

Overcoming the Technical Challenges of Electrochemical Gas Sensing

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Electrochemical gas sensors are a proven technology that dates back to the 1950s, when they were developed for oxygen monitoring. One of the first applications of this technology was a glucose biosensor, where it was used to measure the depletion of oxygen in glucose. Over the following decades, the technology has advanced, allowing the sensors to be miniaturized and to detect a wide variety of target gases.

With the advent of the world of ubiquitous sensing, countless new gas sensing applications have emerged across many industries—for example, automotive air quality monitoring or electronic noses. Evolving regulations and safety standards led to requirements that are much more challenging than in the past for both new and existing applications. In other words, gas sensing systems of the future must accurately measure much lower concentrations, be more selective toward the target gases, operate for longer durations from battery power, and provide consistent performance over longer periods of time while always maintaining safe and reliable operation.

Pros and Cons of Electrochemical Gas Sensors

The popularity of electrochemical gas sensors can be attributed to the linearity of their output, low power requirements, and good resolution. Moreover, once calibrated to a known concentration of the target gas, the repeatability and accuracy of measurement is also excellent. Thanks to the evolution of the technology over the decades, these sensors can offer very good selectivity to a particular gas type.

Industrial applications—for example, toxic gas detection for worker safety—were the first to utilize electrochemical sensors thanks to their many advantages. Economical operation of these sensors enabled deployment of area toxic gas monitoring systems, ensuring safe environmental conditions for employees in industries such as mining, chemical industries, biogas plants, food production, pharmaceutical industries, and many others.

While the sensing technology itself is constantly advancing, its basic operating principle, with the disadvantages that come with it, have not changed since the earliest days of electrochemical gas sensing. Typically, electrochemical sensors have a limited shelf life—usually six months to one year. Aging of the sensor has a major impact on its long-term performance, too. Sensor manufacturers often specify that the sensor sensitivity can drift by up to 20% per year. Furthermore, even though the target gas selectivity has improved significantly, the sensors still suffer from cross-sensitivity to other gases, resulting in an increased chance of interference in measurement and erroneous readings. They are also temperature dependent and have to be internally temperature compensated.

Technical Challenges

The technical challenges that need to be overcome while designing an advanced gas sensing system can be split into three groups corresponding to different life stages of the system.

Firstly, there are sensor manufacturing challenges such as manufacturing repeatability, and sensor characterization and calibration. The manufacturing process itself, while highly automated, inevitably introduces variability to every sensor. Due to these variances, the sensors must be characterized and calibrated in production.

Secondly, technical challenges exist throughout the system's life. These include system architecture optimization; for example, signal chain design or power consumption consideration. Primarily in industrial applications, a large emphasis on electromagnetic compatibility (EMC) and functional safety compliance negatively impacts design cost and time to market. Operating conditions also play a significant role and pose challenges to maintain the required performance and lifetime. It is the nature of this technology that the electrochemical sensors age and drift during their life, resulting in frequent calibration or sensor replacement. This change in performance is further accelerated if operating in harsh environments, as covered later in this article. Prolonging the sensor's life while maintaining its performance is one of the key requirements for many applications, especially in cases where the cost of ownership of the system is critical.

Thirdly, even after employing techniques prolonging their operation, all electrochemical sensors ultimately reach their end of life, when the performance no longer meets the requirements and the sensor needs to be replaced. Effectively detecting the end-of-life condition is a challenge that, when overcome, can substantially decrease cost by reducing unnecessary sensor replacements. By taking a step further, and predicting when exactly the sensor will fail, the cost of operating a gas sensing system can be reduced even more.

The utilization of electrochemical gas sensors is increasing in all gas sensing applications, and this creates challenges in terms of logistics, commissioning, and maintenance of these systems, which results in increased total cost of ownership. Therefore, application specific analog front ends with diagnostic capabilities are employed to reduce the impact of disadvantages of the technology, mainly the limited sensor life, to ensure long-term sustainability and reliability of the gas sensing systems.

Signal Chain Integration Reduces Design Complexity

The complexity of traditional signal chains, which are in most cases designed with standalone analog-to-digital converters, amplifiers, and other building blocks, forces designers to compromise on power efficiency, measurement precision, or PCB area consumed by the signal chain.

An example of such a design challenge is an instrument with a multigas configuration, which measures several target gases. Each sensor might require a different bias voltage for its proper operation. Moreover, each sensor's sensitivity might be different—thus the amplifiers' gains must be adjusted to maximize the signal chain performance. For the designer, these two factors alone increase the design complexity of a configurable measurement channel that would be able to interface with different sensors without BOM or schematic changes. A simplified block diagram of a single measurement channel is shown in Figure 1.

Just like in any other electronics system, integration is a logical step in evolution, enabling the design of more efficient and more powerful solutions. Integrated, single-chip gas sensing signal chains simplify the system design by, for example, integrating the TIA (transimpedance amplifier) gain resistors or employing a digital-to-analog converter as a sensor bias voltage source (as seen in Figure 2). Thanks to the signal chain integration, the measurement channel can be fully configurable through software to interface with many different electrochemical sensor types while reducing the complexity of the design. Furthermore, the power requirements of such an integrated signal chain are also notably lower, which is crucial for applications where battery lifetime is a key consideration. Finally, the measurement precision

is improved as a result of decreasing the noise level of the signal chain and, potentially, utilizing signal processing components, such as a TIA or ADC with better performance.

Looking back at the example of a multigas instrument, thanks to the signal chain integration it is possible to:

- ▶ Enable fully configurable measurement channels while reducing the signal chain complexity, thus easily reusing a single signal chain design
- ▶ Reduce the PCB area consumed by the signal chain
- ▶ Decrease power consumption
- ▶ Improve measurement accuracy

Sensor Deterioration and Diagnostics

While the signal chain integration is a significant step forward, on its own it does not address the fundamental disadvantage of electrochemical gas sensors—deteriorating performance over their lifetime. Understandably, this is happening as a result of the sensor's working principle and construction. Operating conditions also contribute to the performance loss and accelerate sensor aging. Sensor accuracy decreases until it becomes unreliable and no longer suitable to fulfil its task. The usual practice in this case is to bring the instrument offline and inspect the sensor manually, which is both time consuming and expensive. Depending on its condition, the sensor then can be either recalibrated and used again, or it might have to be replaced. This incurs considerable maintenance costs. By utilizing electrochemical diagnostics techniques, it is possible to analyze sensor's health and effectively compensate for the performance changes.

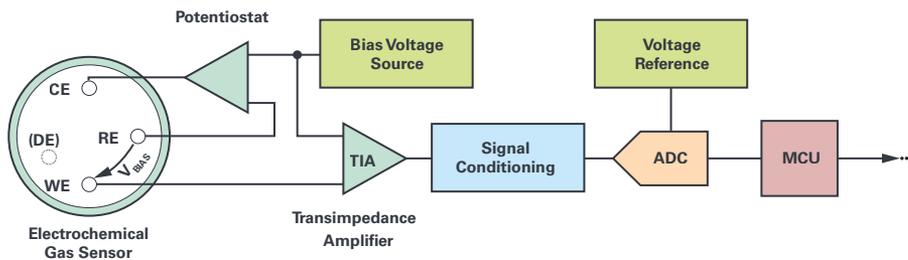


Figure 1. Typical electrochemical gas sensor signal chain (simplified).

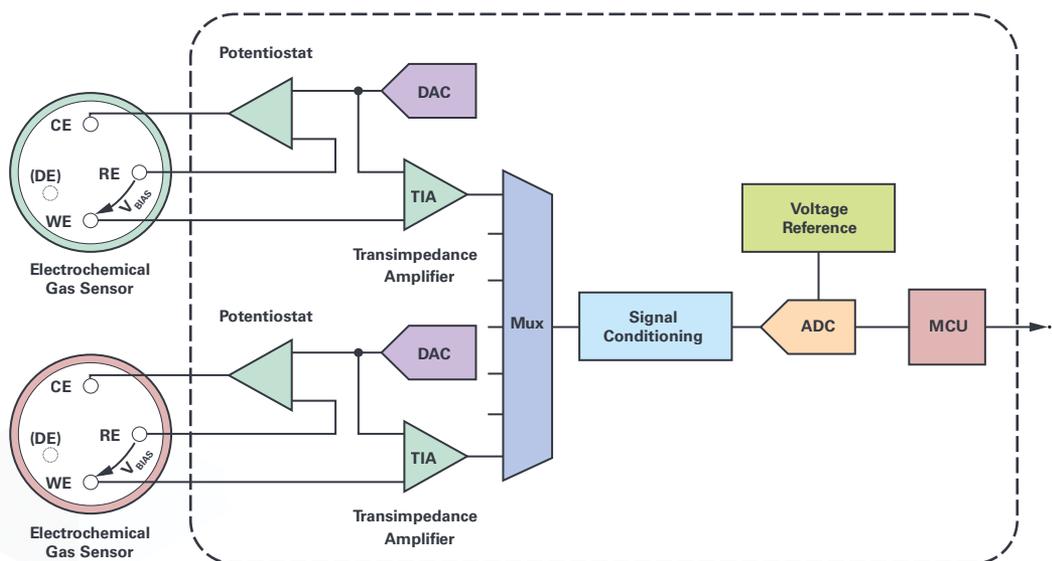


Figure 2. Dual-channel integrated gas sensing signal chain (simplified).

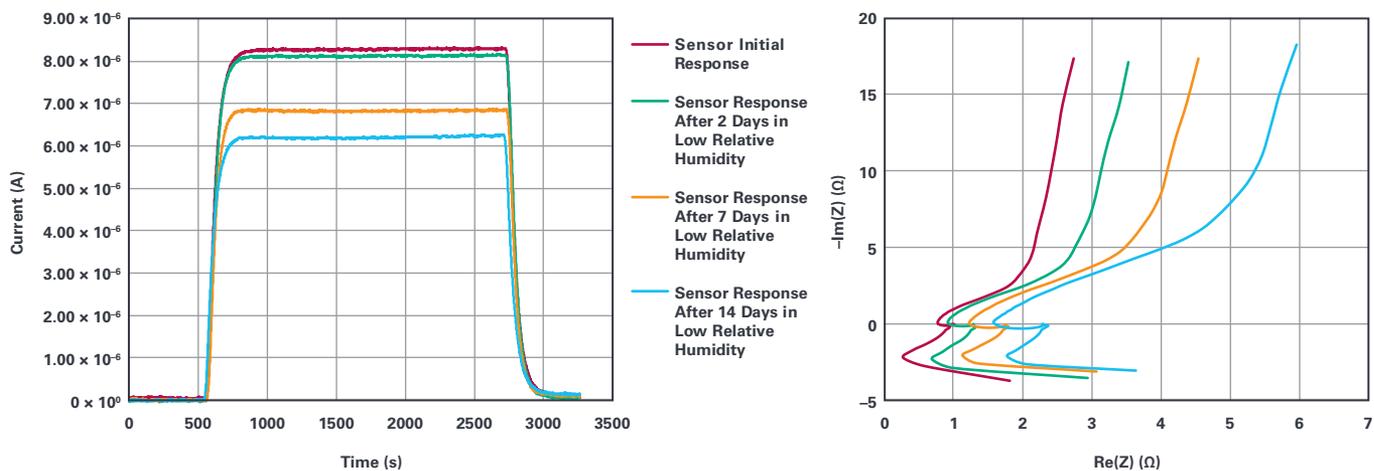


Figure 3. The correlation between sensor sensitivity (left graph) and impedance (right graph) during accelerated lifetime test in low relative humidity.

Common factors contributing to the performance deterioration include excessive temperature, humidity and gas concentration, or electrode poisoning. Short exposure to increased temperatures (over 50°C) is generally acceptable. However, repeatedly stressing the sensor in high temperatures can cause electrolytes to evaporate and inflict irreversible damage to the sensor, such as causing an offset in baseline readings or slower response time. Very low temperatures (below -30°C), on the other hand, significantly decrease the sensitivity and responsiveness of the sensor.

Humidity has by far the greatest influence on the sensor's lifetime. The ideal operating conditions for an electrochemical gas sensor are 20°C and 60% relative humidity. Ambient humidity lower than 60% causes the electrolyte inside the sensor to dry out, affecting the response time. On the other hand, humidity higher than 60% leads to water from the air being absorbed into the sensor, diluting the electrolyte and influencing sensor's characteristics. Additionally, water absorption can cause the sensor to leak, potentially leading to corrosion on the pins.

The aforementioned deterioration mechanisms influence the sensor even if their magnitude is not extreme. In other words, the electrolyte depletion, for instance, occurs naturally and contributes to sensor aging. The aging process limits the sensor life regardless of the operating conditions, although some EC Sense gas sensors could be operating for time periods exceeding 10 years.

The sensor can be analyzed using techniques such as electrochemical impedance spectroscopy (EIS) or chronoamperometry (pulsing the bias voltage while observing the sensor's output).

EIS is a frequency domain analytical measurement made by exciting an electrochemical system with a sinusoidal signal, commonly a voltage. At each frequency, the current flowing through the electrochemical cell is recorded and used to calculate the impedance of the cell. The data is then presented as, most commonly, Nyquist plots and Bode plots. The Nyquist plot shows the complex impedance data, where each frequency point is plotted by the real part on the x-axis and imaginary part on the y-axis. The major shortcoming of this data representation is losing the frequency information. The Bode plot shows impedance magnitude and phase angle vs. frequency.

Experimental measurements have shown a strong correlation between declining sensor sensitivity and change the results of the EIS test. The example in Figure 3 shows the results of an accelerated life test where an electrochemical gas sensor was stressed in low humidity (10% RH) and increased temperature (40°C). Throughout the experiment, the sensor was periodically pulled out from the environmental chamber and allowed to settle for an hour. A baseline sensitivity test with a known target gas concentration and the EIS test were then carried out. The test results clearly

demonstrated the correlation between sensor sensitivity and impedance. The disadvantage of this measurement might be its length, as obtaining measurements at low, sub-Hz frequencies is very time consuming.

Chronoamperometry (pulse test) is another technique that can aid with sensor health analysis. The measurement is done by applying a voltage pulse superimposed on the sensor bias voltage, while observing the current through the electrochemical cell. The pulse amplitude is generally very low (for example, 1 mV) and short (for example, 200 ms), so that the sensor itself is not disturbed. This allows the test to be performed quite frequently, while maintaining normal operation of the gas sensing instrument. Chronoamperometry can be used to check if the sensor is physically plugged into a device, and also as an indication of change in sensor performance, before performing the more time-consuming EIS measurement. An example of sensor response to the voltage pulse is shown in Figure 4.

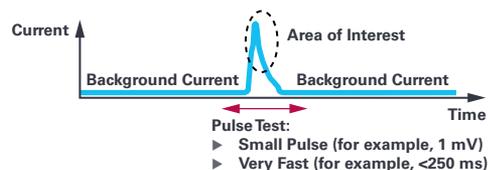


Figure 4. Example result of chronoamperometry test.

The previous sensor interrogation techniques have been used in electrochemistry for decades. However, the equipment required for these measurements is usually expensive and bulky. From both a practical and financial perspective, use of such equipment is simply not viable for testing a large number of gas sensors deployed in the field. In order to enable remote, built-in sensor health analysis, the diagnostics features must be integrated directly as part of the signal chain.

With the integrated diagnostics, it is possible to autonomously test gas sensors without the need of human interaction. If the gas sensors are characterized in production, the data obtained from a sensor can be compared to these characterization datasets and provide insight into the current condition of the sensor. Smart algorithms will then be used to compensate for loss in sensor sensitivity. Furthermore, recording the history of the sensor might then enable end of life prognosis, alerting the user when the sensor needs replacement. Built-in diagnostic features will, ultimately, reduce maintenance needs of gas sensing systems and prolong the operating life of a sensor.

System Design Challenges of Industrial Applications

Especially in an industrial setting, safety and reliability are paramount. Strict regulations are in place to ensure that gas sensing systems meet these requirements and maintain reliable, full functionality when operating in harsh industrial environments such as chemical factories.

Electromagnetic compatibility (EMC) is the ability of different electronic devices to function properly, without mutual interference, in a common electromagnetic environment. Tests involved in EMC are, for instance, radiated emissions or radiated immunity. While the emission testing studies the unwanted emissions of a system to help reduce them, the radiated immunity test examines the system's ability to maintain its functionality in the presence of interference from other systems.

The construction of an EC gas sensor itself has a negative impact on EMC performance. The sensor electrodes act like antennas that can pick up interference from nearby electronic systems. This impact is even more notable in wirelessly connected gas sensing devices, such as portable worker safety instruments.

EMC testing is usually a very time-consuming process that might, eventually, require iterating the system design before the requirements are finally met. This testing contributes significantly to the cost and time invested into product development. Both time and cost expenses could potentially be reduced by using integrated signal chain solutions that have been pretested to meet EMC requirements.

Another serious consideration, and also a technical challenge, is functional safety. By definition, functional safety is the detection of a potentially dangerous condition that results in activation of a protection or correction mechanism to prevent any hazardous events. The relative level of risk-reduction provided by this safety function is then defined as the safety integrity level (SIL). Functional safety requirements are, naturally, captured in industrial standards.

The importance of functional safety in industrial gas sensing applications relates most frequently to a safe operation in environments, where the presence of explosive or flammable gases is possible. Chemical plants or mining facilities are a good example of such applications. To comply with the functional safety standards, a system must be qualified as functionally safe at a satisfactory safety integrity level.

Single-Chip Electrochemical Measurement Systems from Analog Devices

To address the aforementioned challenges and enable customers to design smarter, more accurate, and competitive gas sensing systems, Analog Devices introduced the [ADuCM355](#)—a single-chip electrochemical measurement system targeted at gas sensing and water analysis applications.

The ADuCM355 integrates two electrochemical measurement channels, an impedance measurement engine used for sensor diagnostics, and an ultra low power, mixed-signal ARM® Cortex®-M3 microcontroller for running user application and sensor diagnostics and compensation algorithms. A simplified functional block diagram of the ADuCM355 can be seen in Figure 5.

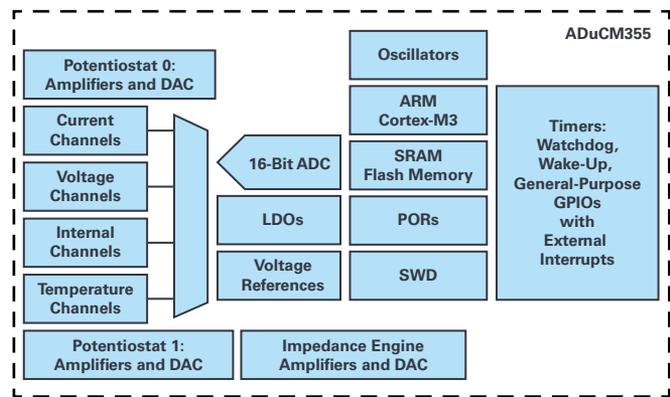


Figure 5. Simplified functional block diagram of the ADuCM355.

Understanding the market trends and needs of the customers helped Analog Devices design a highly integrated, on-chip measurement system that includes:

- ▶ A 16-bit, 400 kSPS ADC
- ▶ Two dual output DACs generating the bias voltage for electrochemical cells
- ▶ Two ultra low power, low noise potentiostats with TIA amplifiers
- ▶ A high speed, 12-bit DAC with high speed TIA
- ▶ Analog hardware accelerators (waveform generator, digital Fourier transform block, and digital filters) that enable diagnostic measurements
- ▶ Internal temperature sensor
- ▶ A 26 MHz ARM Cortex-M3 microcontroller

The ADuCM355 provides the means to overcome the technical challenges of electrochemical gas sensing. Two measurement channels support not only the most common 3-electrode gas sensors, but also the 4-electrode sensor configuration. The fourth electrode is used either for diagnostic purposes, or, in case of dual gas sensors, as a working electrode for the second target gas. Any of the potentiostats can also be configured to hibernate to decrease the power consumption, while maintaining the sensor bias voltage, thus reducing the time sensors might need to settle before proper operation. Analog hardware accelerator blocks enable sensor diagnostic measurements such as electrochemical impedance spectroscopy and chronoamperometry. The integrated microcontroller can be then used for running compensation algorithms, storing calibration parameters, and running user application. The ADuCM355 was also designed with EMC requirements in mind and was pretested to meet the EN 50270 standard.

For applications where the integrated microcontroller is not required, there is also a front-end only version available—[AD5940](#).

Conclusion

As a result of technological innovation, we now have all the necessary knowledge and tools to effectively deal with the technical challenges that have, up until recently, prevented electrochemical gas sensors from entering the era of ubiquitous sensing. From low cost, wireless air quality monitors to process control and worker safety applications, signal chain integration and built-in diagnostic features will enable widespread usage of these sensors, while reducing the maintenance needs, improving the accuracy, prolonging the sensor lifetime, and lowering the cost.

About the Author

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