

Three-Electrode Electrochemical Sensors

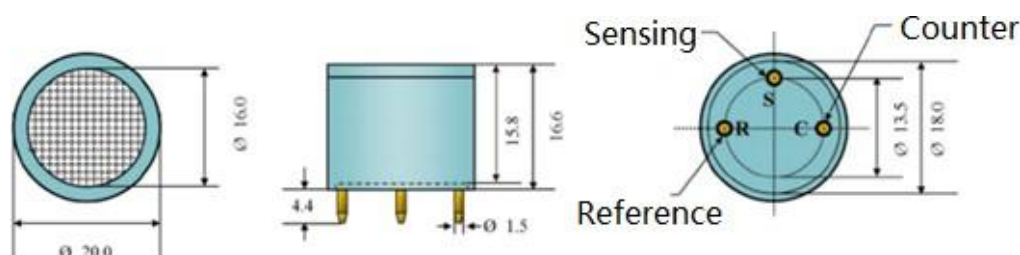
ABOUT SEMEATECH

SemeaTech is a global leader in sensing technologies, spearheading hazardous material detection for workplace safety, occupational health, and environmental protection. The company specializes in monitoring toxic gases, including CO, H₂S, Cl₂, NH₃, SO₂, NO₂, H₂, and O₃. Its flagship product lines features the widely adopted 4-series and 7-series industrial-grade electrochemical (EC) sensors. Built on standard three-electrode technology, these sensors are seamlessly interchangeable in form, fit, and function with standard market alternatives. SemeaTech guarantees uncompromised sensor quality, delivering exceptional detection range, stability, linearity, repeatability, and resolution, combined with minimized cross-sensitivity.



FUNCTION PRINCIPLE

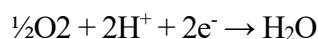
The three electrodes on an EC sensor are defined as R (Reference Electrode), S (Sensing Electrode), and C (Counter Electrode), as shown below:



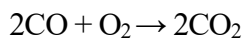
The EC sensor functions by reacting to the target gas and then producing an electrical output signal that is proportional to the gas concentration. The target gas in contact with the sensor first passes through a capillary-type opening and then diffuses through a hydrophobic barrier. It eventually reaches Sensing Electrode surface. The molecules on the electrode are immediately oxidized or reduced to consequently produce or consume electrons to generate an electric current. This is a catalyzed process based on the electrode materials specifically developed for the target gas. For example, carbon monoxide is oxidized at Sensing Electrode per following chemical equation:



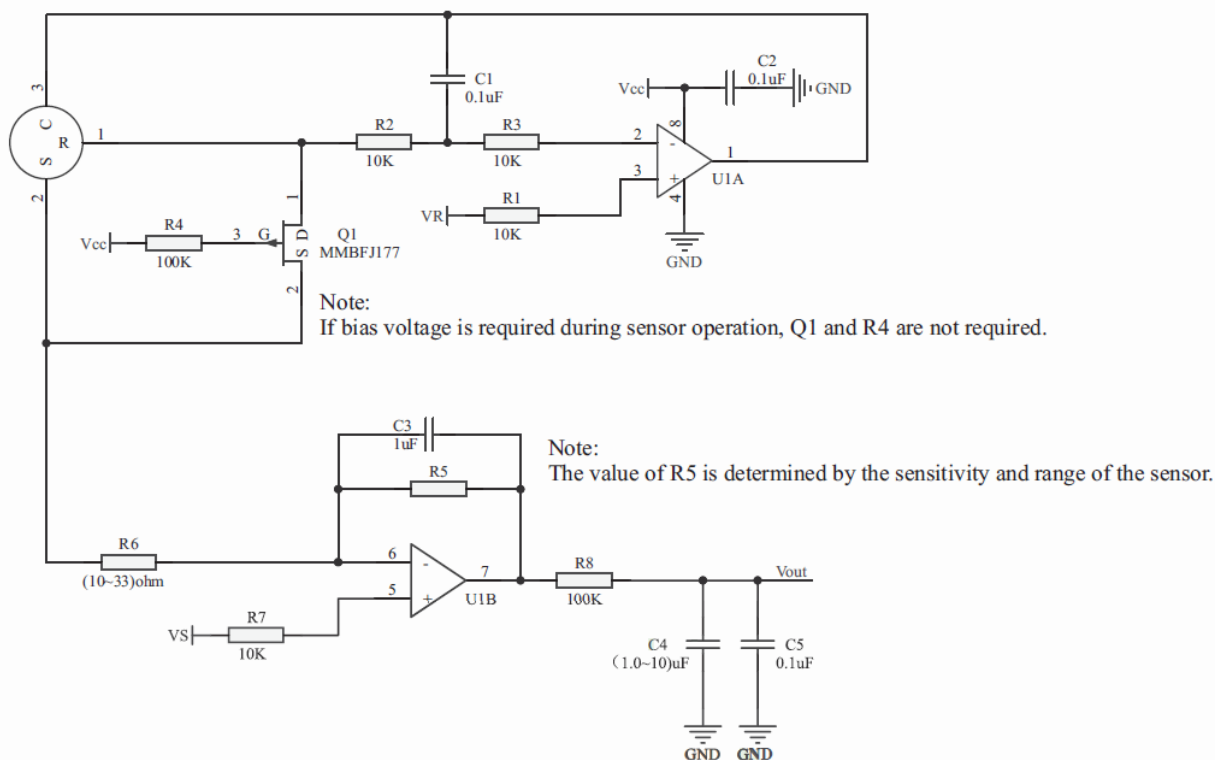
The Counter Electrode works to balance out the reaction on the Sensing Electrode. When oxidation occurs on the Sensing Electrode, oxygen is reduced to form water on the Counter Electrode. Conversely, if a reduction reaction takes place on the Sensing Electrode, the Counter Electrode undergoes the corresponding reverse reaction. In this example, water gets oxidized per the chemical equation shown below:



And the overall reaction in this case is as follows:



RECOMMENDED CIRCUITRY



The diagram above is a recommended circuitry for three-electrode EC sensors. It consists of three parts: Potentiostatic Circuit, I/V (current/voltage) Converting Module and Short-circuit Configuration.

1. Potentiostatic Circuit

The potential difference between the Sensing Electrode and the Counter Electrode must not fall below a specific threshold (depending on the sensor type) to ensure normal sensor operation. Physically, the Reference Electrode is positioned between the Sensing Electrode and the Counter Electrode within the sensor's mechanical structure. Consequently, the potential of the Reference Electrode lies between that of the Sensing and Counter Electrodes along the current path. Under the combined effect of the potentiostatic circuit for the Reference Electrode and the output circuit for the Sensing Electrode, the potential difference between the Sensing and Reference Electrodes is maintained exactly at the minimum value required for normal sensor operation. As a result, the potential difference between the Sensing and Counter Electrodes remains above this minimum threshold, thereby satisfying the requirements for normal sensor functionality.

The potentiostatic circuit is made up of U1A, R1, R2, R3, C1, C2, C3 and B1 (Ferrite bead). R1, R2 and C3 together form the low-pass filter to reduce high frequency noise between the Reference Electrode and the Counter Electrode; R2 and R3 are impedance matching resistors. Assuming U1A and U1B are ideal operational amplifiers, V_R is the potential of the Reference Electrode, and V_S is the potential of the Sensing Electrode. Consequently $(V_S - V_R)$ is the minimum potential difference between the Sensing Electrode and the Counter Electrode to keep the sensor working normally.

2. Measurement of Sensor Current

The output signal of a three-electrode gas sensor is an electric current flowing through the Sensing Electrode and the Counter Electrode. The best way to measure this current is to use I/V (Current/Voltage) converting module that is made up of U1B, R5, R6, C4, C5, C6, C7, B2, R_Load and R_Gain. In most cases (oxidation), the output current flows out from U1B and then flows into Sensing Electrode through R_Gain and R_Load. The current is proportional to the concentration of target gas. V_o is the output signal that can be calculated using the following equation:

$$V_o = (I + I_{base}) \times R_{gain} + V_S \quad (I = \text{sensitivity} \times \text{concentration})$$

Here,

- i) I_{base} is the output current while the concentration of target gas is zero (I_{base} value can be found in the sensor datasheet), and
- ii) C4, C5, C6, C7, R5 and B2 are used for the suppression of signal noise. R6 and R7 act as impedance matching the operational amplifier input.

3. Short-Circuit Configuration

For unbiased sensors, the Sensing Electrode and the Reference Electrode should be short-circuited when the circuit is powered down. This ensures that the Sensing Electrode is maintained at the same potential as the Reference Electrode, allowing the sensor to be ready for immediate operation upon power-up. This short-circuit configuration consists of Q1 and R4. Specifically, the Reference Electrode and the Sensing Electrode are connected via a P-channel transistor (Q1), which shorts the two electrodes in the powered-off state and opens them during the powered-on state.

Sensors that require a bias voltage do not utilize such a short-circuit configuration. Conversely, it is recommended to maintain the voltage (typically 300 mV) continuously between the Sensing Electrode and the Reference Electrode. This can be achieved by connecting the sensor to a battery during main power-down.

CONFIGURATION OF BIAS VOLTAGE

1. Biased

The bias voltage of corresponding sensors is shown in the table below.

Sensor Type	V _{bias}
ETO, NO, C ₂ H ₃ Cl, TEOS, THT	+300 mV (±10 mV)
HCl, HBr, C ₃ H ₃ N	+200 mV (±10 mV)
C ₂ H ₄	+250 mV (±10 mV)
O ₂	-600 mV (±10 mV)

Notes:

- i) When using biased sensors, the short-circuit configuration is not needed. Therefore, Q1 and R4 should be removed in the circuitry;
- ii) $V_{bias} = V_S - V_R$ (V_R and V_S is provided by voltage reference IC).

2. Unbiased

For unbiased sensors, the Sensing Electrode and the Reference Electrode should be short-circuited.

Q1 and R4 are required in the circuitry.

KEY POINTS FOR CIRCUIT DESIGN

1. Sensor Polarity

For reductive gas sensors (such as CO, H₂S, SO₂, PH₃, and H₂), the sensor output current flows out from the Counter Electrode, which functions as the positive (+) terminal. After passing through the external circuit, it flows back to the Sensing Electrode, acting as the negative (-) terminal. Conversely, for oxidative gas sensors (such as O₂, NO₂, Cl₂, ClO₂, and HF), the sensor output current flows through the circuit in the opposite direction.

2. OPA(U1)

The OPA should have very low input bias current on the inverting pin (U1B-6) and low input voltage noise, such as OP07, OPA2378, MCP6V02.

3. Voltage Reference IC

The IC provides the fixed voltage for V_S and V_R . It requires high precision and low temperature drift coefficient, such as LM285, REF3325, REF1112.

4. R_Gain

The sensor output current flows through R_Gain and then converts to the voltage output signal. Therefore, it is very important to select R-Gain with high precision and low temperature drift coefficient. The resistor value is determined based on the sensor sensitivity and maximum measuring range (maximum load).

5. R_load

R_load should be selected with the value between 10 ohm and 33 ohm. The higher resistor value is selected, the better performance will be in noise reduction. However higher resistor value meanwhile results the sensor in long response time to the target gas.

6. RC Filter

Connecting to U1-B output pin-7, a RC filter consisting of R5, C6 and C7 is recommended to add into the circuitry. To stabilize the voltage output, the RC parameters need to be adjusted.

7. Filter Capacitor

C3, C4 and C5 are used as filter capacitors for better EMC performance.

8. VS Configuration

1) When using CO, H₂S, SO₂, PH₃, HCN, H₂, NH₃, CH₂O, CH₃SH, H₂O₂, C₂H₂, AsH₃, SiH₄, GeH₄, N₂H₄, NO-U, HCl-U or other unbiased sensors, (V_S = V_R) ≥ 1.0V. When concentration increases, the output voltage (V_{out}) increases.

2) When using NO₂, Br₂, Cl₂, ClO₂, HF, COCl₂ or O₃ sensor, V_S = V_R. V_R is more than 1.0V lower than the OPA's power supply V_{cc}. When concentration increases, the output voltage (V_{out}) decreases.

3) When using NO (biased), ETO, C₂H₃Cl, TEOS or THT sensors, (V_S-V_R) = 300mV (error is less than 10mV). V_S ≥ 1.0V. When concentration increases, the output voltage (V_{out}) increases.

4) When using the C₂H₄ sensor, (V_S-V_R) = 250mV (error is less than 10mV). V_S ≥ 1.0V. When concentration increases, the output voltage (V_{out}) increases.

5) When using HCl (biased), HBr or C₃H₃N sensor, (V_S-V_R) = 200mV (error is less than 10mV). V_S ≥ 1.0V. When concentration increases, the output voltage (V_{out}) increases.

6) When using the O₂ sensor, (V_S-V_R) = -600mV (error is less than 10mV), and V_R is more than 1.0V lower than the OPA's power supply V_{cc}. When concentration increases, the output voltage (V_{out}) decreases.

7) V_S and V_R are obtained by voltage reference chips through resistor division.