AN4348
Application note

Signal conditioning for electrochemical sensors

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Introduction

Unmonitored gas can rapidly become a danger. Consequently, in many industries such as refining, mining, and semiconductor industries, monitoring air quality is mandatory for security reasons. Gas monitoring is also important in parking lots and in connection with domestic use. For example, thousands of people are killed every year by carbon monoxide poisoning due to bad combustion.

For these reasons, different gas sensor technologies exist. Of these, the electrochemical sensing technique has the advantage of having a linear output and operating with a low consumption. Consequently, it operates on batteries for a long period of time (particularly true for the toxic gas sensor which delivers almost no current in ambient air), and therefore is used for portable personal protection equipment.

The gases most frequently monitored by handheld safety detectors which use electrochemical sensors are oxygen (O_2), carbon monoxide (CO), hydrogen sulfide (H_2S) and nitrogen dioxide (NO_2). However, many other gases can also be monitored with electrochemical sensors.

Electrochemical sensors are widely used in the medical sector. For example, to monitor the concentration of glucose in the blood of diabetic patients, a glucometer (glucose meter) is used. In this case, the disposable test strips are the electrochemical sensors. *Figure 1* illustrates the carbon monoxide and the glucometer test-strip sensors.

Figure 1: Electrochemical carbon monoxide sensor and glucometer test strip

Electrochemical sensors can also be used in agriculture (to control fruit ripening), the automotive industry (or any activity requiring a combustion control), and for diving and medical reasons.

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1 How does an electrochemical gas sensor work?

An electrochemical gas sensor (see *Figure 2*) contains a gas membrane and two or three electrodes in contact with an electrolyte. The sensor is impermeable to the electrolyte. Gas enters the sensor through the gas membrane which limits the rate of gas diffusion (therefore impacting the sensitivity of the sensor). When gas reaches the working electrode (WE), a chemical reaction occurs: either oxidation (loss of electrons) occurs from the gases CO, H_2S, sulfur dioxide (SO_2), and nitrogen monoxide (NO), or reduction (gain of electrons) occurs from the gases O_2, NO_2, and chlorine (Cl_2). The reaction depends on the sensor.

If oxidation occurs at the WE, the complimentary reaction (reduction) occurs at its counter electrode (CE).

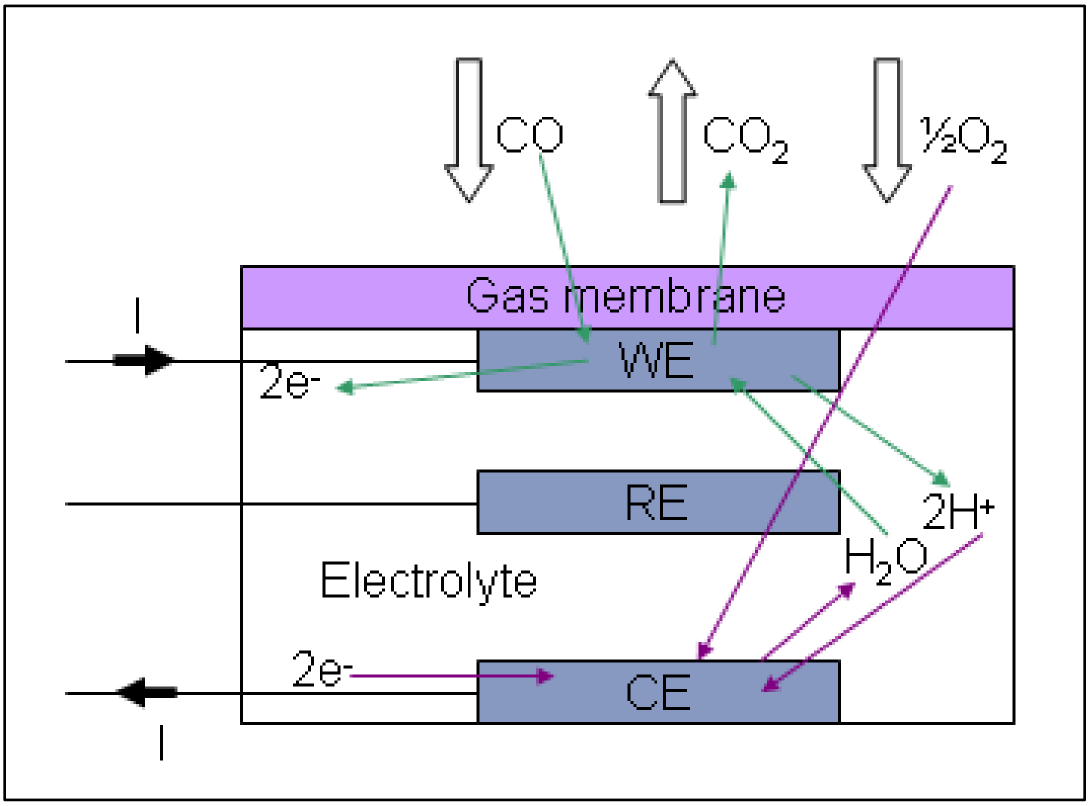
For example, in the case of a CO sensor (see *Figure 2*), oxidation occurs at its WE:

$CO + H_2O \rightarrow CO_2 + 2H^+ + 2e^-$

At the CE, the reaction is:

$½O_2 + 2H+ + 2e- \rightarrow H_2O$ (consumption of oxygen)

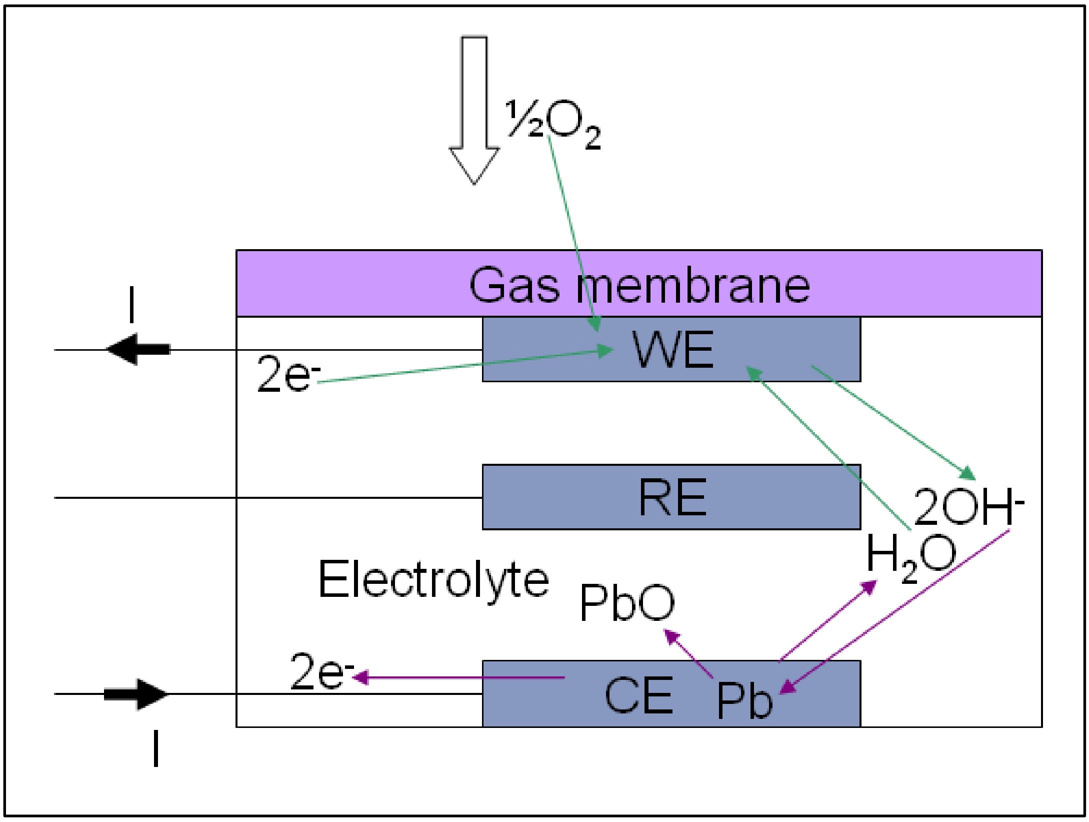
Figure 2: Electrochemical gas sensor (CO)



WE = working electrode (often called the "sensing electrode"), CE = counter electrode, RE = reference electrode (see explanation below).

Figure 3 shows an O_2 sensor.

Figure 3: Electrochemical gas sensor (O2)



WE = working electrode, CE = counter electrode, RE = reference electrode (see explanation below).

Some electrical charges travel through the electrolyte. To keep the charge constant in the electrolyte, some electrons flow through the circuitry (which could be as simple as a resistor) connected to the sensor between the WE and the CE. In the case of the CO sensor, H+ moves in the electrolyte from the WE to the CE whilst in the external circuitry, e- moves from the WE to the CE. Effectively, the sensor generates a current flowing from the CE to the WE. This is why the sensor is also called an amperometric sensor.

The current generated by these chemical reactions is proportional to the gas concentration.

So, in the presence of a targeted gas, a current flows through the CE and changes the potential at the electrolyte/electrode interface. This can slightly impact the sensor response.

To maintain a stable potential difference between the WE and the electrolyte of the sensor, some sensors are fitted with a third electrode in which no current flows (i.e. there is no chemical reaction occurring at the surface). This electrode is called a reference electrode (RE).

2 Signal conditioning with a three-electrode sensor

To use a three-electrode sensor, a voltage has to be applied between the WE and the RE according to the specification of the sensor. The current generated on the WE has to be balanced by the electronics on the CE. No current should flow through the RE. A trans-impedance amplifier configuration is used to convert the current generated by the sensor into a voltage that can be read by the ADC of a microcontroller. This whole electronic design is called a potentiostat. Sensors are generally specified for a given resistive load which must be "seen" by the sensor. This value is generally in the range 10 Ω to 100 Ω.

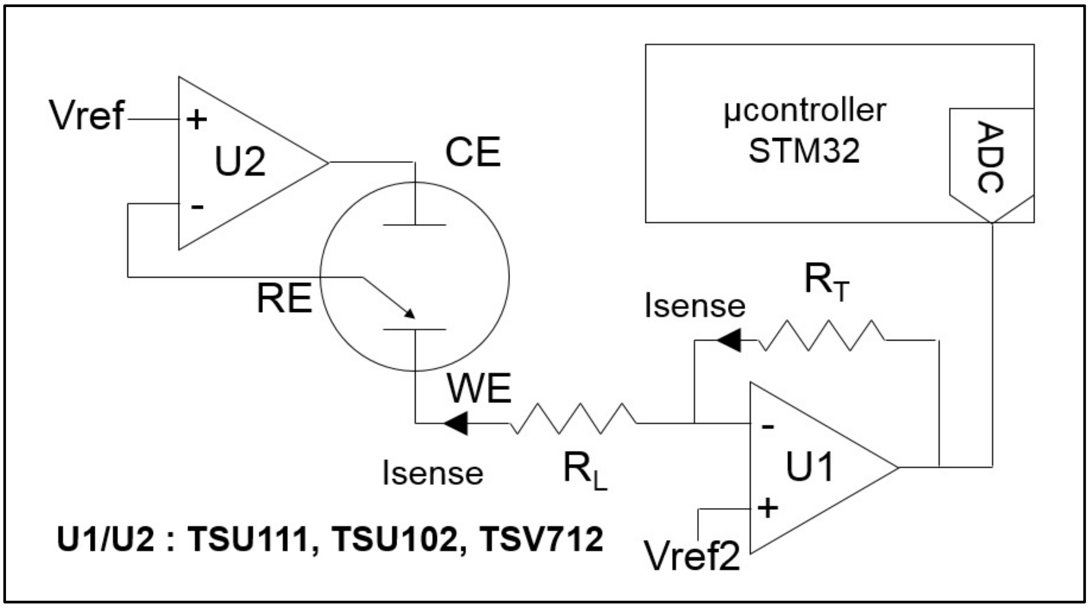
Figure 4 exhibits the main parts of the potentiostat circuitry. The U1 op-amp converts the current generated by the sensor into a voltage thanks to R_T. The output voltage sensed by the ADC is then $R_T \times I_{sense}$.

Depending on the sensor (gas detected) this current can be either positive or negative (see *Figure 2* and *Figure 3*).

U1 also ensures that the sensor is loaded by the specified load (R_L) and keeps the working electrode at a fixed potential. U2 fixes the specified voltage between the WE and the RE (V_{WE}-V_{RE} = -Vref). It also ensures that no current flows through the RE while providing the right amount of current to the CE to compensate the one on the WE.

The microcontroller then computes the gas concentration from its ADC reading given that the gas concentration is proportional to I_{sense}.

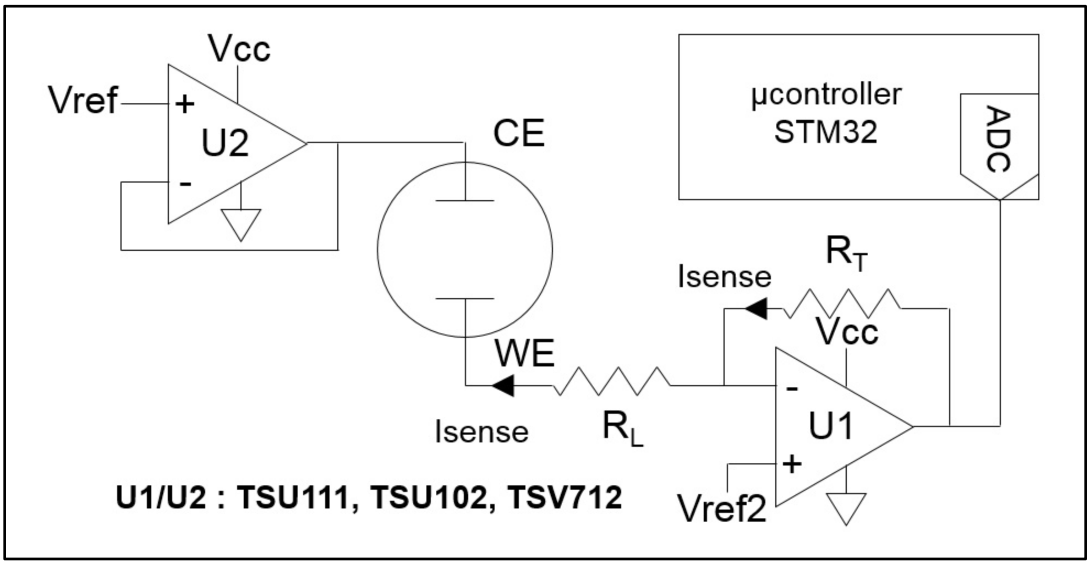
Figure 4: Potentiostat principle



3 Signal conditioning with a two-electrode sensor

For a two-electrode sensor where there is no RE, the same schematic as the potentiostat applies except that the RE and the CE nodes should be shortened. U2 is then configured in buffer configuration. Therefore, Vref is applied to the CE (see *Figure 5*).

Figure 5: Two-electrode electrochemical sensor signal conditioning



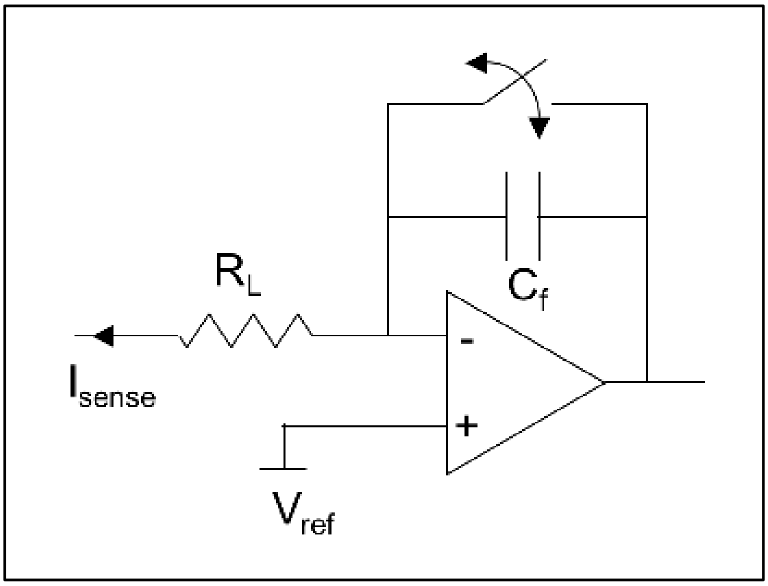
The WE is virtually grounded by U1 and the output voltage read by the ADC is $R_T \times I_{sense}$. Clearly, if the sensor is specified to operate at $V_{WE} = V_{CE}$ (Vref = 0 V), U2 can be omitted and the CE can be directly connected to ground.

Depending on the sensor type, i.e. on the direction of the current generated by the chemical reaction (see *Figure 2* and *Figure 3*), the WE and CE should be swapped.

4 Integrator configuration

For the amplification of the signal, an alternative configuration to trans-impedance is shown in *Figure 6*. It symbolizes an integrator configuration where the number of charge and discharge cycles of the feedback capacitor are representative of the current generated by the sensor.

Figure 6: Integrator configuration



5 Constraints of gas sensor on the design of an application

The sensor's bias voltage (V_{WE}-V_{RE}) and polarity (sign of I_{sense}) can vary between sensors.

Although most sensors are specified to operate with no potential difference between the WE and the RE, some sensors may need one. For example, a potential difference exists and is positive for hydrogen chloride (HCl) and NO, but negative for O_2.

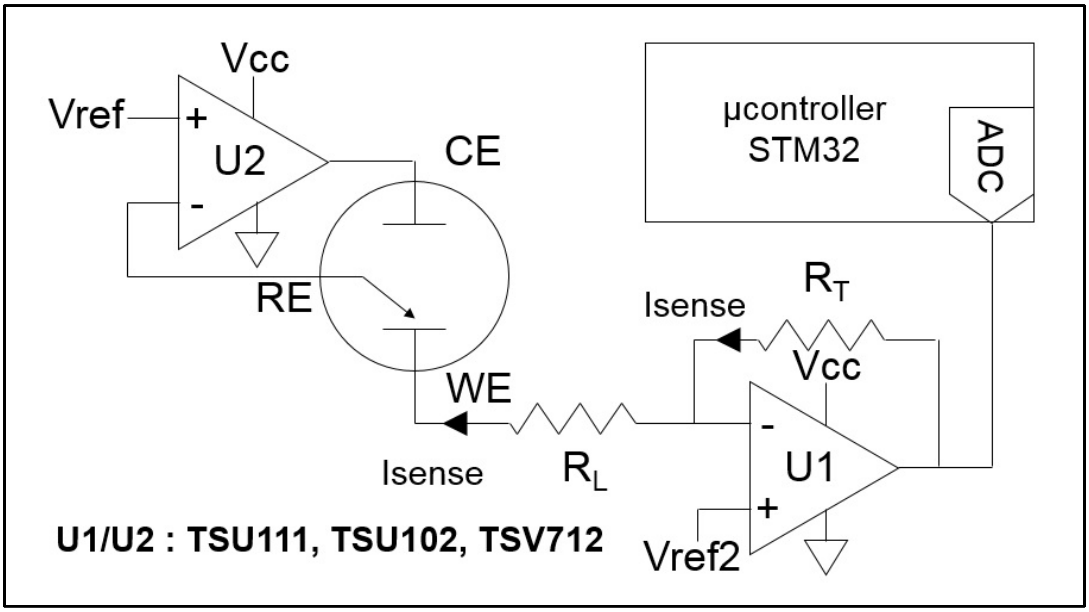
Polarity can be negative for NO_2, Cl_2, chlorine dioxide (ClO_2), and O_2 (I_{sense} is negative when the chemical reaction occurs).

Considering *Figure 4*, where bias voltage and polarity variations depend on power supply values, U1 may become saturated (for example if I_{sense} is negative). U2 may also become saturated if the voltage required on the CE is too close or beyond the U2 power-supplies (this voltage can be up to ±1 V beyond Vref). Finally, by using a sensor that requires a positive V_{WE}-V_{RE}, the negative power supply of U2 has to be negative (Vref is negative).

One solution to overcome these problems is to bias the op-amps in dual-supply (for example +5 V and -5 V). Even if this is possible for some industrial applications, it is generally not the case for portable applications. For the latter, the most appropriate solution is to generate a secondary reference voltage (Vref2) and connect it to the non-inverting input pin of U1 (instead of grounding it).

The output reading is then Vref2 + $R_T \times I_{sense}$ (see *Figure 7*).

Figure 7: Potentiostat for a single power supply



For low voltage applications, the op-amp should be rail to rail on its input so it is not too constrained by the above limitations.

6 From sensor specification to functional application

From the sensor specification, the minimum and maximum sensitivity (S) is known and is generally expressed in nA/ppm. However, in the case of O_2 the output signal in air (in µA) is usually reported. The output signal in air is for 20.9 % O_2. So, in this case, to find the sensitivity of the sensor, divide by 20.9 % and express the result in µA/% of O_2.

The range of the sensor ($[gas]_{max}$) is another important parameter which is expressed in ppm for CO or % for O_2. If the whole range is required for your application, the output voltage on the ADC is between Vref2 (where there is no gas) and Vref2 ± R_T × Smax × $[gas]_{max}$.

Be careful with the polarity of the sensor. I_{sense} can be either positive or negative so, the "±" sign is "+" for CO but "-" for O_2.

The R_T value should be maximized to have the widest possible range at ADC level. But, it should also be kept low enough to avoid saturating U1 (keeping some headroom in case of over-range). This ensures the highest possible resolution.

The recommended load resistor of the sensor, specified in its datasheet, gives the value R_L.

R_L is a tradeoff between response time and noise. Indeed, any noise on the WE node is amplified by the op-amp with a gain of 1 + (R_T/R_L).

Due to its capacitive behavior, the output signal converges with a time constant $C_s(R_s+R_L)$, assuming that the sensor is a capacitor, C_s, in series with a resistor, R_s.

Also, R_L should not be too high or it may unbias the sensor (because of an $R_L \times I_{sense}$ voltage drop).

7 Consumption considerations

For portable safety applications, consumption is a critical point. It is also important for domestic CO detectors if the owner does not want to change the batteries every other week.

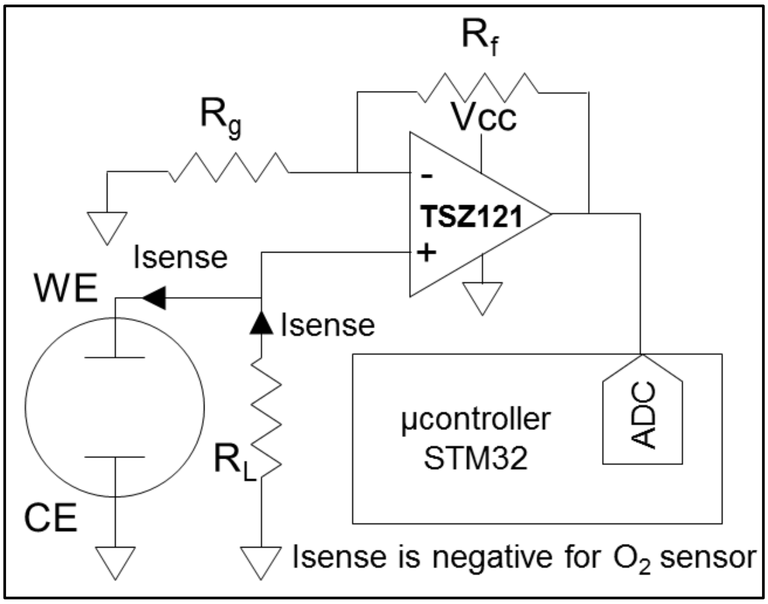
With regard to toxic gases in a normal environment, the sensors deliver almost no current. Therefore, consumption of the application comes only from the active device including the op-amp(s). The TSU102 is a perfect choice for the above applications as it has a consumption of only 600 nA per channel. This is the equivalent of 19 years of battery use for two channels with a 200 mAh battery. Clearly, this op-amp consumption is very small and is suitable for these types of applications.

8 Galvanic configuration

If we consider an O_2 sensor used to detect under- or over-exposure to O_2 in a "breathable environment", the current generated by the sensor is hundreds of µA. In this case, the TSV711 (9 µA) is a good candidate in the application because the current level is big enough.

An alternative configuration is to use the voltage drop through the load resistor and amplify this voltage with a suitable op-amp. The current to voltage conversion is made by R_L rather than by the trans-impedance amplifier (see *Figure 8*).

Figure 8: Low consumption galvanic oxygen sensor configuration



The scale of the signal to be amplified is then relatively low ($R_L \times I_{sense}$ is in the range mV). For this configuration, the op-amp has to be a precision one, and above all, its input offset temperature derating has to be very good. Indeed, input offset voltage compensation should be possible, but temperature compensation may be harder to achieve. The best op-amp choice for this application is the TSZ121 which is a chopper op-amp. Its specifications are 0.06 µV/°C maximum and 5 µV maximum. Therefore, a 20 °C variation causes a variation of only 1.2 µV which corresponds well with the accuracy required by the application. With this configuration a good accuracy is reached (1 µV is only 0.01 % of a full scale 10 mV).

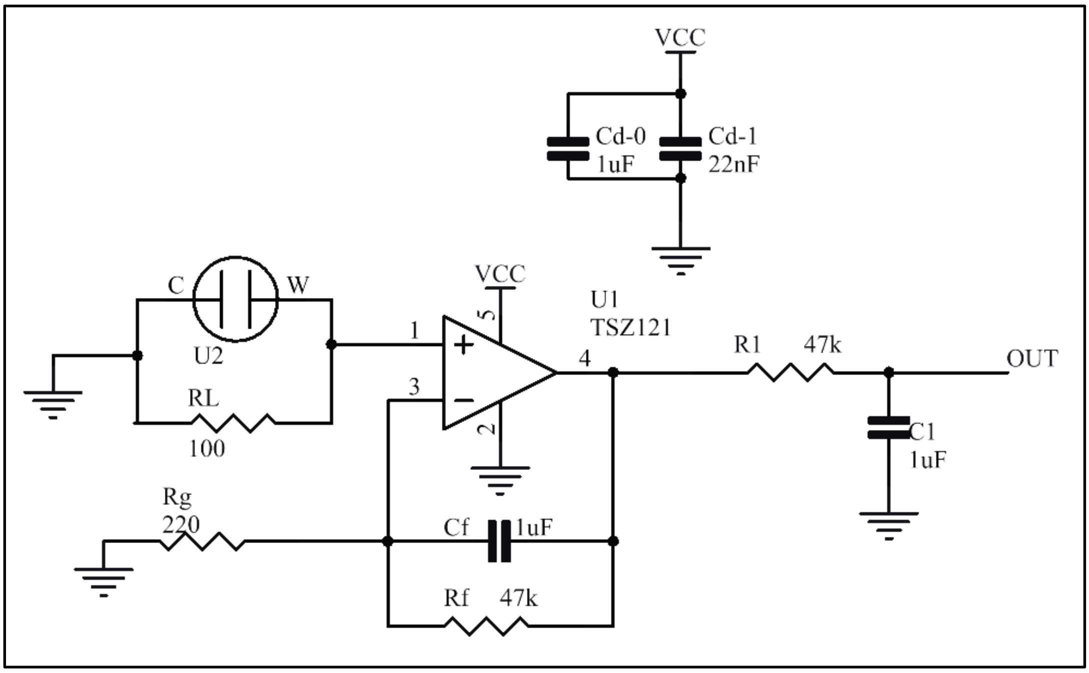
Another advantage of this configuration is that even if the power supply is turned off, the sensor is kept biased thanks to R_L. Consumption of the application can be reduced by powering it periodically (keeping in mind that the capacitors have to be charged at each cycle).

The output signal read by the ADC is: $-(1 + (R_f/R_g))I_{sense}R_L$

Note that I_{sense} is negative (as we are dealing with O_2), so this voltage is positive.

Figure 9 shows a configuration that is very suitable for a galvanic O_2 sensor whose output current is around 100 µA in air. The voltage gain is 215 resulting in an output voltage in air of about 2.15 V. This leaves a margin for higher O_2 concentrations or higher sensitivity of the sensor. It also utilizes most of the output scale and consequently gives a better resolution.

Figure 9: Galvanic configuration using the TSZ121



9 Other op-amp parameters to consider

Consumption is the most critical parameter for devices that are battery powered. However, if the application is aggressive in terms of accuracy, the input/offset voltage (Vio) of the op-amp should also be considered even in the case of a potentiostat. In fact, the Vio of a potentiostat is subtracted from the output signal. For example, a Vio of 3 mV means an error of 0.3 ppm for a NO_2 sensor with a sensitivity of 100 nA/ppm used with an R_T of 100 kΩ. Vio also impacts startup time. Most sensors are highly capacitive and are in the range of 100 mF. At startup, once the output is no longer saturated, the sensor shifts the charge to the Vio with a constant time of $R_T C$ (tens of seconds).

To operate correctly, the potentiostat configuration requires that the input bias current (Iib) of the op-amp is low to prevent some current flowing into the reference electrode (see U2 in *Figure 7*), and to avoid an additional offset caused by R_T. The accuracy of the application does not generally require the Iib to be lower than 1 nA. Therefore, any CMOS or JFET op-amp is a good candidate in this respect.

Both Vio and the Iib can be compensated by calibration. As long as the system remains linear, the output signal read by the ADC is in the form Req × I_{sense} + Voffset. The output signal depends on the sensitivity of the sensor, R_T accuracy, Vref, Vref2, Iib, and the Vio of U2. By measuring the gas at two different concentrations, one can determine the equation to set in the microcontroller to retrieve the gas concentration.

However, even if Vio and Iib can be compensated, their variation with temperature cannot. Therefore, for very high accuracy applications, the TSZ121, whose temperature coefficient is only 0.06 µV/˚C maximum, is perfect. With this op-amp, a 30 ˚C variation causes a shift of only 1.8 µV which is clearly much lower than the resolution of a 12-bit ADC powered by 3.3 V.

The TSU111 circuit also offers an improved temperature coefficient compared to TSU101.

Any change in Vref2 can be monitored with an additional ADC channel.

As shown in *Table 1*, TSU111, TSU10x, TSV71x, TSZ12x, and TSV73x are very good CMOS op-amps that fulfill the requirements of electrochemical sensing-based applications.

Table 1: Op-amp selection specifications at 3.3 V

Product	Iib max (pA)	Vio max (mV)	Noise 0.1 to 10Hz (uVpp)	Vcc min (V)	GBP (kHz)	Icc (uA)
TSU111	10	0.15	3.7	1.5	11	0.9
TSU101 TSU102 TSU104	5	3	8.6	1.5	8	0.6
TSV711 TSV712 TSV714	10	0.2	10	1.5	120	9
TSZ121 TSZ122 TSZ124	200	0.005	0.8	1.8	400	29

Product	Iib max (pA)	Vio max (mV)	Noise 0.1 to 10Hz (uVpp)	Vcc min (V)	GBP (kHz)	Icc (uA)
TSV731 TSV732 TSV734	10	0.2	7	1.5	850	59

It is recommended not to use the op-amp at an input common mode voltage which is close to the input differential pair transition. This point is about Vcc-0.7 V for the TSU10x and Vcc-0.9 V for the TSV71x and TSV73x. For the TSZ12x, it is about Vcc-0.7 V, but its Vio is so low that the transition has almost no impact.

Many domestic carbon monoxide detectors are disposable. They often use a lithium cell whose voltage decreases with usage. Choosing an op-amp with a low minimum operating voltage helps extend the application lifetime. The TSU111 and TSU10x, with a minimum operating voltage of 1.5 V, are perfectly suitable for this application.

10 Filtering

The signals to be monitored by the electrochemical sensor are very slow. Therefore, to reduce noise level it is recommended to filter the signal chain either with a simple RC low-pass filter or with an active filter using an additional op-amp (a spare channel if available). The cut-off frequency of the filter can be as low as 1 Hz as it has to be compared with the response time of the sensor. This response time is usually some tens of seconds and is referred as t_{90} in the sensor datasheet.

In the case of a galvanic sensing circuit (see *Figure 9*), a capacitor is added in parallel with R_f to prevent amplification of the signals (i.e. noise) beyond the interesting frequency range. The cut-off frequency is given by: $1/2\pi R_f C_f$.

The same bandwidth limitations may be added for a potentiostat schematic.

In addition to this filtering a simple RC filter may also be added on the output of the op-amp to obtain an overall second order filter. If we consider an equivalent input white noise source (e_0) with a gain (G) for a first order low-pass filter whose cut-off frequency is f_c, the overall noise over an infinite bandwidth is:

Equation 1

$$e_0 G \sqrt{\int_0^{\infty} \frac{df}{1+\left(\frac{f}{f_c}\right)^2}} = e_0 G \sqrt{\left[f_c Atan\left(\frac{f}{f_c}\right)\right]_0^{\infty}} = e_0 G \sqrt{\frac{f_c \pi}{2}} = e_0 G \sqrt{1.57 f_c}$$

In the case of a second order filter at the same -3dB (f_c) cut-off frequency, the overall noise over an infinite bandwidth is:

Equation 2

$$e_0 G \sqrt{\int_0^{\infty} \frac{df}{\left(1+\left(\frac{f\sqrt{\sqrt{2}-1}}{f_c}\right)^2\right)^2}}$$

$$= e_0 G \sqrt{\left[\frac{f_c}{f\sqrt{\sqrt{2}-1}} Atan\left(\frac{f\sqrt{\sqrt{2}-1}}{f_c}\right) + 2\left(1+\left(\frac{f\sqrt{\sqrt{2}-1}}{f_c}\right)^2\right)^2\right]_0^{\infty}}$$

$$= e_0 G \sqrt{\frac{f_c \pi}{4\sqrt{\sqrt{2}-1}}} = e_0 G \sqrt{1.2 f_c}$$

So, with the same -3dB bandwidth, a second order filter can reduce the output noise level by 13% with respect to a first order filter.

Although the order of the low-pass filter implemented directly impacts the noise level, the calculation of the real overall noise level on the output is much more complicated. Overall noise depends on the characteristics of the op-amp (such as bandwidth and input equivalent voltage noise density) and the sensor (the model of which is generally not available from manufacturers). Op-amps are generally specified for their 1/f noise (rms value in the 0.1 Hz to 10 Hz range) and white noise density (at 1 kHz). The former is the most critical as white noise can be filtered (as the signal to be amplified is at a very low frequency).

Note that the output noise between 0.1 Hz and 10 Hz is not simply:

$$\left(1 + \frac{R_T}{R_g}\right) \times Noise_{rms}^{0.1Hz-10Hz}$$

This is because of the sensor model and the GBP limitation of the op-amp.

The integrated noise of the op-amp over the bandwidth 0.1 Hz to 10 Hz gives us the first impression of the noise caused by the op-amp in the application:

$$Noise_{rms}^{0.1Hz-10Hz}$$

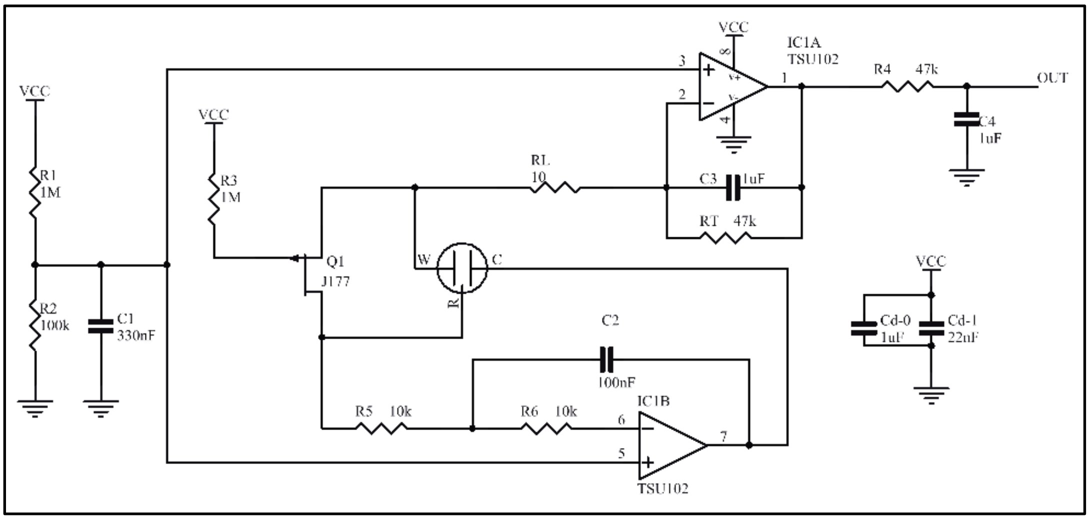
In the case of a very low signal (large gain, few ppm of gas), an op-amp with low noise is required. For such an application, the TSZ121 is a perfect choice. It has a very low noise at low frequency (1.8 µVpp only in the 0.1 Hz to 10 Hz bandwidth). In addition, 1/f noise is reduced due to the internal architecture (chopper) of this op-amp.

But, for further applications in which current consumption is key, the TSU111 is preferable because the integrated noise over the same bandwidth is 3.7 µVpp for a supply current which is more than 30 times less.

11 Maintaining the sensor biased

If the sensor is left unbiased it becomes polarized. Due to its capacitive behavior, it then requires a long time to stabilize again (from a few minutes up to a day). For sensors specified by $V_{WE} = V_{RE}$ (three-electrode sensors) or $V_{WE} = V_{CE}$ (two-electrode sensors), the sensor can be kept biased during power-off. Note that the power-off state can exist when the batteries are being replaced. In portable applications, power-off may sometimes exist in-between measurements (to minimize consumption). The solution to keep the sensor biased is to use a P-JFET (such as J177) connected between the WE and the RE. In the case of a two-electrode sensor the connection is between the WE and the CE as its gate is connected to the power line via a resistor. When in power-off mode, the P-JFET shorts the two electrodes to maintain the correct biasing of the sensor (see *Figure 10*).

Figure 10: Carbon monoxide sensing with TSU102



While the power is on, the P-JFET is in the pinch-off region (i.e. there is no current between the drain and the source) and it has no impact on the application. In this case, the input offset voltage of the two op-amps creates a V_{ds} voltage which can be different to 0 V. Therefore, the V_{gs} voltage should be kept sufficiently high to avoid any unwanted current flowing through the transistor. This is because this current would be amplified by the trans-impedance stage (like the current generated by the sensor) which would result in an offset error. Particular attention should be paid to low power supply values. However, since the user wishes to benefit from the widest ADC range possible, it is recommended to use the op-amp with a low Vicm value (e.g. for carbon monoxide sensing) which results in a large V_{gs} voltage.

If the sensor is biased with $V_{WE} \neq V_{RE}$ (three-electrode sensors) or $V_{WE} \neq V_{CE}$ (two-electrode sensors), an additional battery may be used to continue biasing the sensor while the application is switched off.

In the case of a two-electrode galvanic sensor with a voltage gain configuration as shown in *Figure 9*, the load resistor converting I_{sense} into a voltage continues biasing the sensor even during power-off mode.

Note that the R, C network around the driving op-amp (IC1B) may be changed for stability reasons depending on the sensor used. However, the TSU102 was tested with different sensors, and good performances were obtained even with a simple direct connection (R = 0 Ω, C = 0 F).

The reference voltage is set to 300 mV for a power supply of 3.3 V.

If biasing is required for the sensor (e.g. an oxygen sensor), a secondary divider bridge can be used to independently drive the input common mode voltage of the two op-amps. The P-JFET should also be removed.

For a two electrode sensor, IC1B should be configured in follower to drive the CE to a fixed voltage (no R5, R6 and C2 shorted).

12 Cross-sensitivity, environmental variation, and long-term output drift

Even if they are a good choice for many applications, electrochemical sensors are not perfect. For example, they are generally sensitive to gases other than the targeted one. So, depending on the environment targeted, cross-sensitivity values should be considered even if the sensor is fitted with a filter.

Electrochemical sensors are also sensitive to temperature. For the same gas concentration, the output reading is different if the temperature is different. This dependency is illustrated in the sensor datasheet. With the help of a temperature sensor, compensation is generally achievable at the micro-controller level.

Finally, pressure and humidity can cause the sensor to generate current spikes.

STMicroelectronics proposes miniature MEMS sensors to help improve the accuracy of an application by compensating for these environmental parameter changes.

Drift in time of the sensor (sensitivity decreasing) should also be considered to maintain the accuracy of the application. Consequently, regular calibrations are requested in the user manuals of gas detectors.

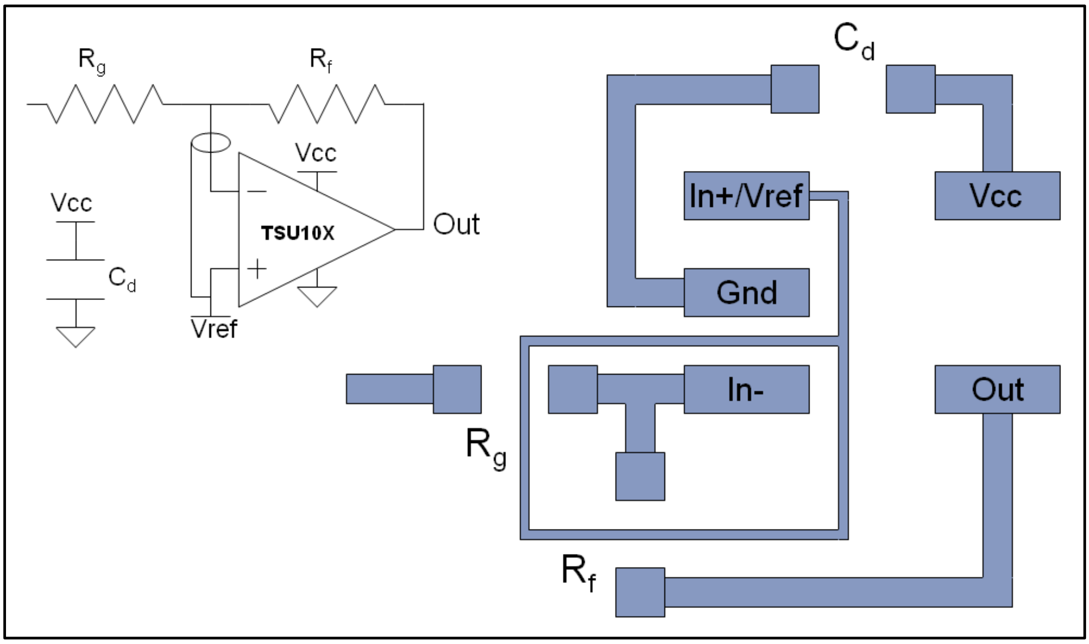
13 Layout recommendations

Apply standard recommendations to the layout of your electrochemical sensing application.

A good decoupling of the power supplies should be observed. Please refer to the datasheet of the op-amps TSU10x, TSV71x, TSV73x, and TSZ12x. Alternatively, use a 1 µF capacitor and a 22 nF capacitor close to each integrated circuit.

Pay attention to the nodes around the sensor which are in relative high impedance. The use of short tracks is recommended. A guard ring around the sensitive (high impedance) nodes is illustrated in *Figure 11* and is also recommended with a proper coating of PCB.

Figure 11: Application layout with guard ring



14 Testing the hardware

Different tests can be performed to check that the hardware is functional.

Test 1

1. Remove the sensor (normally sensors are not soldered or they would be damaged)
2. Short the RE and the CE on the PCB.
3. On this node, check that the reference voltage is obtained (note that the op-amp is now configured in buffer configuration)
4. Still working without the sensor, verify the output of the second op-amp. It should be at the WE voltage as this op-amp is also in buffer configuration since R_{load} is left open.
5. Both the RE and the WE voltages can be fine-tuned in this way.

Test 2

1. Add a current source on R_{load} to check that the trans-impedance amplifier is operating correctly (V_{out} should equal $V_{WE}+R_T \times I$)
2. Try the application with the sensor (first removing the short circuit and the current source).

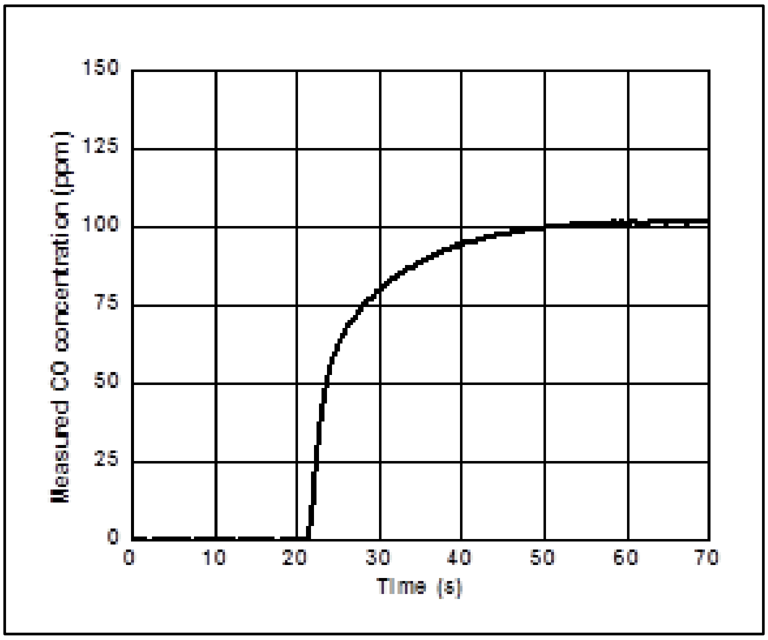
In the absence of the targeted gas, $V_{out} = V_{WE}$. During exposure to the gas, the output should vary according to the sensitivity of the sensor. Note that if the sensor was left unbiased, it may take several minutes up to several hours for it to operate correctly.

As the sensitivity of the sensors is not well controlled during their manufacturing, it is necessary to calibrate your application with different gas concentrations.

Alternatively, a quick reading can be taken by performing a bump test. This is the sudden exposure to a gas, for example, in the case of O_2 sensing, it is the measurement of an exhalation.

Figure 12 illustrates the result obtained with a three-electrode CO sensor using the TSU101.

Figure 12: Response to a carbon monoxide step using the TSU101



15 P-NUCLEO-IKA02A1 evaluation pack

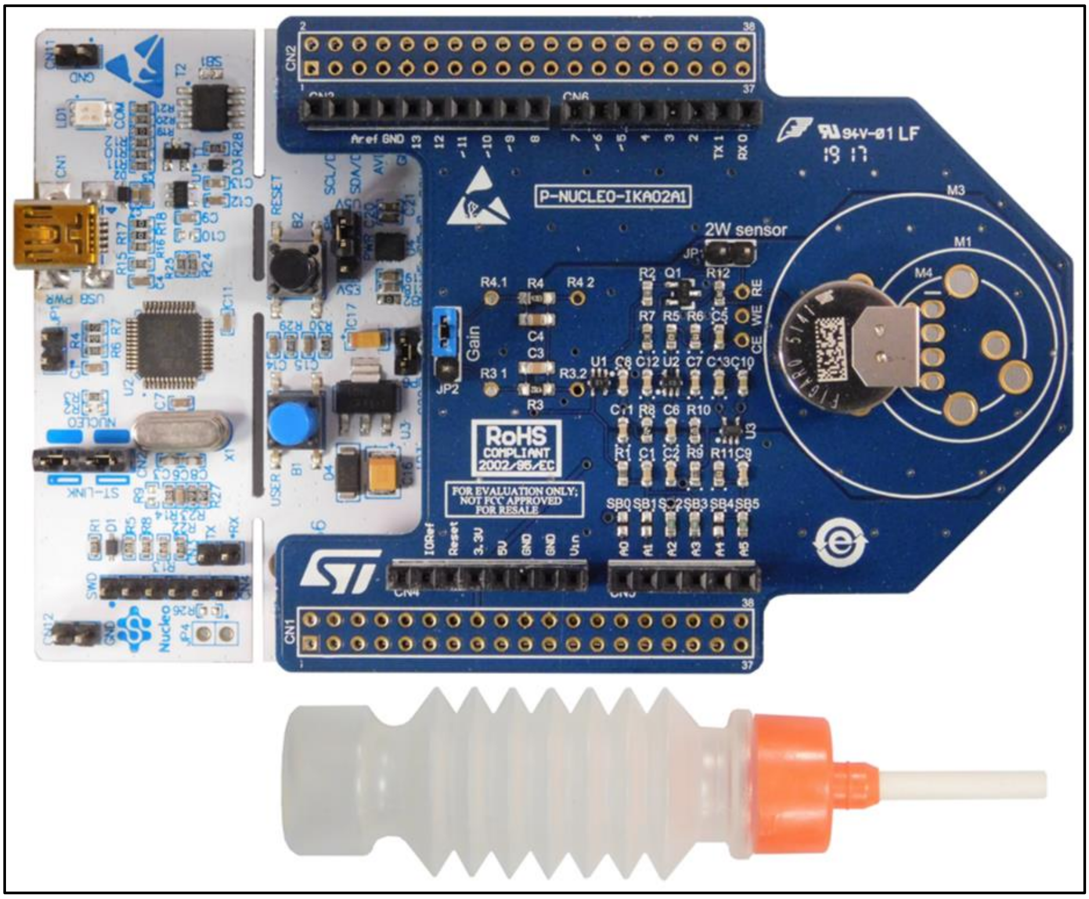
The P-NUCLEO-IKA02A1 evaluation pack provides a reference design for various electrochemical sensors.

The STM32 Nucleo gas expansion board interfaces electrochemical sensors with the MCU on the STM32 Nucleo development board. Two TSU111 operational amplifiers provide signal conditioning; they are ideal for electrochemical sensing thanks to their high precision and low power consumption. The expansion board includes an ultra-low current precision analog temperature sensor STLM20 used for compensation of gas readings.

STM32 Nucleo boards provide an affordable and flexible way for users to experiment with new ideas and build prototypes with any STM32 microcontroller line. The NUCLEO-L053R8 is designed for low power applications.

The design and componentry are optimized for battery operation and maximum battery life time.

Figure 13: P-NUCLEO-IKA02A1 evaluation pack



16 Conclusion

Electrochemical sensors are widely used. They require specific op-amps to drive them and to amplify the signal (current) they generate which is proportional to the concentration of the gas being measured. The best choice of op-amp is generally a low-power, low voltage, rail-to-rail output CMOS device.

Regarding the ST product suite, the op amp offering the best compromise for disposable CO detectors is generally the TSU111, but if you need to be even more aggressive in terms of consumption, you can choose the TSU101 (600 nA typ at 3.3 V); TSV611(A) can be sufficient for a number of applications (10 µA). If higher accuracy is required, the TSV711 (9 µA, 200 µV max) is a good choice. For the most demanding applications the TSZ121 (29 µA @3.3 V, 5 µV max) should be considered.

Table 2 illustrates the advantages of the different op-amp products with regard to electrochemical sensors.

Table 2: Advantages of various op-amps

Product	Features (all specifications given at 3.3 V)
TSU111	Ultra low consumption: 900 nA typ Low low noise: 3.7 μV_{pp} from 0.1 Hz to 10 Hz Good precision: 150 µV max
TSU101 TSU102 TSU104	Ultra low consumption: 600 nA typ Battery life extension
TSV711 TSV712 TSV714	Good compromise between consumption and precision Icc: 9 µA typ Vio: 200 µV max
TSZ121 TSZ122 TSZ124	Excellent precision: Vio 5 µV max Ultra low noise: 0.8 μV_{pp} from 0.1 Hz to 10 Hz Ideal for galvanic use

All op-amps in *Table 2* are CMOS devices. They are available in small packages and multiple-channel configurations for additional flexibility and space-saving.

If you plan to have a 4 mA to 20 mA output in your application, STMicroelectronics also has high voltage op-amps that would meet your requirements.

You may also benefit from a wide portfolio of analog switches, voltage references, temperature sensors, pressure sensors, or microcontrollers to develop your application.

17 Revision history

Table 3: Document revision history

Date	Revision	Changes
28-Nov-2013	1	Initial release
16-Aug-2017	2	Minor text edits Updated *Figure 4: "Potentiostat principle"*, *Figure 5: "Two-electrode electrochemical sensor signal conditioning"* and *Figure 7: "Potentiostat for a single power supply"* In *Section 9: "Other op-amp parameters to consider"*: - updated content and *Table 1: "Op-amp selection specifications at 3.3 V"* in *Section 10: "Filtering"*: - updated content and *Equation 1* and *Equation 2* Added *Section 15: "P-NUCLEO-IKA02A1 evaluation pack"* In *Section 15: "P-NUCLEO-IKA02A1 evaluation pack"*: - updated content and *Table 2: "Advantages of various op-amps"* In *Section 16: "Conclusion"*: - updated content and *Table 2: "Advantages of various op-amps"*