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1. Introduction

IDT's SGAS line of solid-state chemiresistive sensors are an advanced type of gas-sensitive resistor; i.e., they sense the presence of a target gas through a change in resistance of the sensing element. Most sensors exhibit reduced resistance as gas concentration increases, typically over several orders of magnitude across the sensing range.

The electronic instrumentation used to detect this change in resistance influences the quality and accuracy of the gas sensing result. In particular, the analog front-end circuitry used to measure resistance can have a significant effect on overall measurement characteristics and must be selected with care. The goal in this application note is to describe how the concentration/resistance transfer functions of the sensor combine with those of the electronic circuitry used to measure sensor resistance, with the aim of ensuring that the overall transfer function is well-matched to particular sensing applications.

2. Resistive Characteristics of Sensors

Solid-state chemiresistive sensors show a reduced resistance with increasing gas concentration according to Equation 1:

$$R = A * C^{-\alpha} \tag{Equation 1}$$

Where

R is resistance

C is concentration

A and α are constants

Although several alternate or refined versions of this equation have been posited for chemiresistive sensors, the fundamental resistance versus concentration relationship described in Equation 1 is applicable for all SGAS sensors produced by IDT. Taking the log of both sides of Equation (1) results in Equation 2:

$$\log(R) = \log(A) - \alpha * \log(C) \tag{Equation 2}$$

This illustrates the basis for the chemiresistor-related paradigm that *log resistance versus log concentration is linear*.

An immediately observable consequence of Equation 1 is that sensor resistance will change rapidly if low concentrations are applied and much slower at high concentrations. This is illustrated in the following real example, based on actual behavior observed with an SGAS701 Hydrogen Sensor, which has a baseline (air) resistance of approximately 5M Ω ; a resistance in 100ppm hydrogen of approximately 300k Ω ; and a resistance in 1000ppm hydrogen (full-scale) of approximately 70k Ω .

Fitting this data to Equation 2 produces

$$A_{H_2} = 5.51 * 10^6$$

$$\alpha_{H_2} = 0.632$$

Figure 1 and Figure 2 illustrate the resistance versus concentration relationship for the example of the hydrogen sensor.

Figure 1. Resistance versus Gas Concentration Plotted Linearly – SGAS701 Hydrogen Sensor

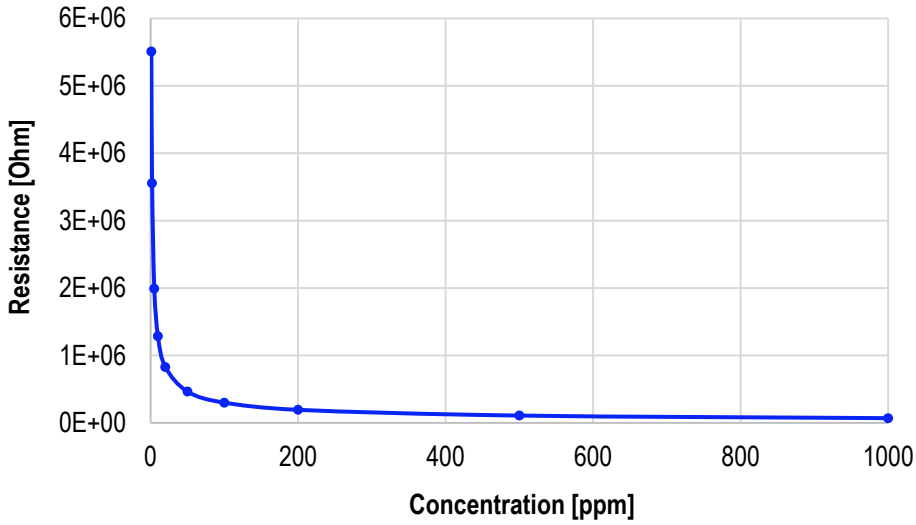
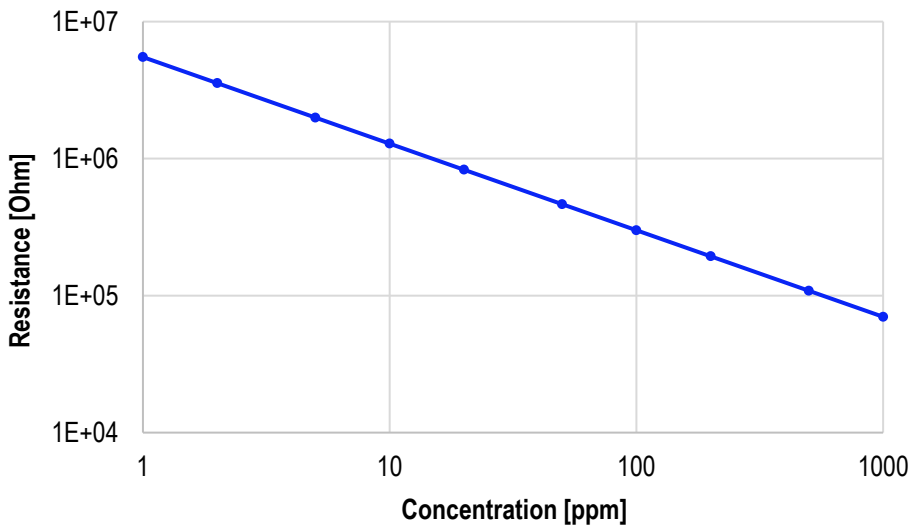


Figure 2. Resistance versus Gas Concentration Plotted Logarithmically – SGAS701 Hydrogen Sensor

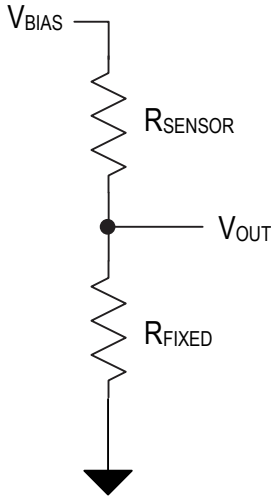


Since simple resistance measurement circuits will have a non-logarithmic transfer function, the fundamental measurement challenge illustrated by Figure 1 is expected when making gas sensor measurements. Additional nonlinear effects from the measurement circuitry exacerbate this challenge and must be understood in order to account for or eliminate these effects.

3. Voltage Divider

The voltage divider shown in Figure 3 is a very simple circuit for producing the sensor signal V_{OUT} .

Figure 3. Voltage Divider Circuit



The sensor signal relates to sensor resistance according to Equation 3:

$$V_{OUT} = V_{BIAS} * \frac{R_{FIXED}}{R_{FIXED} + R_{SENSOR}} \tag{Equation 3}$$

Sensor resistance can be calculated with Equation 4:

$$R_{SENSOR} = R_{FIXED} * \left(\frac{V_{BIAS}}{V_{OUT}} - 1 \right) \tag{Equation 4}$$

V_{OUT} increases as the sensor responds to higher gas concentrations (as the sensor resistance decreases). Both voltage and current through the sensor change as the sensor responds to the changing gas concentration. If R_{SENSOR} is very small compared to R_{FIXED} , then $V_{OUT} \approx V_{BIAS}$. If R_{SENSOR} is very large compared to R_{FIXED} , then $V_{OUT} \approx 0$. Therefore, selecting R_{FIXED} involves identifying a response voltage range suitable for follow-on measurement circuitry. The practical example below (utilizing the hydrogen sensor described above) illustrates the selection process.

A typical SGAS701 gas sensor has a resistance in air of approximately $3M\Omega$ and a resistance under full-scale gas exposure (1000ppm hydrogen) of approximately $70k\Omega$. Start the selection process by rearranging Equation 3:

$$R_{FIXED} = R_{SENSOR} * \left(\frac{response}{1 - response} \right) \tag{Equation 5}$$

Where:

$$response = \frac{V_{OUT}}{V_{BIAS}} = \frac{R_{FIXED}}{R_{FIXED} + R_{SENSOR}} \tag{Equation 6}$$

Equation 3 makes clear that a full-scale response equal to V_{BIAS} cannot be achieved, as this would require a fixed resistor that is infinitely large. However, it is easy to reach 90% of full-scale with practical resistance values:

$$response_{H2_FullScale} = 0.9$$

$$R_{FIXED} = R_{H2_FullScale} * \left(\frac{response_{H2_FullScale}}{1 - response_{H2_FullScale}} \right) = 70k\Omega * \left(\frac{0.9}{1 - 0.9} \right) = 630k\Omega$$

Taking Equation 6 into consideration, the response in air for this value of R_{FIXED} would be

$$response_{AIR} = \frac{R_{FIXED}}{R_{FIXED} + R_{AIR}} = \frac{630k\Omega}{630k\Omega + 5M\Omega} = 0.112$$

For perspective, on a 3.3V measurement system, the voltage in air would be 369mV and the full-scale response would be 2.97V. Alternative full-scale response targets can be selected (3.3V system assumed) as given in Table 1.

Table 1. Alternative Full-Scale Response Targets for 3.3V System

Full Scale Response	R_{FIXED} [Ω]	V_{OUT} (air) [V]	V_{OUT} (full-scale) [V]
0.75	210k	0.133	2.475
0.80	280k	0.175	2.640
0.90	630k	0.369	2.970
0.95	1.33M	0.693	3.135

It is clear that a trade-off is made between low baseline ("in air") and full-scale response signals. In general, a full-scale response voltage close to V_{BIAS} is preferred (for reasons discussed below), and thus a full-scale response value at the lower end of the table is favored.

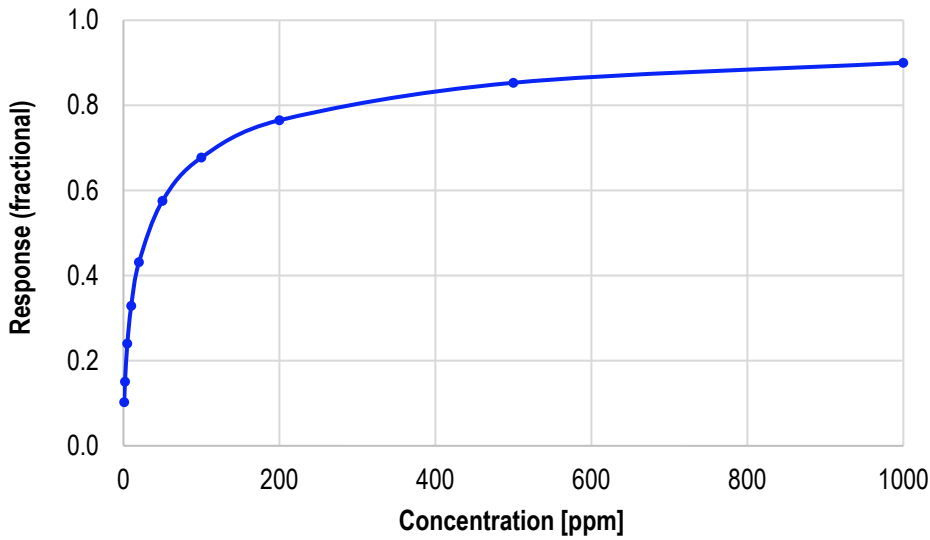
How the response scales with the sensor resistance is also important. From Equation 6, it can be seen that the sensor response scales in proportion to the inverse of the sensor resistance. It is also seen that sensor response (compared to a percent change of resistance) is much smaller near full-scale than it is near zero. For instance, a halving of the sensor resistance from $4M\Omega$ to $2M\Omega$ (with a 3.3V divider drive and a $630k\Omega$ load resistor) results in a response voltage increase from 449mV to 790mV, or a 75% response to the halving of sensor resistance. By comparison, a halving of sensor resistance from $10k\Omega$ to $5k\Omega$ results in a response voltage increase from 2.51V to 2.85V, an increase in response of only 14%. Stated another way, response is much greater near zero than near full-scale.

The discussion above relates to the transfer function sourcing from the characteristics of the measurement circuit, and it is separate from the resistance-concentration relationship described in Equation 1. Quantitatively, the combination of the resistance to response behavior of the circuit as shown in Equation 6 with the resistance to concentration transform from Equation 1 gives Equation 7:

$$response = \frac{R_{FIXED}}{R_{FIXED} + A * C^{-\alpha}} \tag{Equation 7}$$

The resulting sensor response is shown in Figure 4. The graph shows the anticipated rapid rise in response at lower concentrations and the slowing of response at higher concentrations.

Figure 4. Linear Hydrogen Sensor Response versus Gas Concentration for a Voltage Divider

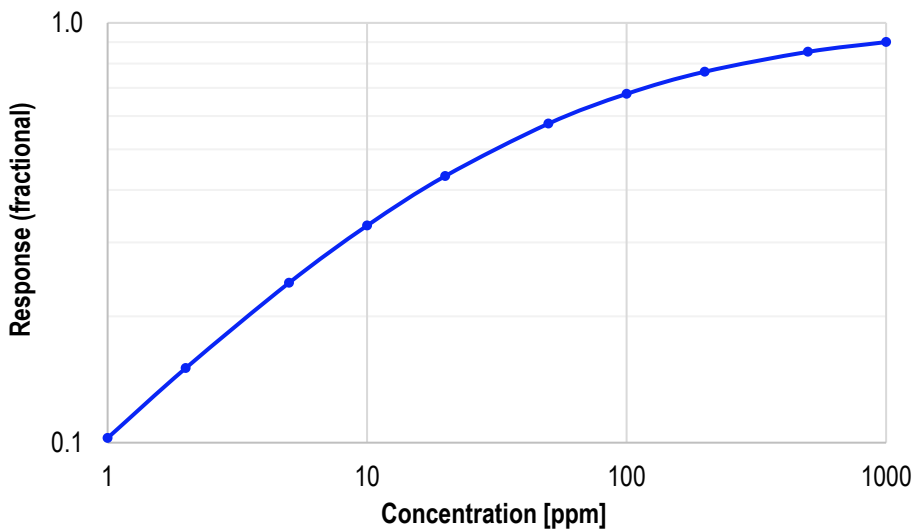


Taking the log of both sides of Equation 7 gives Equation 8:

$$\log(\text{response}) = \log(R_{FIXED}) - \log(R_{FIXED} + A * C^{-\alpha}) \tag{Equation 8}$$

When $R_{FIXED} \ll R_{SENSOR}$ (i.e., when the gas concentration is low), $\log(R_{FIXED} + A * C^{-\alpha})$ reduces to $\log(A * C^{-\alpha})$, which gives a linear relationship between $\log(\text{Response})$ and $\log(C)$. At higher response levels (i.e., lower R_{SENSOR}), R_{FIXED} will start to dominate the $\log(R_{FIXED} + A * C^{-\alpha})$ term, and the $\log(\text{Response})$ versus $\log(C)$ relationship will become increasingly nonlinear. The nonlinearity is demonstrated in Figure 5 for the hydrogen sensor example.

Figure 5. Logarithmic Hydrogen Sensor Response versus Gas Concentration for a Voltage Divider

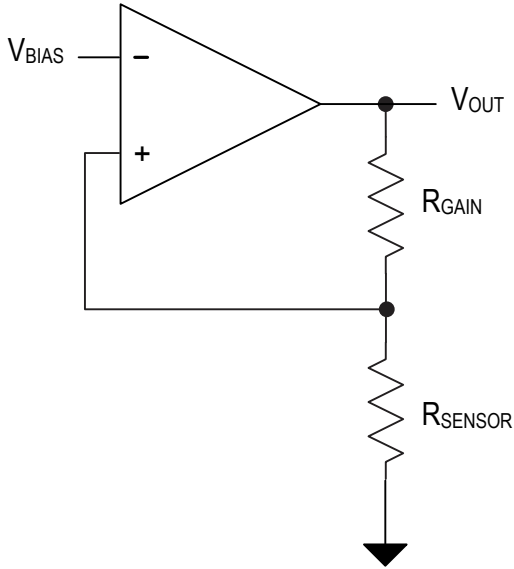


There is no algorithmic way to linearize the log of the response, since R_{SENSOR} and R_{FIXED} are inseparable in Equation 6. How important this is depends upon the needs of the application. However, the analysis above shows that a voltage divider would not be favored in applications where the response signal requires linearization as part of a calibration or analysis scheme.

4. Constant Voltage Sensor Drive

Several practical circuits are available for driving the sensor element with a constant voltage. Resistance is then determined by measuring the current through the sensor. The simplest approach uses a non-inverting amplifier configuration as illustrated in Figure 6.

Figure 6. Constant Voltage Driving Circuit



The sensor signal V_{OUT} relates to sensor resistance according to Equation 9:

$$V_{OUT} = V_{BIAS} * \left(\frac{R_{GAIN}}{R_{SENSOR}} + 1 \right) \tag{Equation 9}$$

Sensor resistance is calculated using Equation 10:

$$R_{SENSOR} = V_{BIAS} * \frac{R_{GAIN}}{V_{OUT} - V_{BIAS}} \tag{Equation 10}$$

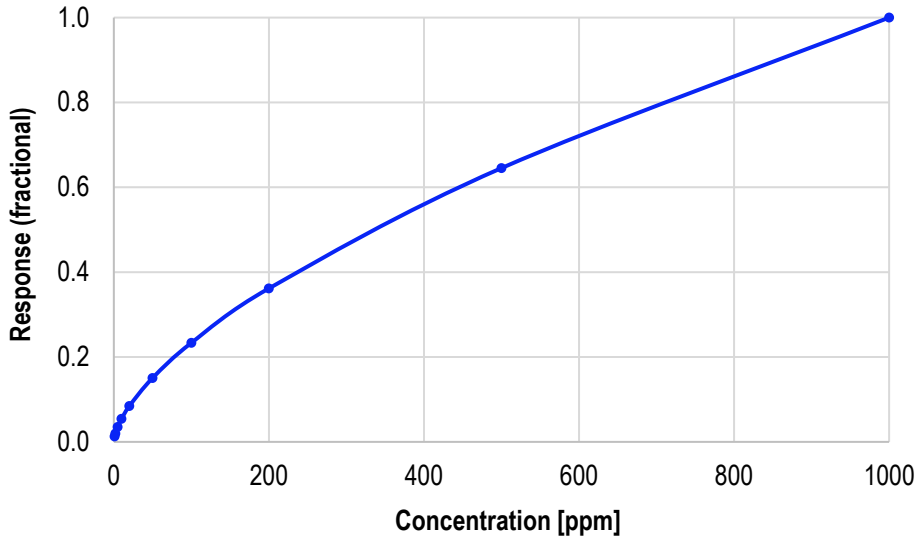
V_{out} increases as the sensor responds to higher gas concentrations (as sensor resistance decreases), varying from a minimum of V_{BIAS} (at infinite R_{SENSOR}) to a full-scale reading of 2.5V (at $R_{SENSOR} = R_{GAIN}$). Selecting R_{GAIN} is straightforward: it is equal to the targeted full-scale resistance. An obvious drawback of this particular front-end design is the offset (by V_{BIAS}) of V_{OUT} . However, offset and scaling of the output signal, either before or as part of the analog-to-digital conversion process, are easily implemented to overcome this drawback.

If the response is taken by $\left(\frac{V_{OUT}}{V_{BIAS}} - 1 \right)$, then

$$response = \frac{R_{GAIN}}{R_{SENSOR}} = \frac{R_{GAIN}}{A * C^\alpha} \tag{Equation 11}$$

As immediately seen from Equation 11, the response is inversely proportional to R_{SENSOR} . When comparing Equation 11 to Equation 6, it can be seen that the fixed resistance is no longer intertwined with the sensor resistance for the constant voltage drive, making response less rapid at lower concentrations. This is borne out comparing the plot of sensor response versus concentration shown in Figure 7 to the corresponding plot (Figure 4) for the voltage divider.

Figure 7. Linear Hydrogen Sensor Response versus Gas Concentration at Constant Voltage

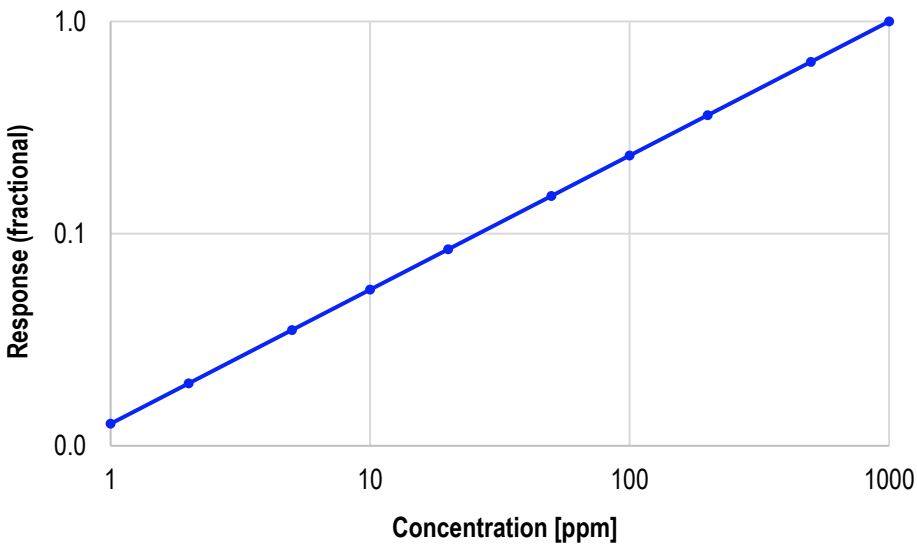


Taking the log of both sides of Equation 11:

$$\log(\text{response}) = \log(R_{GAIN}) - \log(A) + \alpha * \log(C) \tag{Equation 12}$$

With this method, the response should be fully linear in a $\log(\text{response})$ versus $\log(C)$ plot as shown in Figure 8 using the SGAS hydrogen sensor example.

Figure 8. Logarithmic Hydrogen Sensor Response versus Gas Concentration at Constant Voltage

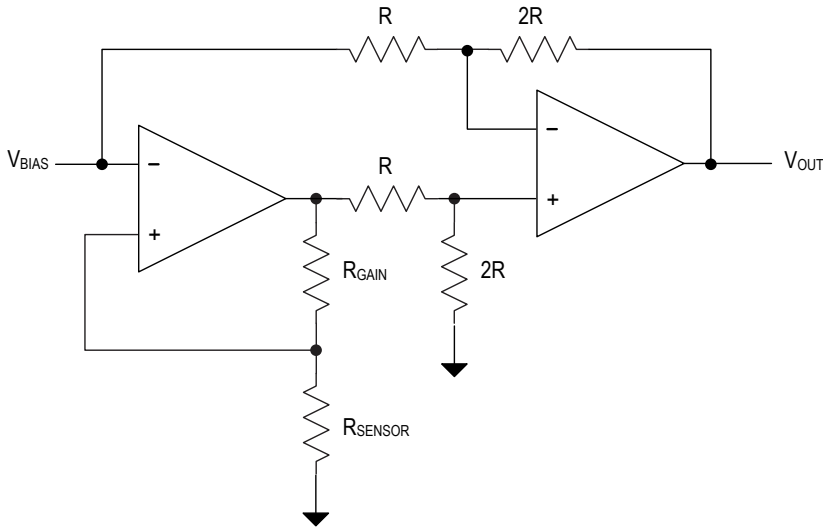


When comparing this plot to the corresponding plot for the voltage divider (Figure 5), it can be seen that there is more responsiveness over the three orders of concentration magnitude in the constant voltage case.

Note that taking the response to be $\left(\frac{V_{OUT}}{V_{BIAS}} - 1\right)$ effectively normalizes and offsets the response to a 0 to 1 basis.

The same offset effect can be achieved in hardware by adding an analog differentiator to the non-inverting amplifier as shown in Figure 9.

Figure 9. Constant Voltage with Offset and Amplification Circuit

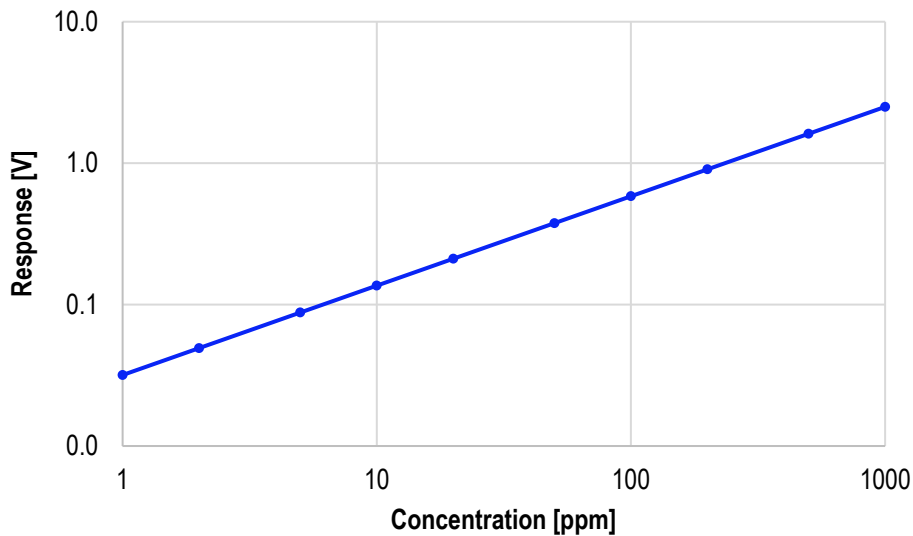


The output of this circuit is given by Equation 13:

$$V_{OUT} = 2 * V_{BIAS} * \frac{R_{GAIN}}{R_{SENSOR}} \tag{Equation 13}$$

Using V_{OUT} directly as response produces a linear $\log(response)$ versus $\log(C)$ plot as shown in Figure 10 using the SGAS hydrogen sensor example (with $V_{BIAS} = 1.25V$).

Figure 10. Offset Corrected Logarithmic Hydrogen Sensor Response versus Gas Concentration at Constant Voltage



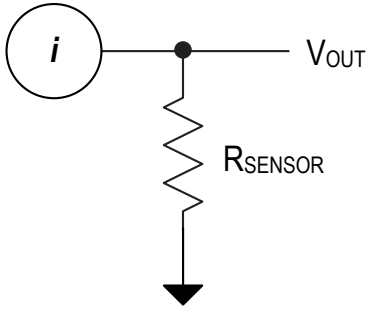
Except for the sensor response change of basis (from (0 to 1) to (0 to 2.5)), the $\log(response)$ versus $\log(C)$ plot remains the same.

There are several other constant voltage circuit topologies available to determine sensor resistance, but all have response characteristics similar to the circuit shown above.

5. Constant Current Sensor Drive

The sensor resistance can also be measured by driving the sensor with a constant current, followed by measurement of the voltage drop across the sensor.

Figure 11. Constant Current Driving Circuit



The sensor signal (V_{OUT}) relates to sensor resistance according to Equation 14:

$$V_{OUT} = i_{DRIVE} * R_{SENSOR} \tag{Equation 14}$$

Sensor resistance is calculated using Equation 15:

$$R_{SENSOR} = \frac{V_{OUT}}{i_{DRIVE}} \tag{Equation 15}$$

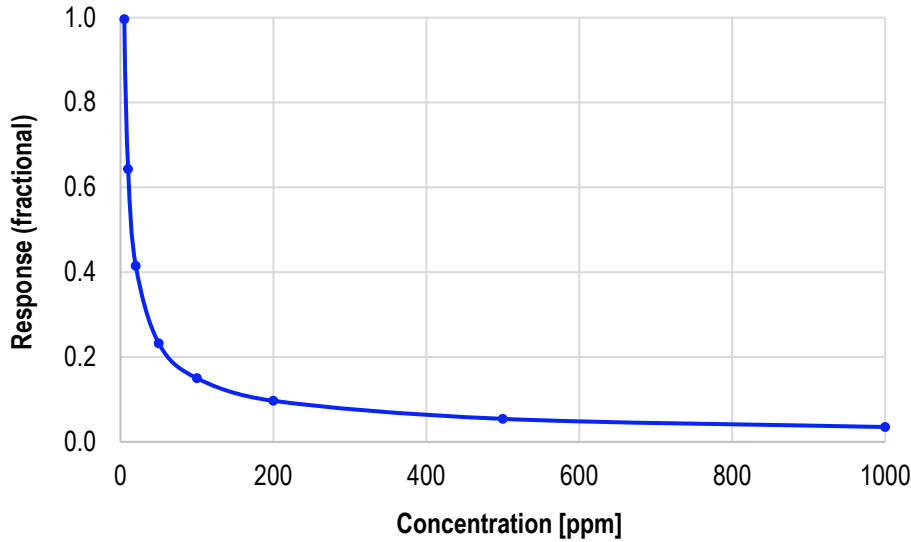
This method has one distinct difference in comparison to the voltage divider and constant voltage measurement methods: the output signal (V_{OUT}) is directly proportional to sensor resistance, rather than inversely proportional. The practical result of this is a more even spreading of resistance change over the readable range. Whether or not this is an advantage is determined by application needs.

If the response is taken to be V_{OUT} then

$$response = i_{DRIVE} * R_{SENSOR} = i_{DRIVE} * A * C \tag{Equation 16}$$

A plot of the response (with $i_{DRIVE} = 20\mu A$) produces the result shown in Figure 12.

Figure 12. Linear Hydrogen Sensor Response versus Gas Concentration at Constant Current



Note that the output signal decreases as gas concentration increases with this type of analog front-end. Also note that linearization of response versus resistance is present in different ways at both low and high gas concentrations, but it is of limited utility because of the “flatness” of the response curve at both ends.

The current driving the sensor should be selected to produce a usable voltage at all points across the measurement range. Using the SGAS hydrogen example, a sensor resistance of $5M\Omega$ (corresponding to a gas concentration of between 1 to 2 ppm) would have an output of 2.5V at a sensor current of

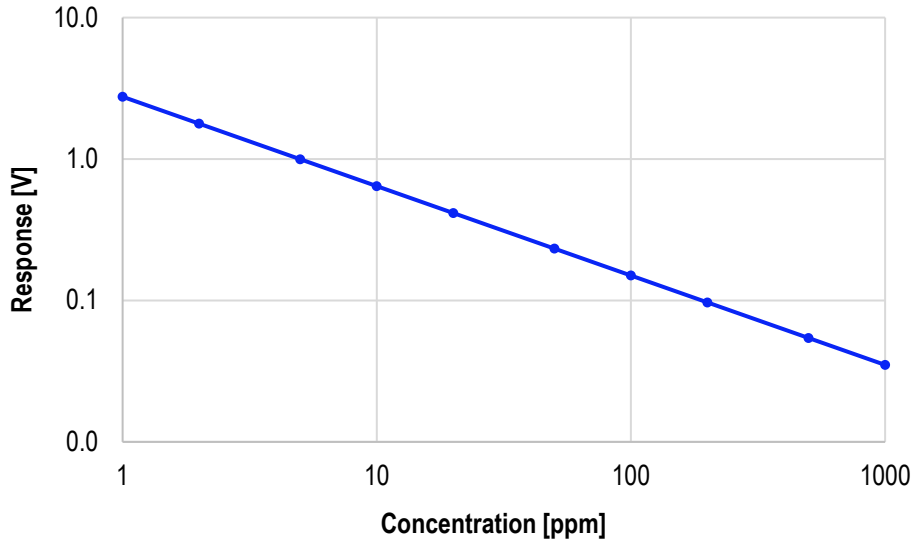
$$\frac{2.5V}{5M\Omega} = 500nA$$

The full-scale hydrogen concentration of (1000ppm at $70k\Omega$) would produce a voltage of

$$500nA * 70k\Omega = 35mV$$

Sensor response (V_{OUT}) is completely linear in a $\log(response)$ versus $\log(C)$ plot as shown in Figure 13 with the SGAS hydrogen sensor example and $i_{DRIVE} = 500nA$.

Figure 13. Logarithmic Hydrogen Sensor Response versus Gas Concentration at Constant Current



The advantages of this circuit relate to compatibility with microcontroller applications. In particular, the ease with which current drive magnitude can be altered under voltage control and the direct compatibility of circuit output with analog-to-digital converters offer significant advantages in applications requiring broad sensor support.

6. Comparison of Circuits

Table 2 summarizes key advantages and disadvantages of each circuit type when used with n-type chemiresistive sensors.

Table 2. Comparison of Sensor Resistance Measuring Circuits

	Advantages	Disadvantages
Voltage Divider	<ul style="list-style-type: none"> ▪ Simple electronics, no active components ▪ Most suitable for detection applications, less so for quantitative analysis 	<ul style="list-style-type: none"> ▪ Less than rail-to-rail use of circuit supply ▪ Direct response is nonlinear ▪ Log response versus log concentration is also nonlinear
Constant Voltage	<ul style="list-style-type: none"> ▪ Next most simple electronics, 2 operational amplifiers maximum ▪ Non-log-corrected response has generally good linearity ▪ Log response versus log concentration is easily made fully linear ▪ Good choice for matching a circuit to a particular sensor 	<ul style="list-style-type: none"> ▪ Requires high value resistors for high impedance sensors
Constant Current	<ul style="list-style-type: none"> ▪ Conforms to standard method for measuring device resistance ▪ Adaptable to a wide resistance range of sensors within a single circuit ▪ Effective, high quality measurement of high impedance sensors ▪ Log response versus log concentration is fully linear ▪ Good choice for general purpose/demonstration type applications 	<ul style="list-style-type: none"> ▪ Direct response is very nonlinear ▪ Most complicated and expensive circuit of the three ▪ Requires a microcontroller to realize advantages; not well adaptable to analog-only circuits

7. Revision History

Revision Date	Description of Change
October 26, 2017	Initial release.

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