

# Optimizing AC Excitation Frequency for Linear Complex Impedance Response in Metal Oxide Semiconductor Gas Sensing

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**Summary:** Metal Oxide Semiconductor (MOS) gas sensors are of high interest in gas detection applications due to their high sensitivity and low cost. However, conventional read-out methods based on resistive measurements often exhibit a highly nonlinear response to gas concentration, limiting their effectiveness for accurate quantification. In this study, we present an alternative approach that leverages impedance spectroscopy to identify an optimal excitation frequency at which the imaginary component of the impedance ( $Z''$ ) exhibits a highly linear correlation with gas concentration. As a case study, we evaluate the AS-MLV-P2 sensor under varying concentrations of ethanol gas. The proposed method demonstrates strong linearity, achieving an  $R^2$  value of 98.26 % for a linear fit between the mean of  $Z''$  over 35 frequency sweeps and Ethanol concentrations ranging from 1000 ppb to 8000 ppb, at an excitation frequency of 3.568 MHz.

**Keywords:** Metal Oxide Gas Sensors Systems, Electrical Impedance Spectroscopy, Complex Response

## Introduction

Metal Oxide Semiconductor (MOS) gas sensors are widely used, especially for the detection of Volatile Organic Compounds (VOCs) in applications such as environmental monitoring, indoor air quality, clinical diagnostics, and food spoilage [1, 2, 3]. These sensors typically rely on DC resistance measurements, where gas exposure causes changes in the resistance of the functionalized metal oxide layers. However, the resistive response is highly nonlinear, especially at higher concentrations. Achieving linearity in MOS gas sensors enhances sensitivity across a wide concentration range, reduces the need for complex calibration, and extends the dynamic range of detection. It also improves baseline stability and minimizes the impact of humidity and temperature, all while using standard commercial sensing elements — making the approach both accurate and practical [4].

On the other hand, exciting these sensors with an alternating voltage and analyzing their impedance response opens the possibility of identifying a frequency at which the imaginary component of the impedance ( $Z''$ ) exhibits a linear relationship with gas concentration. This behavior was first reported by [4], where a linear  $Z''$  response to methane concentration was observed using the thick-film sensor TGS2611. In the present study, we extend this concept by investigating the AS-MLV-P2 thin-film sensor exposed to ethanol gas. We not only validate the linear response of  $Z''$  under specific excitation frequencies but also introduce a methodology for identifying the optimal frequency at which the sensor demonstrates the highest linearity between  $Z''$  and gas concentration.

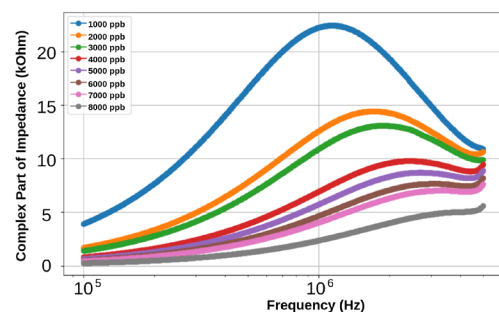


Fig. 1: Mean curve of ( $Z''$ ) over 100 kHz to 5 MHz for ethanol concentrations of 1000–8000 ppb (35 sweeps, concentration step: 1000 ppb, temperature: 150 °C, relative humidity: 50 % at room temperature).

## Methodology

We performed Electrical Impedance Spectroscopy (EIS) [5, 6] on the AS-MLV-P2 sensor exposed to ethanol gas concentrations ranging from 1000 ppb to 8000 ppb at 50% relative humidity, using zero air as the carrier gas. Impedance data were acquired with an Agilent 4292A Impedance Analyzer over the 100 kHz to 5 MHz frequency range. The sensor was maintained at 150 °C using a PID-controlled feedback loop connected to its heater resistor.

Recordings were taken under steady-state conditions using predefined sensor settings and an automated analyzer. Each recording session consisted of 35 frequency sweeps and required approximately 300 seconds. After each session, a 10-minute interval was maintained at constant temperature and gas exposure. For each ethanol concentration, 18 such recordings were

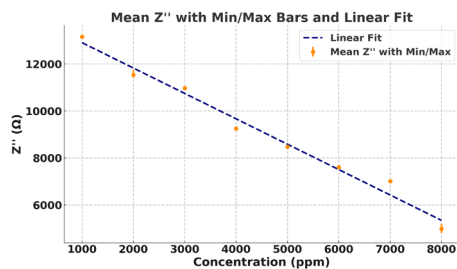


Fig. 2: Mean imaginary impedance ( $Z''$ ) with Min-Max bars for ethanol concentrations from 1000 ppb to 8000 ppb at the optimal excitation frequency (3.568 MHz).

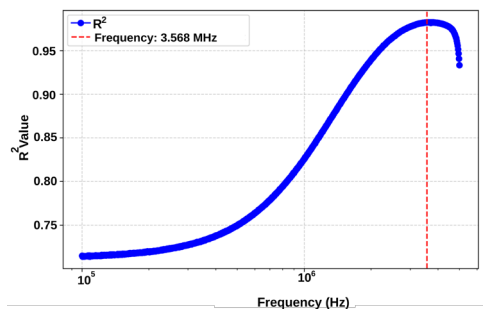


Fig. 3: Coefficient of determination ( $R^2$ ) for linear fit between  $Z''$  for frequencies 100 kHz to 5 MHz. Peak at 3.568 MHz indicates optimal excitation frequency.

conducted. Bode plot analysis showed that the sensor stabilized by the 10<sup>th</sup> session; however, the 18<sup>th</sup> (final) session was used for comparison across concentrations.

To compare  $Z''$  across concentrations and identify the optimal operating frequency, we computed the mean over all sweeps in each recording. Figure 1 shows the mean curve of  $Z''$  across the frequency range for each concentration over 35 sweeps, illustrating the impedance behavior. The mini-max spread of  $Z''$  was within  $\pm 100 \Omega$  which confirms the mean as a reliable representation. This data was provided to Algorithm 1, which returned the frequency corresponding to the maximum  $R^2$  value.

By applying Algorithm 1, we identified the optimal frequency of 3.568 MHz, at which the coefficient of determination  $R^2$  reached 98.26%. Figure 2 shows the mean values of the imaginary impedance component  $Z''_{\text{Mean}}$  and also the minimum-maximum bars across different gas concentrations. Moreover, the  $R^2$  curve for the entire frequency sweep is shown in 3.

### Conclusions and Future Directions

We are investigating how operating temperature affects sensor behavior in the EIS setup and its response to various gas mixtures. The goal is to enhance selectivity and sensitivity by optimizing both operating frequency and temperature.

### Algorithm 1 Optimal Frequency Selection via Linearity of $Z''$

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1: Input:  $D = \{(f_i, c_j, Z''_{ij})\}$ 
2: Output: Optimal freq.  $f^*$  maximizing linearity of  $Z''$  vs. concentration
3:  $R^2_{\text{best}} \leftarrow 0, f^* \leftarrow \emptyset$ 
4: for all  $f \in \text{UniqueFrequencies}(D)$  do
5:    $D_f \leftarrow \{(c_j, Z''_{ij}) \mid f_i = f\}$ 
6:   if  $|D_f| \geq 2$  then
7:     Fit linear model:  $Z'' = \alpha c + \beta$ 
8:     Compute  $R^2_f$ 
9:     if  $R^2_f > R^2_{\text{best}}$  then
10:       $R^2_{\text{best}} \leftarrow R^2_f, f^* \leftarrow f$ 
11:      Store regression model and  $D_f$ 
12:    end if
13:  end if
14: end for
15: Save  $D_{f^*}$  and its linear fit
16: return  $f^*, R^2_{\text{best}}$ 

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### References

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