Electrochemical Sensors: Interface Design Challenges and Solutions

Electrochemical gas sensors are used in industrial, medical, automotive, and other applications to detect and measure the concentrations of a wide range of toxic gases such as carbon monoxide (CO) or hydrogen sulfide (H2S). This article will cover the principle of operation of an electrochemical gas sensor, discuss interface design challenges and solutions, and reviews several Analog Devices reference designs developed specifically for these applications.

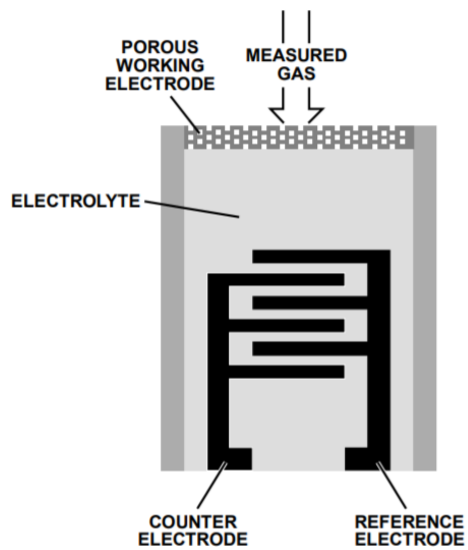

Figure 1: 3 Electrode Electrochemical Gas Sensor

As shown in Figure 1, a typical electrochemical (EC) gas sensor has three electrodes: a working electrode (WE), also known as sensing electrode (SE); a reference electrode (RE); and a counter electrode (CE). The three electrodes are surrounded by an electrolyte. During operation, the target gas enters the sensor through a porous membrane where it interacts with the working electrode; depending on the gas, the resulting electrochemical reaction may be either oxidation or reduction. The reaction generates a current between the working electrode and the counter electrode that is proportional to the amount of gas.

The most common sensors have two or three electrodes; four-electrode versions are also available. Figure 1 shows a simplified diagram of a 3-electrode configuration.

Changing the diffusion characteristics of the membrane allows the sensor manufacturer to tailor the sensor to a desired target gas concentration range.

Designing the electrochemical gas sensor interface

The basic circuit required to control the electrochemical gas sensor is called a potentiostat. The circuit adjusts the current at the counter electrode CE to maintain a constant bias voltage between the working electrode WE and the reference electrode RE. A transimpedance amplifier converts the current to a voltage that represents the gas concentration.

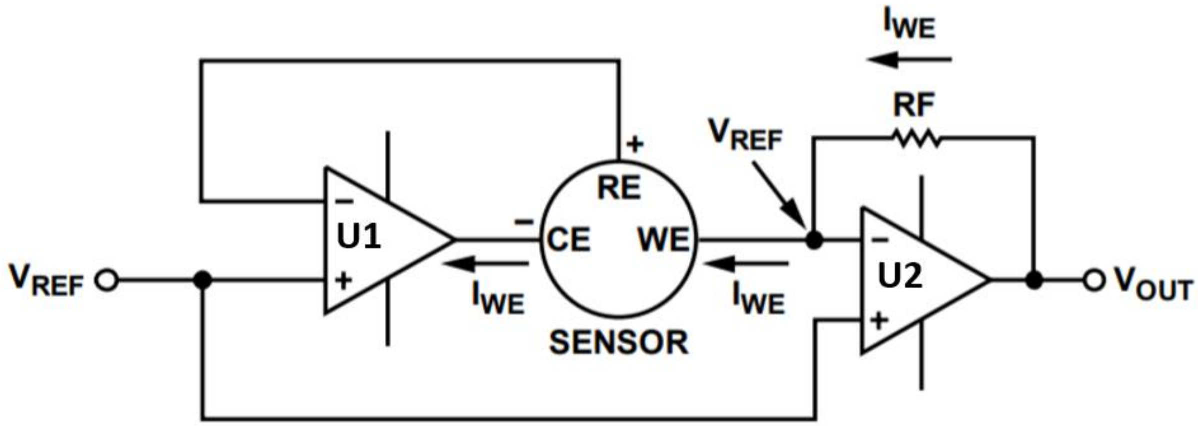

Figure 2: A simplified interface for an electrochemical sensor (Image Source: Analog Devices)

Figure 2 shows a simplified schematic of the potentiostat. The sensor reference electrode RE provides feedback to amplifier U1, which maintains a constant potential with the WE by varying the voltage at the counter electrode (CE). U2 is the transimpedance amplifier.

Reading the EC sensor output presents several challenges for the interface.

- The current into or out of the WE terminal is less than 100 nA per ppm of gas concentration; converting this current into an output voltage requires a transimpedance amplifier with a very low input bias current.
- The magnitude of the current flowing in an EC sensor for a given concentration of target gas varies with temperature. Temperature compensation must be applied to the gas sensor's current reading to determine the final ppm level.
- The direction of the current at the WE terminal depends on whether the reaction occurring within the sensor is oxidation or reduction. With a carbon monoxide sensor, for example, oxidation occurs; the current flows into WE, which requires CE to be at a negative voltage (typically 300 mV to 400 mV) with respect to WE. The op amp driving the CE terminal should have an output voltage range of approximately ±1 V with respect to VREF to provide sufficient headroom for operation with different types of sensors.
- Electrochemical sensors have a very long time constant. When first powered up, the output can take several minutes to settle to its final value. When a step change occurs in the target gas concentration, the sensor output can take from 25 to 40 seconds to reach 90% of its final value. If the voltage between RE and WE changes suddenly, it can take several minutes for the output current to stabilize. This long time constant also applies when cycling power to the sensor; the interface design should act to minimize slow response on power-up.

Interface designs must accommodate real-world challenges
The basic potentiostat circuit discussed above must often be modified to handle the challenges posed by real-world applications:

- Like other electronic devices, electrochemical gas sensors contain metallic elements such as bond wires, plates, and pins that make them susceptible to electromagnetic interference (EMI) from nearby RF emitters such as cellphone towers, communication networks, etc.; such interference can cause an error in the sensor output that can lead to a false reading.
  In some applications, such as a toxic gas detection instrument, a false negative reading can cause the non-detection of a dangerous gas level; a false positive reading, while not life-threatening, can cause a needless building evacuation or shutdown of an industrial process. Consequently, European standard EN 50270: 2015, “Electrochemical compatibility – Electrical apparatus for the detection and measurement of combustible gases, toxic gases or Oxygen”, specifies the RF frequency ranges and power levels over which a toxic gas detection instrument must operate.
- Since there is a large number of gases that might be monitored, a practical design should have the flexibility to accommodate the different operating characteristics of the sensors used.
- Sensor aging is another fact of life. Although the diffusion barrier is primarily mechanical, and the calibration of electrochemical sensors tends to be relatively stable over time, their electrical response does change over time due to aging of the electrolyte and other factors. Many industrial applications are expected to operate for years without problems; a real-world design must monitor sensor performance, correct for age-related performance changes, and provide timely notification of impending failure.

Circuits from the Lab reference design address EC sensor design challenges
As part of their “Circuits from The Lab” portfolio, Analog Devices offers four unique reference designs that address different electro-chemical sensor interface and application challenges. Each reference comes complete with design and integration files, factory-tested evaluation hardware, application source code, and a comprehensive documentation package; click on the appropriate link for more information or visit the Analog Devices website.

Single-supply, low noise, portable gas detector

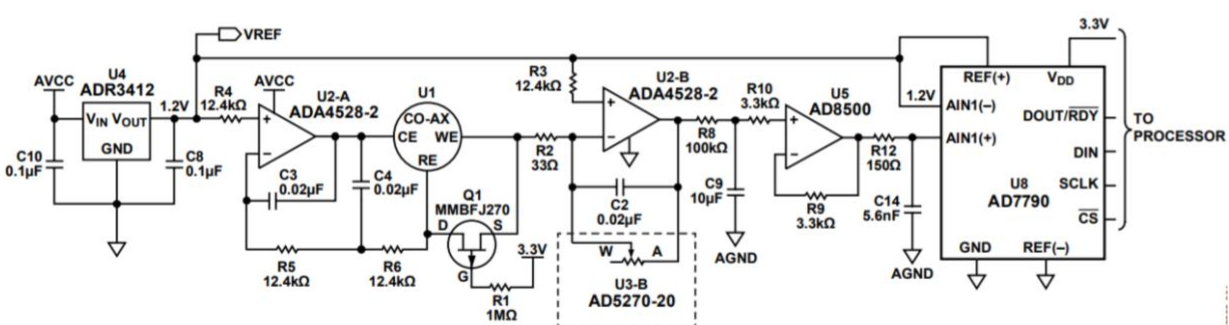

Figure 3: Low-noise gas detector (Image Source: Analog Devices)

Reference design CN0357 (Figure 3) is a low noise, single-supply, toxic gas detector design that includes a transimpedance amplifier (TIA) with programmable gain for rapid evaluation and prototyping of a variety of EC sensors.

The design accomplishes this by replacing the fixed transimpedance resistor with an AD5270-20 programmable rheostat: this device is a 1024-position resistor with 1% tolerance error and an SPI interface.

In common with other reference designs discussed, CN0357 includes a feature that helps avoid the very long start-up times of EC sensors: P-channel JFET Q1 shorts the RE terminal to the WE terminal when the supply voltage drops below the gate-to-source threshold voltage of the JFET, approximately 2.0V.

The CN0357 evaluation board is available in the Pmod and Arduino form factor and interfaces to Analog Devices' shield-compatible platform board for rapid prototyping.

Dual Electrochemical Gas Sensor with Temperature Compensation

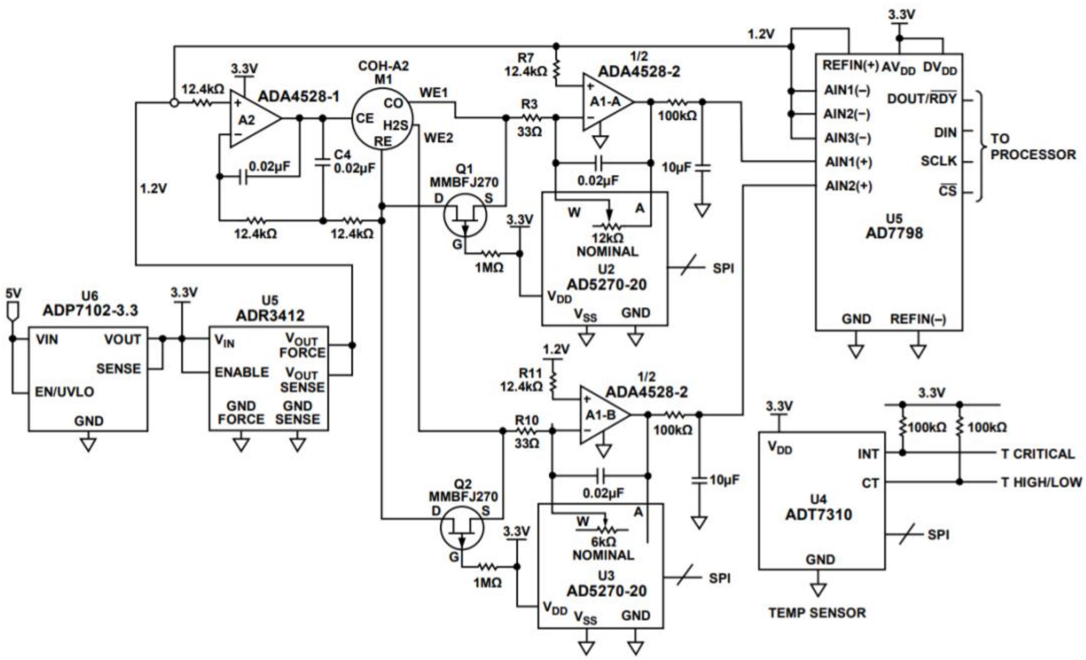

Figure 4: Simplified block diagram for CN0396 dual gas sensor (Image Source: Analog Devices)

Reference design CN0396 (Figure 4) is an interface design for a gas detector that can detect two different gases simultaneously. The reference design combines low-noise performance with low-power, single-supply operation, making it suitable for portable applications. It also provides a high degree of programmability to accommodate a variety of sensors for different types of gases.

The Alphasense COH-A2 sensor contains four electrodes with two working electrodes WE1 and WE2; one electrode responds to CO and the other responds to H2S. The two working electrodes share a common RE and CE electrode. Special chemical filters prevent each gas from affecting the other working electrode.

The reference design uses the AD7798 precision analog front end; this device includes a 3-channel, low noise 16-bit sigma-delta (ΣΔ) analog to digital converter (ADC), an instrumentation amplifier, and a flexible serial interface. The reference design also includes an onboard ADT7310 16-bit digital temperature sensor for temperature compensation.

The CN0396 printed circuit board (PCB) is designed in the popular Arduino shield form factor and interfaces to Analog Devices' shield-compatible platform board for rapid prototyping.

Electrochemical gas measurement system with sensor diagnostics
Reference design CN0429 (Figure 5) also uses the ADuCM355 as the EC sensor interface, but instead of EMC performance, the design highlights the ADuCM355's built-in sensor diagnostics.

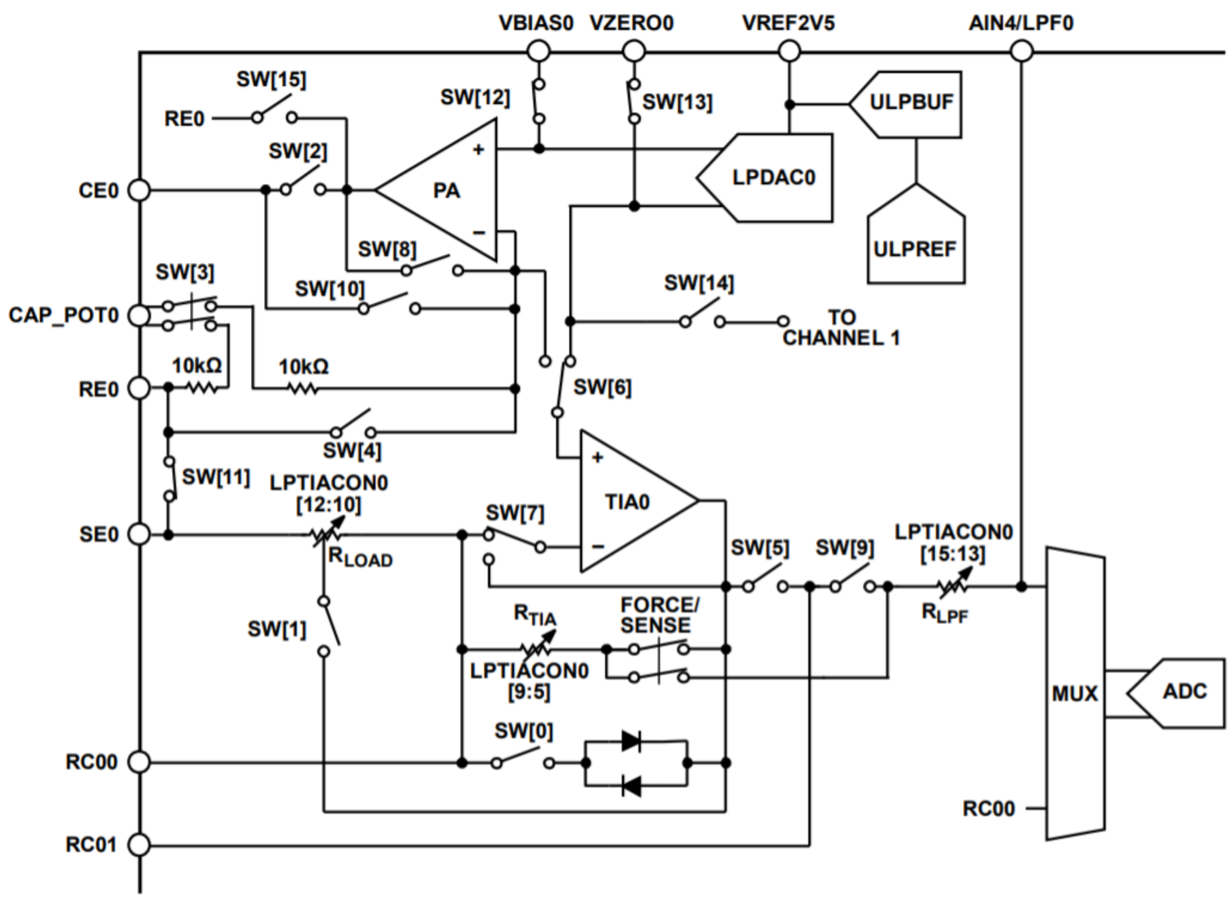

Figure 5: Simplified block diagram for CN0429 Electrochemical Gas Measurement System with Sensor Diagnostics (Image Source: Analog Devices)

These diagnostics allow the design to compensate for accuracy drift due to aging or temperature, estimate the remaining lifetime of the sensor, and indicate the need for replacement without user intervention.

The ADuCM355 includes a built-in waveform generator and discrete Fourier transform (DFT) block; together these perform impedance spectroscopy by applying an AC signal sweep to the counter electrode and measuring the results. The measurements indicate the quality of charge transfer between electrodes, effectively detecting aging of the sensor's electrolyte. Laboratory tests show good correlation between impedance and sensitivity of the sensor.

Other methods of detecting sensor health include a pulse test and a ramp test. These tests apply a voltage pulse or ramp on top of the bias voltage to test the sensor responsivity and charge transfer respectively. These measurements combine with algorithms running on the ADuCM355 to improve the accuracy, performance, and operating life of the sensor.

Implementing smart diagnostics such as these requires that the sensor manufacturer characterize the performance of a large number of sensors using accelerated aging and similar methods. Contact the sensor manufacturer for the appropriate data sets.

The CN0429 printed circuit board (PCB) is designed to connect to the popular Arduino shield form factor via an interposer board, which interfaces to Analog Devices' shield-compatible platform board for rapid prototyping.

Radiated Immunity Compliant Reference Design

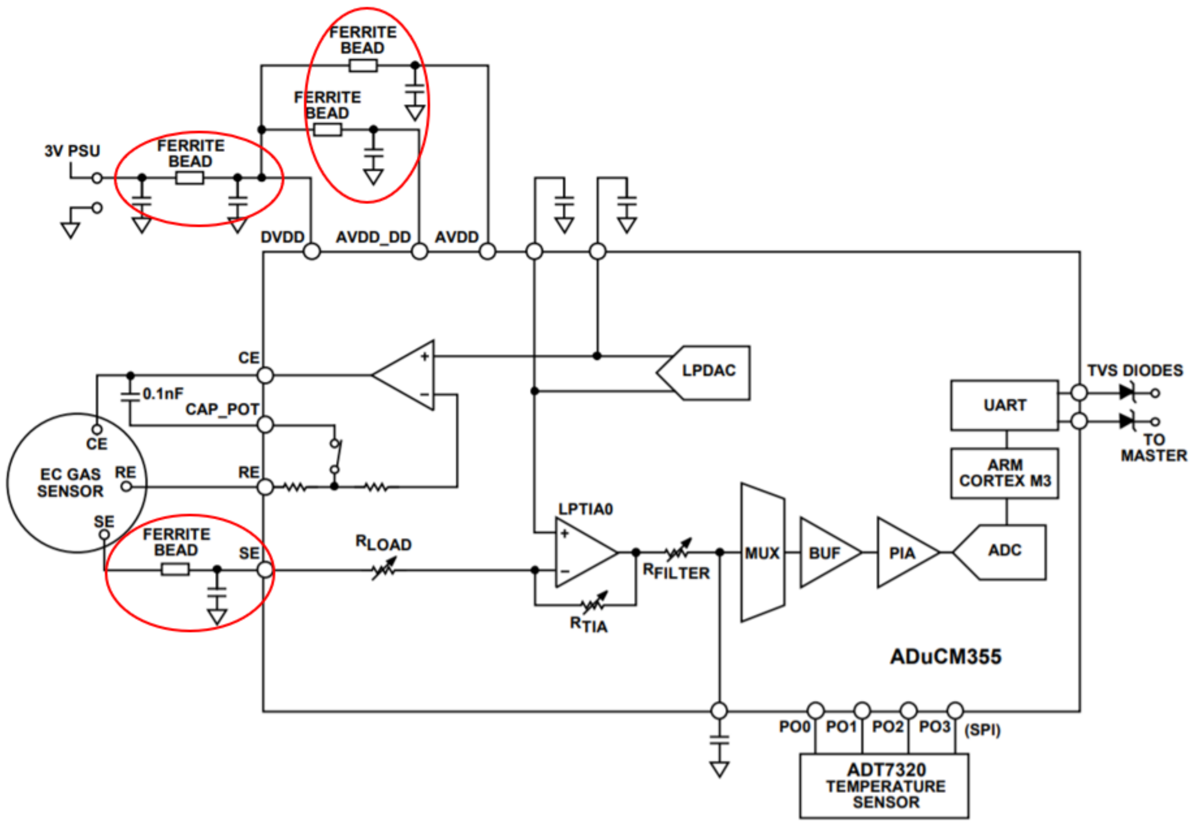

Figure 6: EMI-resistant reference design showing some of the added filters (Image Source: Analog Devices)

Reference design CN0425 is optimized for use in high-EMI environments. Figure 6 shows the main circuit. The reference design uses an ADuCM355 to implement the chemical sensor interface. This device is an ultralow power, mixed-signal microcontroller based on the Arm® Cortex™-M3 processor with a peripheral set that includes two potentiostat functional blocks.

Several external filters are added to ensure that the potentiostat circuit and EC sensor are stable in the presence of RF fields. These include: a low-pass filter with ferrite bead and capacitor between the SE electrode and the ADuCM355's SE input pin; a similar ferrite bead/capacitor combination in the RE pin connection (not shown); and similar filters on the power supply pins. Consult the CN0425 circuit note for a full discussion.

The ADuCM355 has an on-chip temperature sensor, but the reference design includes an external temperature sensor for more accurate results; the ADT7320 connects to the ADuCM355 via an SPI port.

After converting the measured current to a ppm gas concentration, the device can send the result to the UART port for display on a PC.

This reference design has been extensively tested with a variety of sensors for compliance with the EN50270 radiated immunity specifications. The target power level in the specification varies with frequency: 10 V/m from 80 MHz - 1 GHz and from 1.4 GHz - 2.0 GHz; and 3 V/m from 2.0 GHz - 2.7 GHz.

Conclusion

Electrochemical sensors are a popular choice for many gas sensor applications but designing an interface for real-world applications can be challenging. Analog Devices offers a range of EC interface reference designs complete with evaluation boards and comprehensive documentation. These resources simplify the design task and help the designer to leverage the layout and placement of these sensitive devices into an end application.