Dependent on sensor: typically ±2 ppm	Amplifier only: ± 0.1 ppm
Accuracy	Dependent on sensor: typically ±5%	Amplifier only: ±0.2%
Response time	Dependant on sensor: typically < 30 s	Amplifier only: < 1 s
Operating temperature range	−20°C to +50°C	Mainly limited by sensor
Supply current, 0 ppm	<1 µA	Amplifier only: sensor current extra
Supply current, 300 ppm	Sensor current + 1 µA	

2   System Overview

2.1   Block Diagram
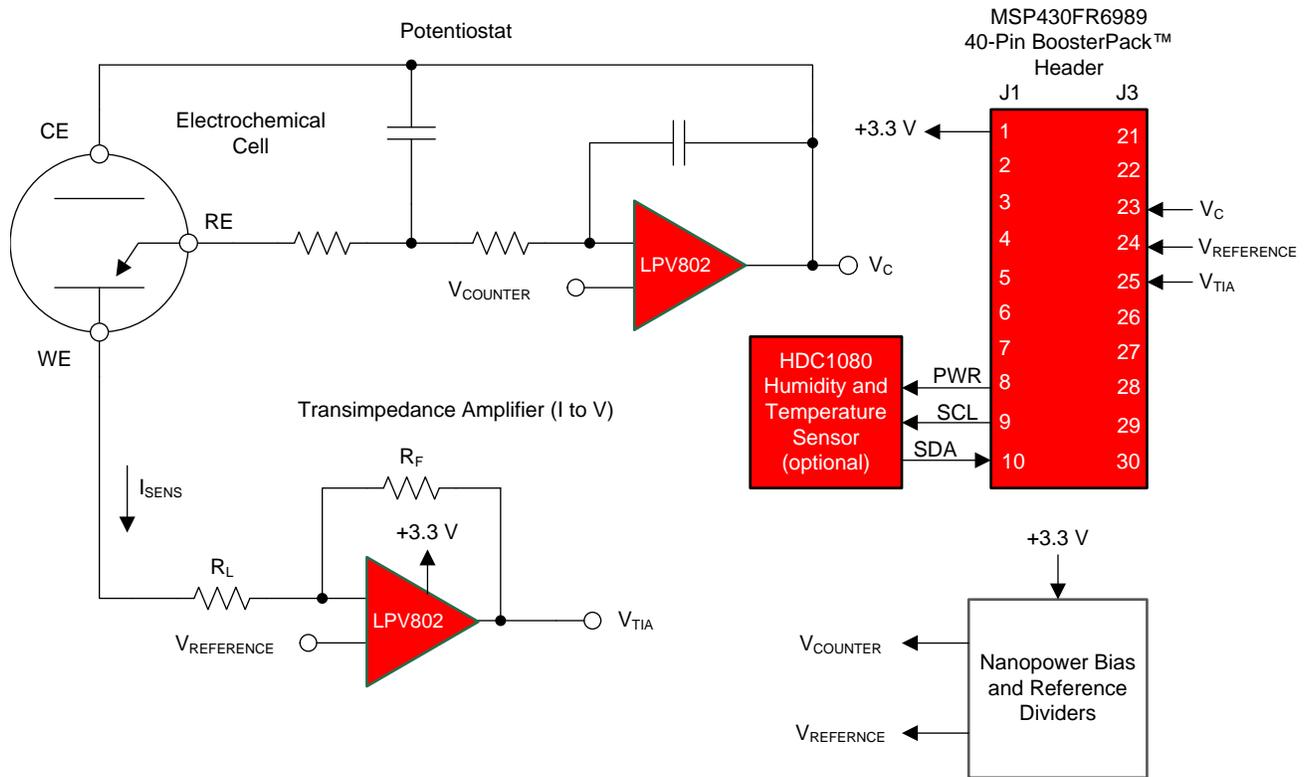
Figure 1. TIDA-00854 Block Diagram

2.2 *Highlighted Products*

2.2.1 LPV802 Dual, Nano-Power Operational Amplifier

The LPV802 is a dual, nano-power operational amplifier (op amp). The low, 640-nA typical total supply current for both channels allows the amplifier to be continuously powered to maintain continuous cell bias. This feature avoids power-cycling measurements with the resulting lengthy start-up times.

Table 2. Precision Nano-Power Amplifier Family

FAMILY	CHANNEL COUNT	I_Q PER CHANNEL	V_{OS} (MAXIMUM)	V_{SUPPLY}
LPV821	1	700 nA	20 µV	1.7 to 3.6 V
LPV811	1	450 nA	370 µV	1.6 to 5.5 V
LPV812	2	425 nA	300 µV	1.6 to 5.5 V
OPA369	1,2	800 nA	750 µV	1.8 to 5.5 V

2.2.2 REF1112 Nano-Power Voltage Reference

The REF1112 provides a stable reference voltage at sub-microamp supply currents. The REF1112 can be operated at currents as low as 900 nA.

2.2.3 HDC1080 Self-Contained, High-Accuracy Humidity and Temperature Sensor

The HDC1080 is a digital humidity sensor with an integrated temperature sensor that provides excellent measurement accuracy at very low power in a tiny 3x3-mm package. The 14-bit factory calibrated temperature and humidity readings are simply read directly over a standard two-wire I^2C interface.

2.2.4 MSP430FR6989 LaunchPad Development Kit

The MSP430FR6989 LaunchPad Development Kit is used as the basis for the analog-to-digital conversion, processing, serial communication, and LCD. The MSP430RF6989 features a standby current as low as 350 nA, sixteen 12-bit analog-to-digital converter channels, an internal 2.5-V reference, a Flash Emulation Tool (FET) programmer, and an onboard LCD.

2.3 System Design Theory

A basic understanding of the electrochemical or amperometric sensor operation is helpful before addressing the operation of the amplifier circuitry.

2.3.1 Three-Terminal Sensor Description

The basic electrochemical cell has three electrodes. As Figure 2 shows, these electrodes are the working electrode (WE), which is also known as the sense electrode (SE), the counter electrode (CE), and the reference electrode (RE).
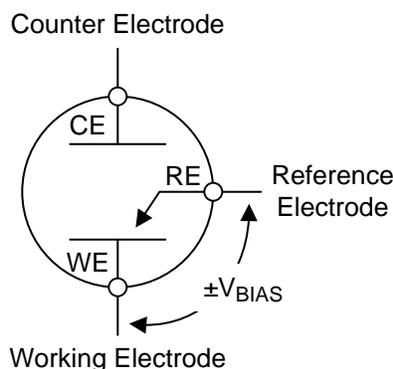
Counter Electrode

CE

RE Reference
Electrode

WE

$\pm V_{BIAS}$

Working Electrode

Figure 2. Basic Three-Terminal Electrochemical Cell Connections

A current is generated between the CE and the WE in proportion to the detected concentration.

The RE monitors the potential of a reference point internal to the sensor. The reference terminal is a high-impedance voltage monitoring point and must not have any current flowing in or out of the terminal.

The RE-monitoring amplifier input must have very low bias currents to avoid causing errors. CMOS or JFET input amplifiers are typically used because of their input-low bias currents (<1 pA). The LPV802 is a CMOS input amplifier with bias currents typically sub-picoamp and easily meets this requirement.

2.3.1.1 Sensor "Bias" Voltage

For the three-terminal sensor to operate correctly, the WE must be kept at a constant potential with respect to the RE.

The voltage potential difference between the WE and RE is referred to as the sensors "bias" voltage.

For the majority of sensors, the bias voltage is 0 V (RE and WE potentials are the same). However, some sensors may require the RE potential to be between –300 mV to +1 V in relation to the WE. The possibility of this sensor requirement must be accommodated for when designing the biasing of the amplifier circuit.

The polarity of the current generated by the sensor requires observation. Depending on the type of sensor chemistry, the generated current can be positive or negative.

2.3.2 Basic Three-Terminal Sensor Circuit Description

The basic three-terminal sensor circuit comprises two main sections (see Figure 3):

1. A potentiostat bias feedback circuit to maintain the proper sensor RE to WE electrode bias
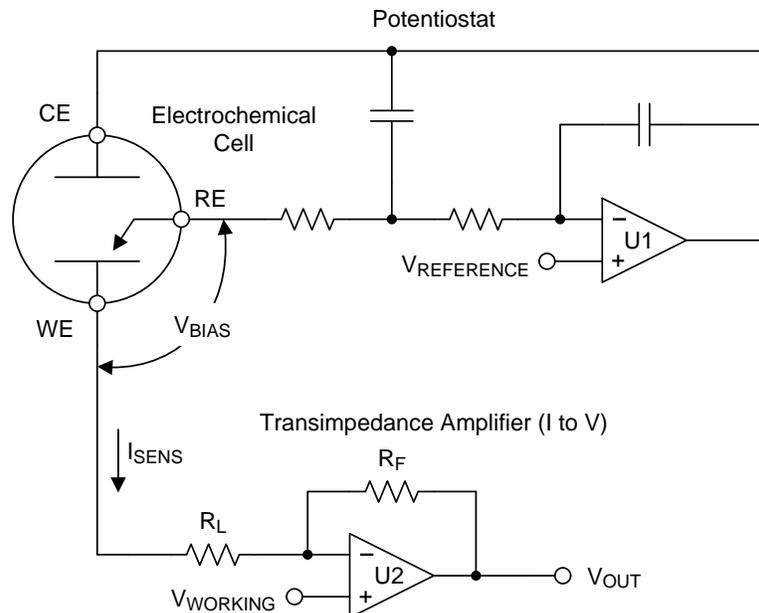2. A transimpedance amplifier (TIA) to convert the sensor current into a voltage

Figure 3. Simplified Electrochemical Measurement Circuit

2.3.2.1 Potentiostat Section

The potentiostat-biasing circuit forms a feedback loop with U1. The loop maintains the proper bias potential at the RE, which adjusts the voltage on the CE to maintain the balance.

The voltage at which to maintain RE is set by the non-inverting input of U1, which the preceding Figure 3 labels as $V_{REFERENCE}$. Through the feedback action, the U1 amplifier output continuously adjusts the CE potential to maintain the correct bias potential at the RE (as set by $V_{REFERENCE}$).

Be sure to allow for enough U1 lower output swing (or "foot room") for the CE drive. Depending on the sensor type, the voltage difference between CE and WE can vary between ±50 mV to ±1 V. The difference between CE and WE is small at low sensor currents (zero concentration), but increases as the sensor current increases (high concentrations). If the $V_{REFERENCE}$ voltage is set too low, the amplifier output may hit the rail before the maximum sensor current is achieved. If this incident occurs, proper sensor bias voltage is no longer maintained, the resulting readings are incorrect, and sensor damage is also possible. TI recommends to additionally monitor the CE drive voltage during operation to make sure it is within the proper operating range and that it has not railed or encountered some other sensor failure.

The feedback capacitor sets the time constant of the potentiostat loop and must be a quality low-leakage capacitor, such as a poly type. The typical value is 100 nF to 1 µF. Avoid using ceramics when expected currents are below 1 nA. Ceramics tend to be microphonic and exhibit piezoelectric properties that may cause a charge to generate when stressed. Do not use electrolytics because of high leakage and soakage memory effects.

2.3.2.2 Transimpedance Amplifier

The current out of the WE is converted to a voltage by U2, which is configured as a classic TIA.

The output of the TIA is defined in Equation 1 as:

$$V_{TIA} = V_{WORKING} + (-I_{SENS} \times R_F) \tag{1}$$

R_L is the load resistor. The sensor manufacturer generally specifies this value and it is usually in the 5- to 100-Ω range.

As Equation 2 shows, a voltage is applied to the non-inverting input ($V_{WORKING}$) to establish both the TIA zero-current output voltage level (V_{ZERO}) and the potential on the TIA input, therefore establishing the WE potential (V_{WE}).

$$V_{WORKING} = V_{WE} = V_{ZERO} \tag{2}$$

2.3.3 Micropower Design Considerations and Tradeoffs

Meeting the less than 1-µA supply current requirement requires making some critical design tradeoffs.

To reduce the quiescent current, the reference voltage dividers must be high value resistors, up in the several MΩ range. A 10-MΩ resistor string draws only 330 nA from a 3.3-V supply. Even larger resistors draw less, but the upper limit to the resistor string values is a result of the loading of the bias current error from the amplifier inputs. Large resistors also introduce large Johnson noise (or resistor noise), as well as the requirements to guard against humidity and leakage because of the low currents involved.

The noise of an amplifier is proportional to the supply current. The 320-nA LPV802 device is noisier than a standard power op amp. This op amp raises the noise floor slightly; however, this is one of the compromises required for micropower operation.

Amplifier and resistor noise contribute to the increase in the noise floor by adding extra noise to the signal and reference paths. Fortunately, these paths are slow or held at a constant level, which enables the use of large capacitors to filter the resistor and amplifier noise. Large filter capacitors can be used on the reference lines and a large feedback capacitor can be used to lower the signal bandwidth.

Using large capacitors has the consequence of a longer start-up time or settling time, which is the time required for the caps to charge through the large resistors. The circuit is designed for continuous powering, so the timing increase is not an issue after the initial turnon period.

Normally, the use of a fixed reference is to establish a fixed zero reference voltage. For example, if the output zero reference voltage has been set at 300 mV, then the output swings between 300 mV and 2.5 V.

One of the compromises involves the reference voltages. To save almost 1 µA of extra supply current required by the voltage reference, a fixed reference is not used; however, note that this only applies to unbiased sensors. Instead, a non-absolute reference voltage is used by dividing down the battery voltage. The reference voltage is derived from the battery and thus drops over time as the battery discharges.

Even with the reference voltage shifting, the voltage difference between the reference and the TIA output still represents the measured current. The transfer function of the TIA is set by the RF resistor, which means a change in the reference voltage does not change the I-V conversion accuracy, and thus the change in output level according to the concentration. Only the baseline reference voltage changes. In either the case of a fixed reference or divided reference, a subtraction must be made between the reference voltage and TIA output to obtain the resulting measurement.

The difference between the reference voltage and the TIA output can be subtracted electronically with a simple difference circuit; however, this task requires a third amplifier with its contribution to supply current, in addition to the static currents required in the feedback network and the added noise and drift of an additional stage.

The next compromise is to only use two of the available ADC inputs on the processor to measure both the reference voltage and TIA output voltages, separately, and mathematically subtract the two values. Because the processor ADC input is multiplexed internally, the same internal ADC core and reference voltage are used for both channels, reducing channel-to-channel errors. A part of the compromise is the increased least significant bit (LSB) error as a result from using two conversions per measurement.

Measuring the reference voltage, which is directly derived from the battery voltage, also provides a divided-down measurement proportional to the battery voltage, which can then be used to determine battery health.

The RC network on the outputs of the amplifiers serves several functions. The network creates a low-pass filter to smooth the signal, provides output capacitive load isolation, and functions as the ADC charge reservoir capacitor.

The sensor current is sourced through the loop amplifier and into the TIA. This current must be sourced from the amplifier supply. So at moderate or high concentration levels, the current draw from the battery is dominated by the sensor current. If the sensor is exposed to extended- or continuously-elevated concentrations, this extra current must be accounted for in the battery life calculations.

2.3.4　Two-Terminal Sensors

Two-terminal sensors do not have a reference electrode (RE) and therefore do not require a feedback loop. The sensor current flows between the counter electrodes (CEs) and working electrodes (WEs).

The same basic circuit can be used for two-terminal sensors but with one minor change. The potentiostat feedback circuit is converted into a simple buffer by tying the (former) reference input to the CE pin. This task is easy to accommodate with a jumper, as Figure 4 shows, which then applies a voltage at the CE pin equal to the applied $V_{REFERENCE}$. The TIA section remains unchanged. Most two-terminal sensors do not require a bias voltage, so $V_{REFERENCE}$ and $V_{WORKING}$ are set to the same potential. If a bias voltage is required across the sensor, which is very uncommon, the $V_{REFERENCE}$ and $V_{WORKING}$ voltages can be adjusted to accommodate the sensors bias requirements.
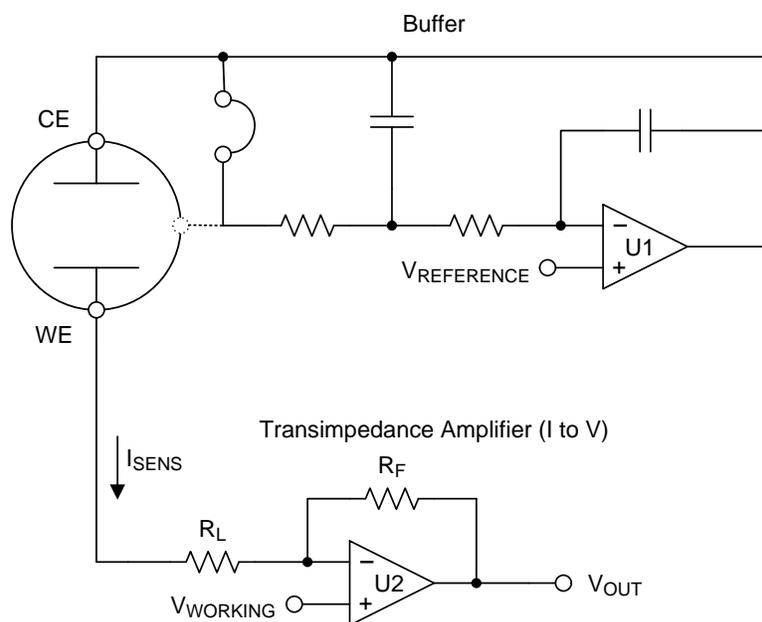
Figure 4. Modified Circuit for Two-Terminal Sensors

2.3.5 Four-Terminal Sensors

Four-terminal sensors are capable of simultaneously sensing different gases and have a shared CE and RE and a separate WE for each gas. Each WE requires a separate TIA and a separate JFET protection circuit. See Figure 5 for an example of a four-terminal sensor circuit (the JFETs have been left out for clarity).
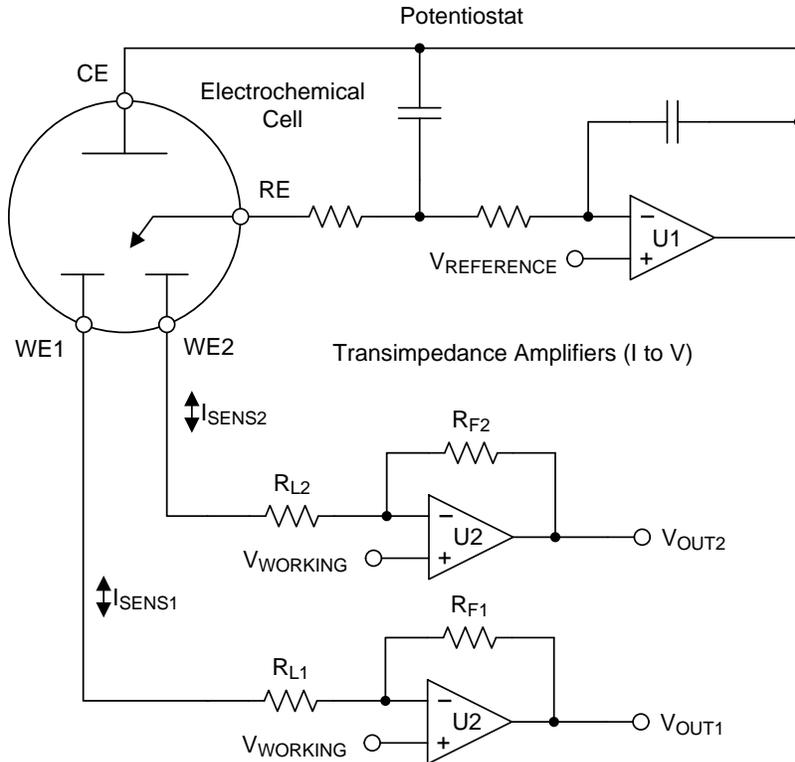

Figure 5. Four-Terminal Sensor Circuit

2.4 Three-Terminal Potentiometric Circuit Design

This reference design uses a three-terminal CityTech CF4+ Carbon Monoxide (CO) sensor as the electrochemical sensor. The targeted maximum sensitivity is 300 ppm. View the Section 4 for access to the full schematic.

2.4.1 Targeted Performance

To enable a battery life in the scope of ten years or more, including the rest of the system, TI recommends that the entire amplifier portion of the circuit, including the reference generator, draw less than 1 µA.

2.4.2 Two-Terminal Use

J1 can configure the circuit for use with two-terminal sensors. With J1 shorted, U1A becomes a simple follower, buffering the $V_{REFERENCE}$ voltage for the sensor and applying it to the CE. The RE pin is no longer used.

2.4.3 Sensor Power-Off Protection

For most sensors, if the WE and RE terminals are allowed to float, a voltage can build up between the WE and RE electrodes. This buildup can cause long recovery times, up to several hours, or even permanent damage to the sensor. If power is removed from the circuit, even briefly, then the correct terminal bias is no longer maintained and the sensor terminals then float.

To prevent the consequences of buildup, Q1, a MMBFJ177 ("J177") type P-channel JFET, is added so that it effectively shorts the WE and RE electrodes together to protect the sensor when the power has been removed.

When supply voltage is present, V_{GS} is greater than 2 V, which turns off the JFET. The gate leakage of the JFET is sub-pA and is negligible. When power is removed, V_{GS} drops to zero and the JFET turns on and shorts the WE and RE terminals through a low impedance.

> ## WARNING
>
> **Some sensors are not to be shorted, such as biased nitric oxide (NO), hydrogen chloride (HCl), ammonia (NH$_3$), and ethylene oxide (C$_2$H$_4$O) sensors. Consult with the sensor manufacturer to determine how to properly handle the sensor while in an unpowered state.**

2.4.4 MSP430 ADC Inputs

The corresponding outputs are monitored by the internal 12-bit ADC of the MSP430 processor. Three ADC inputs are used. A5 is used to monitor the TIA output, pin A6 is used to monitor the reference voltage, and pin A7 is used to monitor the CE voltage. The MSP430 ADC internal reference is set to 2.5 V.

To accurately measure the sensor current, both the TIA output and the $V_{WORKING}$ voltage are measured. The actual sensor measurement value is the TIA output minus the $V_{WORKING}$ voltage. The calculation for Equation 3 cancels out any change in the reference voltage as a result of battery depletion.

$$V_{MEAS} = V_{WORKING} - V_{TIA} \tag{3}$$

The CE drive voltage is also monitored to make sure it is within the proper operating range. In most cases, the voltage must be within 250 mV of $V_{COUNTER}$, but this amount varies by sensor type.

2.4.5 Optional Temperature and Humidity Measurement

Temperature and humidity affect the readings of the sensor, up to ±20%, and therefore must be monitored for ultimate accuracy. To allow for this accuracy, a provision has been made for an optional HDC1080 temperature and humidity sensor to add to the board. The HDC1080 sensor can communicate directly to the processor through the I2C bus.

The HDC1080 sensor does not require continuous powering, so to save 100 nA of standby current, the HDC1080 sensor and the associated 10-kΩ I2C pullup resistors are powered off an MSP430 GPIO pin. The GPIO pin must be brought high 20 ms before the measurement is initiated and set low after the measurement has completed. See the HDC1080 data sheet for more information [2].

2.4.6 Determining Component Values

To determine component values, the following items must first be determined:

- The sensitivity of the sensor, usually expressed in current per concentration (nA per ppm)
- The desired system zero-current reference voltage (V_{ZERO})
- The full-concentration output voltage (VO_{MAX}) of the TIA output
- The minimum battery voltage (VB_{MIN}) to determine CE swing footroom

The first requirement is to establish the system reference voltage level. Because this is a zero-bias sensor, $V_{WORKING}$ and $V_{REFERENCE}$ are at the same potential and may be tied together. Two items determine the required reference voltage: the minimum output swing footroom required for the CE and the minimum battery voltage. To allow for the required 200-mV headroom for proper operation of the 2.5-V reference internal to the MSP430 processor, the minimum battery voltage must be 2.7 V.

The difference in potential between the WE and RE changes as the concentration increases. Unfortunately, most sensor data sheets do not specify this voltage change, so this change may require experimentation to discover or may be obtained from the manufacturer. Bench experiments have discovered that the CE-to-RE difference was about 180 mV at 300 ppm for the CityTech sensor.

There is a trade-off between the allowable CE swing headroom and available output signal range because the TIA output signal contains the sum of the TIA output signal plus the reference voltage. Therefore 300 mV is to used as the minimum V_{ZERO} to add some headroom; see the following calculation in Equation 4:

$$V_{ZERO} = V_{REFERENCE} = V_{COUNTER} = 300 \text{ mV} \tag{4}$$

The maximum TIA output is 2.5 V to drive the ADC. The specification is to measure up to 300 ppm.

The sensor used in the test has a specified current output of 69 nA per ppm (see Equation 5 and Equation 6).

$$I_{SENSE\_ppm} = 69 \text{ nA} \tag{5}$$

$$ppm_{MAX} = 300 \text{ ppm} \tag{6}$$

The maximum sensor current at the highest expected concentration is calculated in Equation 7:

$$I_{MAX} = I_{SENSE\_ppm} \times ppm_{MAX} = 69 \text{ nA} \times 300 = 20.7 \text{ μA} \tag{7}$$

The available output swing range above the reference voltage available for the measurement is calculated in Equation 8:

$$V_{SWING} = V_{OUTMAX} - V_{ZERO} = 2.5 - 0.3 - 2.2 \text{ V} \tag{8}$$

The transimpedance resistor (RF) value can be calculated in Equation 9 using the maximum swing and the maximum sensor current:

$$R_F = \frac{V_{SWING}}{I_{MAX}} = \frac{2.2}{20.7 \text{ μ}} = 106.28 \text{ kΩ} \tag{9}$$

Use 110 kΩ as the next convenient common value and to also allow for some headroom.

The sensitivity in mV per ppm is calculated in Equation 10:

$$V_{SENSE\_ppm} = R_F \times I_{SENSE} = 110 \text{ kΩ} \times 69 \text{ nA} = 7.59 \text{ mV/ppm} \tag{10}$$

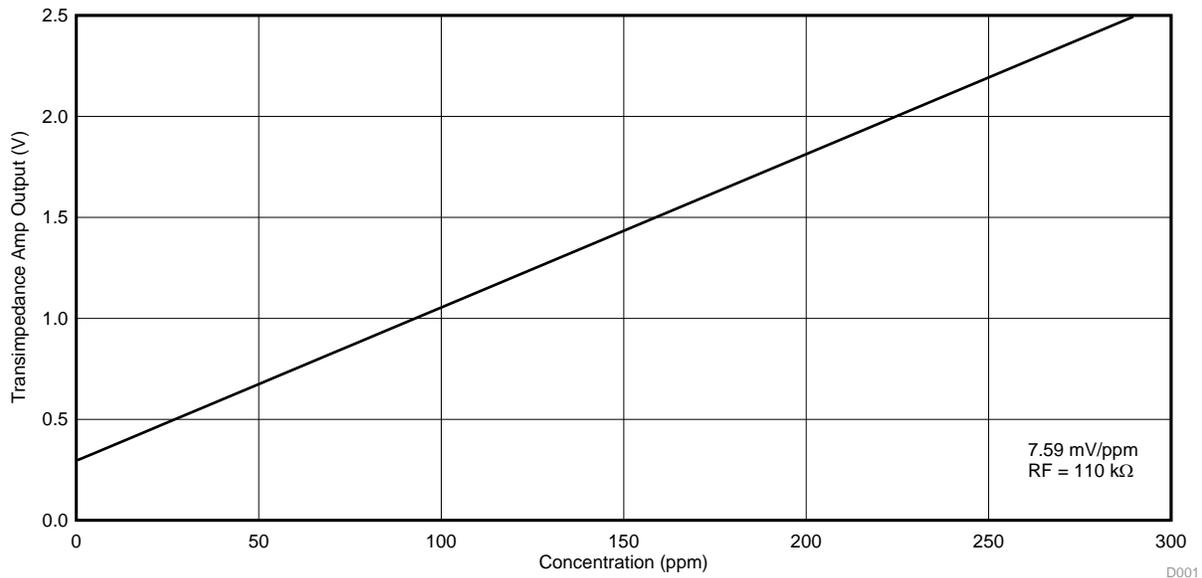With these values, the transfer function of the TIA is shown in Figure 6.

Figure 6. Calculated Transfer Function

The resulting output of the TIA is 300 mV at a 0-ppm concentration and increases at a rate of 7.59 mV per ppm of CO. The readings below $V_{WORKING}$ are invalid and may indicate sensor damage, contamination, or that an overload recovery time is required. The actual concentration measurement is the difference between $V_{WORKING}$ and V_{OUT}, thus a difference measurement must be made. Two channels of the ADC are used to measure both V_{OUT} and $V_{WORKING}$ and obtain the difference of the reading.

To reduce noise, a 1-μF capacitor CF has been added across RF. Because the sensors have a long response time (< 20 s), and the nano-power amplifiers have higher noise than standard power amplifiers, it is beneficial to reduce as much of the broadband noise as possible by limiting the bandwidth of the measurement circuit. The upper limit of the capacitor value would be dominated by leakage issues (do not use aluminum electrolytic).

2.4.7 Reference Voltage Generation

The design allows the generation of the reference voltage through two methods:

1. Using an active series reference consisting of U2 and U3
2. Passively dividing down the battery supply voltage with the R6 and R7 resistive divider string

Both options have trade-offs. A fixed voltage reference provides a known, fixed-voltage reference but at the expense of increased system quiescent current (900 nA more). The passive resistive divider has the lowest quiescent current, but the reference voltage varies with the battery voltage.

> **NOTE:** If the sensor requires a bias voltage, then the fixed-series, reference-based bias circuit must be used because a stable reference must be established to provide the correct fixed potential across the sensor; otherwise, the biasing voltage potential also changes with the battery voltage.

Because the example sensor is a zero-bias sensor, use the passive divider bias option 1 for minimal supply current.

2.4.7.1 Biasing Section

R6 and R7 form the primary reference voltage divider. The R8-to-R2 and R4-to-R5 divider pairs have been provided for when $V_{COUNTER}$ and $V_{WORKING}$ are at different voltages for a biased sensor. Then the resulting sensor bias voltage is the difference between $V_{COUNTER}$ and $V_{WORKING}$. C4 and C9 bypass capacitors reduce the resistor noise.

Because the selected sensor is a zero-bias type, R5 and R2 are open and R1 and R4 are to be shorted with a 0-Ω resistor to set $V_{COUNTER}$ and $V_{WORKING}$ to be equal to the R6 and R7 divider voltage.

The first step is to calculate the reference divider to generate the $V_{WORKING}$ voltage (and by extension, the $V_{COUNTER}$ voltage). Previous determinations show that 300 mV was to be used for the reference voltage to allow for a CE swing at the minimum supply of 2.7 V.

Standard resistor values have been chosen for simplicity. Resistor values are a compromise between quiescent current draw and allowable change as a result of amplifier bias current over temperature.

22 MΩ and 2.7 MΩ provide a 295-mV bias point while drawing only 134 nA at 3.3 V. A worst-case bias current of 10 pA for each amplifier only changes the reference voltage by less than 0.5 mV.

2.4.7.2 Fixed Reference Operation

If required, U2 and U3 form a nano-power 2.5-V reference string using two stacked 1.25-V REF1112 micropower references. The reference string requires a minimum of 900 nA to maintain regulation.

R6 provides the bias for the shunt reference stack and R5 is left open. The 2.5 V off the top of the reference is sent to the reference line through R11.

2.4.8 Sensor Error

A drift of a few ppm around V_{ZERO} is expected as a result of sensor drift and noise and is stated in the sensor datasheet. The expected variation for the test sensor is ±2 ppm at a 0-ppm concentration, which corresponds to a –15- to 15-mV variation at the TIA output. This variation is a limitation of the sensor and not the amplifier circuit.

The sensors also have error terms because of exposure to temperature and humidity. Because this error varies between sensor types and even manufacturers, this subject is beyond the scope of this reference design. Adding the HDC1080 to the board was discussed previously in Section 2.4.5.

3   Hardware, Software, Testing Requirements, and Test Results

3.1   Required Hardware and Software

3.1.1   Hardware

Pair the demo board to the LaunchPad with the power jumper JP1 in the upper-right corner aligned with the reset button (S3) on the LaunchPad.

3.1.2   Software

For proper operation of the programmer, USB drivers are required. These drivers have already been installed if the user has previously installed drivers for any MSP430 tools (such as CCS or Energia) or other LaunchPad-based tools. If these drivers have not been installed and an *unknown hardware* error displays in the lower-right corner hardware icon, then the USB drivers must be installed. The following subsection describes the firmware loading procedure.

3.1.2.1   *MSP430 FET USB Driver Installation*

The FET drivers provide the USB interface to the MSP430 FET programmer on the LaunchPad. The drivers are available from the MSP430 driver download page at http://www.ti.com/MSPdrivers.

Download and follow the installation directions included with the drivers. After installing the drivers, connect the LaunchPad with the board attached using a micro-USB cable to the host computer. The green power LED then illuminates.

3.1.2.2   *Installing MSP430 Flasher Command Line Utility*

The MSP430 command line tool allows uploading source code to the LaunchPad board through the onboard FET programmer. The utility is available for Windows®, OS X®, and Linux operating systems. This demonstration uses the Windows utility: http://www.ti.com/tool/msp430-flasher.

- Download the appropriate installer .zip file from the MSP430 Flasher product downloads section. Unzip and run the installer.exe file.
- Modify the default installation location to C:\ti\MSPFlasher so that the files are in a known location for the following batch file.
- Install the FET USB drivers when prompted if not done previously.

3.1.2.3   *LaunchPad Source Code and Firmware Installation*

Download the TIDA00854_Firmware.zip file from the following link, unzip, and then run the installer .exe: http://www.ti.com/tool/TIDA00854.

By default, the installer places all the files in the C:\Program Files\ folder. For 32-bit systems, the installer places the files in the following directory: C:\Program Files\Texas Instruments\GASBP_TIDA-00854_FW.

For 64 bit systems, they are located in: C:\Program Files (x86)\Texas Instruments\GASBP_TIDA-00854_FW.

These folders contain the source code package for IAR Embedded Workbench and Code Composer Studio, as well as some precompiled firmware files.

3.1.2.4   Simple Batch File for Uploading Firmware Code

The following simple batch file allows the firmware code to be simply dragged and dropped onto the icon to upload to the LaunchPad, avoiding re-typing the lengthy command line command each time.

1. Open the C:\ti\MSPFlasher folder from My Computer.

2. Right-click in the folder and select *New → Text Document* from the pop-up menu.

3. Name the item "Drop_Firmware_Here.bat" (must end with .bat and the icon changes).

4. Right-click on the new "Drop_Firmware_Here.bat" and select *Edit*.

5. Paste the following code into the editor and save:

```
CLS
@echo off
set device=MSP430FR6989
set firmware=%1
C:\ti\MSPFlasher\MSP430Flasher.exe -n %device% -w "%firmware%" -v -g -z [VCC]
pause
```

When first run, the flasher may ask to update the board FET programmer firmware; press "Y" to let it update.

3.1.2.5   Uploading Firmware to LaunchPad

The precompiled firmware file is located in the /Debug/EXE folder in the installed source code folder. The uploadable firmware code has a .txt extension.

For 32-bit systems, gas_demo_plot.txt is located in:
C:\Program Files\Texas Instruments\GASBP_TIDA-00854_FW\TIDA-00854_Firmware-v0.89\Debug\Exe\.

For 64 bit systems, gas_demo_plot.txt is located in:
C:\Program Files (x86)\Texas Instruments\GASBP_TIDA-00854_FW\TIDA-00854_Firmware-v0.89\Debug\Exe\.

The firmware file is called gas_demo_plot.txt (extensions may need to be enabled). The user can now simply drag and drop the gas_demo_plot.txt firmware file onto the Drop_Firmware_Here.bat icon created in the previous step.

The bright yellow light on the LaunchPad starts blinking for a few seconds as the program is uploading. After a few seconds, the MSP430 resets and flashes the GSDEMO on the LCD screen, followed by a continuous numeric reading in ppm.

Upon first application of power, it may take a while for the reference voltages and sensor to stabilize, so the LCD may show "ALARM" with the red LED blinking until the system stabilizes.

If the LaunchPad seems to hang after uploading, try pressing the LaunchPad reset button (S3). If the user wishes to restore the LaunchPad to the out-of-box condition, the binary files are located in the MSP-EXP430FR6989 Software Examples package in the /firmware/Binary/OutOfBox directory.

3.1.3   LaunchPad Demo Operation

When the firmware is uploaded, the LaunchPad continuously displays the calculated ppm value on the LCD.

The LCD display shows "ALARM" with a blinking red LED when the measured concentration is above the maximum setpoint, or that the CE voltage is too close to the negative rail.

To "Null" (or "Zero" or "Tare") the readings, press S1 and S2 simultaneously. The readings are zeroed with the previous reading and the LCD displays the "®" symbol to indicate the readings are zeroed. Null may be cancelled by simultaneously pressing the S1 and S2 buttons a second time.

3.2   *Testing and Results*

The design was tested using 200-ppm calibration gas applied directly to the sensor, as the following Figure 7 shows.

How the gas is applied to the sensor is important. Previous experimentation discovered that applying a pressure directly to a sealed sensor face causes large errors in the readings (> 100%). For a proper reading, the entire sensor must be enclosed in the same pressure. This task is accomplished by either enclosing the entire sensor in a chamber or by applying the gas to a chamber vented to the atmosphere.

While searching for a simple, easily-reproducible test chamber, TI discovered that a Rain Bird® drip irrigation emitter is roughly the same diameter as that of the sensor face (20 mm). The drip emitter was modified by removing the input barb and drilling out the center hole to allow the free flow of gas (thus removing the "drip" restrictions).

A suitable "chamber" was made by wrapping the top of the sensor with a layer of electrical tape and loosely inserting the emitter from the top. See a closeup example of a tape chamber in Figure 8 (clear tape was used in the photo for clarity). The loose-fitting top allows the gas to vent out of the top of the chamber. The emitter was applied just above the face of the sensor to flood the face of the sensor with gas, but also allowing the gas to escape upwards to the atmosphere to avoid the buildup of a large back pressure against the sensor.

Figure 7. Measurement Setup

Figure 8. Closeup of Tape "Chamber"

3.2.1 Open Air Baseline Measurement

Figure 9 shows the equivalent ppm amplifier noise with the sensor removed to show the equivalent ppm system noise contributed by the amplifier circuit and analog-to-digital conversion. The total noise contributed by the amplifier subsystem is less than ±0.025 ppm.

Figure 10 shows the baseline sensor offset in room air. Notice the difference in the vertical scale. The majority of the offset and noise originates from the sensor. The amplifier circuitry contributes little noise or offset to the overall readings.
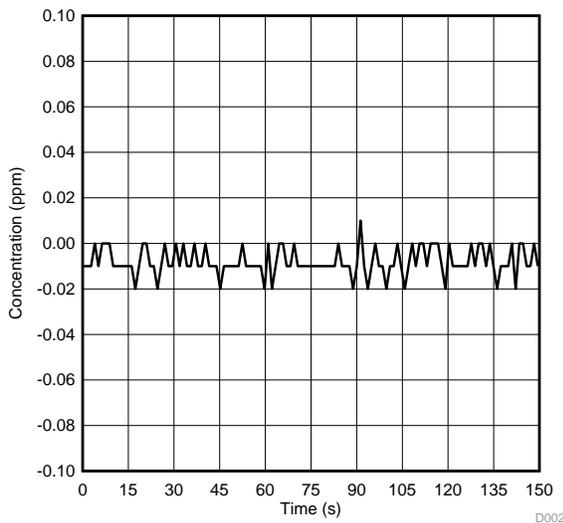
Figure 9. Zero Baseline With Sensor Removed
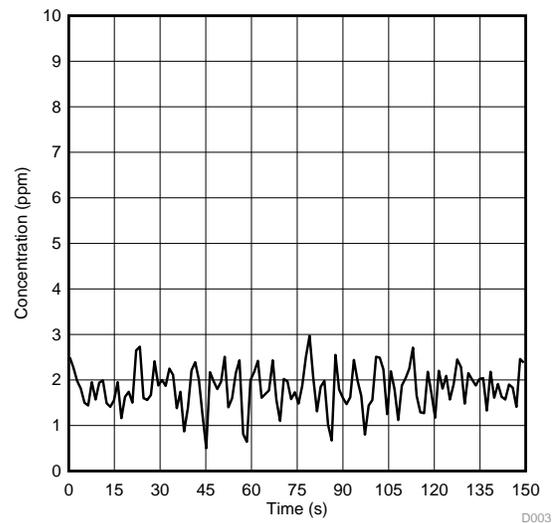
Figure 10. Sensor Baseline in Open Room Air

3.2.2 Supply Current Measurement

JP1 allows the opening of the amplifier power supply to allow direct measurement of the amplifier section supply current, which includes the LPV802 amplifier and the reference voltage resistor string.

With the sensor removed, the amplifier and biasing circuit draws a steady 805 nA at room temperature with a 3.3-V supply. Figure 11 shows the measured supply current of the amplifier section over the entire 2.6- to 3.6-V supply range. With the sensor connected, the supply current then rises to around 900 nA and randomly varies between 850 nA to 1 µA because of sensor current fluctuations, which is in line with the 2-ppm (140-nA) offset and random noise of the sensor.
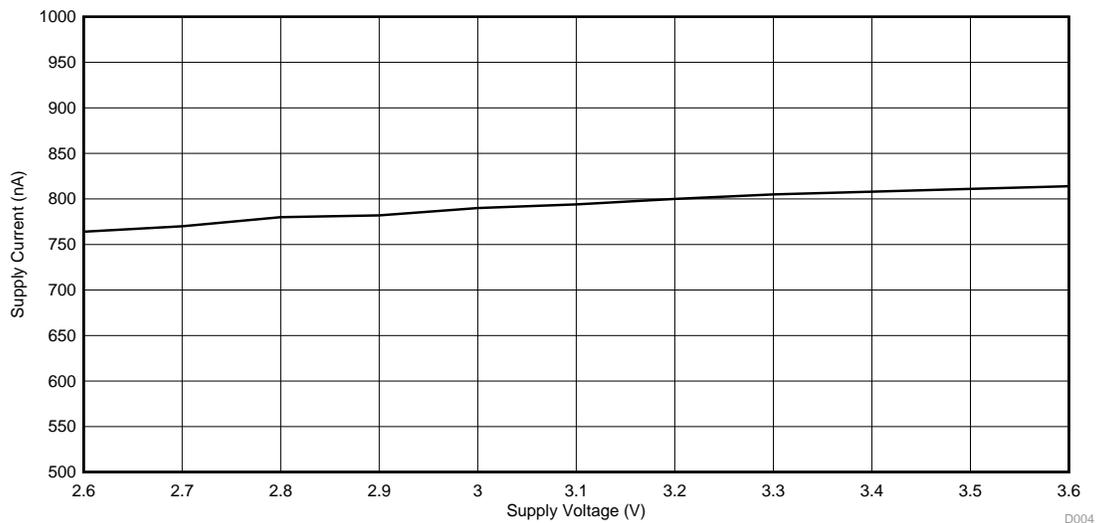
Figure 11. Measured Amplifier Circuit Supply Current

3.2.3 Test Preparation

As per the manufacturer recommendation, the sensors are first "conditioned" for two hours by letting them settle in the powered-up circuit while being exposed to room air. The tests are performed in a well-ventilated area exhausted to the outdoors with a fan blowing across the test area to prevent background accumulation of the exhausted CO within in the immediate environment and thus possibly raising the background zero-CO level.

3.2.3.1 Test Results With Gas Application

The test results using a gas application are obtained as follows:

1. The test is started with the sensor exposed to room air for a zero reading of 30 s.
2. The sensor is then exposed to a flow of CO gas. The test gas used was Gasco 44ES-50-200, 200-ppm CO and air mix calibration gas using a 70-series regulator.
3. The gas was left flowing for 60 s to cover the specified 20-s response time of the sensor.
4. After the test period, the gas is then turned off and the chamber is removed to expose the sensor back to fresh room air and then allowed to settle back to zero.

During the entire test period, the reference voltage, TIA output, and CE voltage are recorded. Figure 12 shows these results.
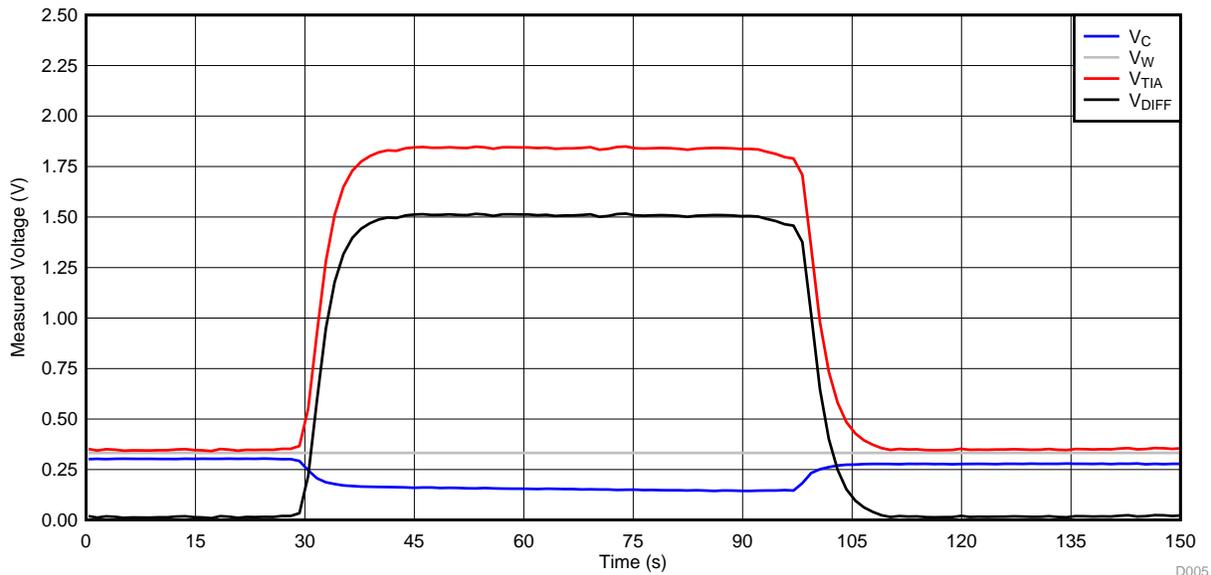
Figure 12. Measured Voltages During Test

The measured parameters for Figure 12 are as follows:

- V_C is the voltage on the CE
- V_W is the WE voltage (reference voltage)
- V_{TIA} is the output of the TIA
- V_{DIFF} is the calculated difference between the V_W and V_{TIA} output voltages

Note how the voltage on the CE (V_C) drops as the concentration increases. This correlation shows the importance of allowing enough negative swing footroom for the CE swing below the reference voltage.

V_{DIFF} then becomes the basis of the measurement. Knowing the feedback resistor value (110 kΩ), the designer can calculate the measured sensor current with Equation 11:

$$I_{SENSE} = \frac{V_{DIFF}}{R_F}$$

$$(11)$$

From the calculated sensor current, the resulting ppm concentration can be calculated as shows. From the calculated sensor current that Figure 13 shows, the resulting concentration in ppm is calculated using Equation 12. Figure 14 shows the results of the calculation in ppm.

$$ppm = \frac{I_{SENSE}}{I_{SENSE\_per\_ppm}}$$

(12)
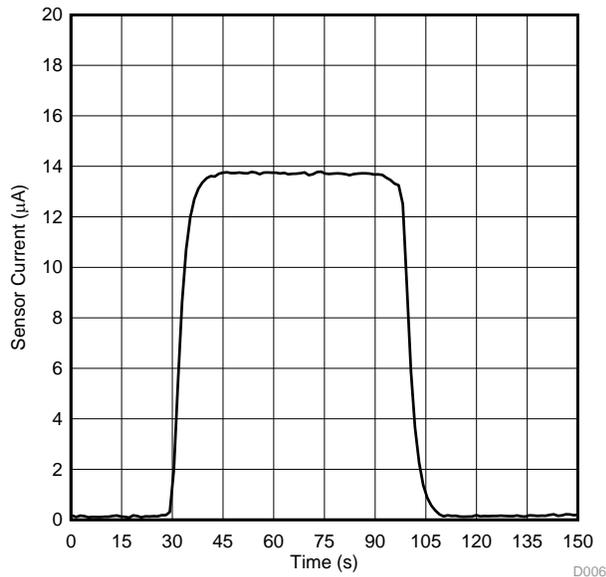
Figure 13. Measured Sensor Current
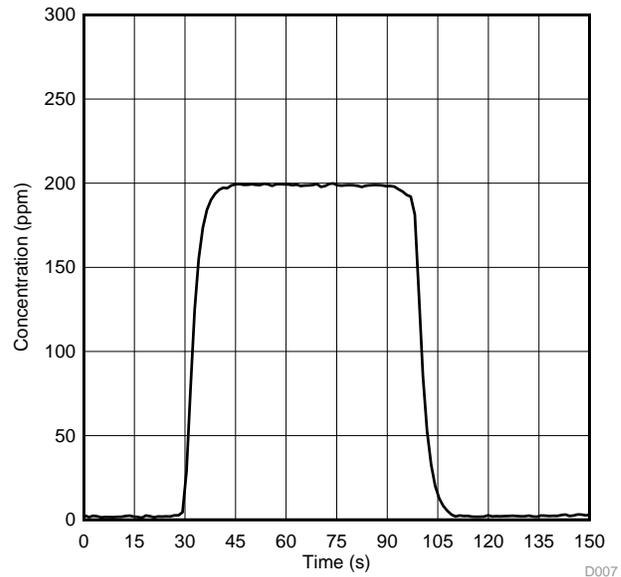
Figure 14. Calculated ppm Concentration

3.2.4 Conclusion

The measurement results are very suitable. The zero concentration offset between 0 s and 30 s was +2 ppm. This offset is right at the specified ±2 ppm on the sensor data sheet, but will normally be zeroed out through initial system calibration.

The average reading between 60 s and 90 s was 198 ppm with the gas applied. Accounting for the sensor offset, the full-scale reading is 198 ppm – 2 ppm = 196 ppm, which is a 2% error (assuming the gas was exactly 200.0 ppm).

The supply standby current was below the requested 1 µA for the amplifier circuit.

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-00854.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00854.

4.3 PCB Layout Recommendations

The layout for the TIDA-00854 design is not too critical, but the RE and WE traces are high-impedance nodes and must be kept short and guarded.

If this design is to be used in an environment where dust or moisture accumulation is possible, be aware that it may be necessary to include a conformal coating to eliminate additional leakage paths because of the operating environment over time.

CAUTION

Do not directly solder the sensor pins. Check with the manufacturer first for mounting recommendations and use the recommended sockets. Install the sensor after cleaning, as some sensors can be damaged by cleaning solvent fumes.

When finished soldering, be sure to rinse and scrub the board with clean isopropyl alcohol to remove contaminates. Allow the board to thoroughly dry before use.

Because the board is simple, the actual test board was "cut" on a prototype LKPF printed-circuit board (PCB) router. Because "cutting" a board does not create plated-through vias, both sides of any vias, or traces with top and bottom layer connections, must be soldered on both sides of the board. If using a "cut" board, do not mount the JA through JD connectors flush. A little space ($\approx$ 2 mm) must be left under the block connectors to allow soldering access to connections that are otherwise covered up by the connector body.

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-00854.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-00854.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00854.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00854.

5 Software Files

To download the software files, see the design files at TIDA-00854.

6 Related Documentation

1. Texas Instruments, *LPV801/LPV802 320 nA Nanopower Operational Amplifiers Data Sheet*
2. Texas Instruments, *HDC1080 Low Power, High Accuracy Digital Humidity Sensor with Temperature Sensor Data Sheet*
3. Texas Instruments, *10ppm/ºC, 1μA, 1.25V SHUNT VOLTAGE REFERENCE Data Sheet*
4. City Technology, *4CF+ CiTiceL® Carbon Monoxide Sensor Data Sheet*
5. Alphasense, *How Electrochemical Gas Sensors Work Application Note*
6. Alphasense, *Designing A Potentiostatic Circuit Application Note*
7. Membrapor, *Electrochemical Gas Sensor Application Note*
8. Gasco, *44ES Carbon Monoxide Calibration Gas*

6.1 Trademarks

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Windows is a registered trademark of Microsoft Corporation.
Rain Bird is a registered trademark of Rain Bird.
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7 Terminology

CE— Counter electrode

CO— Carbon monoxide

CMOS— Complimentary metal-oxide semiconductor

JFET— Junction gate field-effect transistor

RE— Reference electrode

SE— Sense electrode, also referred to as Working electrode

TIA— Transimpedance amplifier

WE— Working electrode, also referred to as sense electrode

8 About the Author

PAUL GROHE is an applications engineer in the Precision Sensor Products group in Santa Clara, California and is responsible for supporting both new development and the former National Semiconductor operational amplifier family.

Revision History

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