

A Functionalization-Free Acetone Detector Based on Low Frequency Interfacial Dielectric Relaxation

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Summary:

A novel concept for miniaturized, low-power gas detection without surface functionalization or elevated temperatures, is presented using acetone as a model analyte. MEMS Si-electrodes apply electric fields exceeding 1 MV/m to induce Maxwell-Wagner-Sillars interfacial polarization at device-gas interface. This yields a dielectric loss peak with relaxation time ≈ 0.45 ms as an acetone-specific signature. Loss peak scales with concentration attaining over 20 dB SNR for 25 ppm acetone. The detector consumes ~ 6 μ W below 1 kHz, making it well suited for battery operated and MEMS-integrated sensing platforms.

Keywords: acetone detection, dielectric relaxation, MWS polarization, low-power sensing, functionalization-free.

Introduction

Acetone is a clinically volatile biomarker for non-invasive point-of-care diagnostics. Industrial exposure monitoring and food quality control represent additional application domains where compact, battery operated and low-cost detectors are needed [1]. Existing acetone sensors mostly relies on surface-functionalized sensors operating at elevated temperatures (200-400 °C), limiting scalability and power efficiency [2]. Here, we take fundamentally different approach where the sensor exploits the intrinsic dielectric properties of acetone vapor rather than relying on a chemical reaction between acetone and functional surface [3], [4]. This enables reagent free, thermally passive and low power detection with CMOS-MEMS compatible platforms.

Theory

The sensing cell consists of parallel electrodes separated by gas domain (Fig. 1a), forming a two-layer dielectric interface that supports Maxwell-Wagner-Sillars (MWS) interfacial polarization. When acetone enters gap between sensing cells, it alters the dielectric contrast at interface producing MWS polarization, measurable in the low frequency impedance spectrum. Fig. 1b shows the microscopic image of Si-electrode device (~ 200 sensing cells with 5 μ m gap). For a bilayer system with electrode and gas regions of permittivity ϵ_i and conductivity σ_i , the MWS relaxation time is $\tau_{mws} = (\epsilon_1 + \epsilon_2)/(\sigma_1 + \sigma_2)$. A 5V electrodes DC bias establishes dielectric

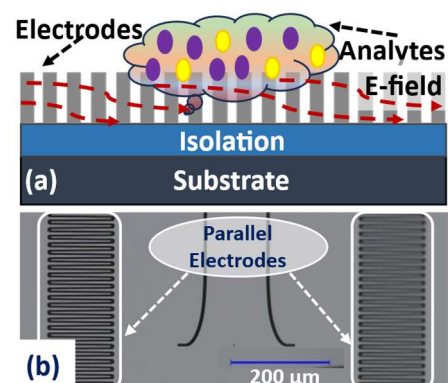


Fig. 1. (a) Schematic of the sensing principle. (b) Microscopic image of parallel Si-electrode device.

contrast at interface due to high electric field of 1MV/cm. A 0.5 V superimposed AC sweeps the frequency range from 20 Hz to 100 kHz to map the impedance response. Complex permittivity $\epsilon^*(\omega)$ is extracted via broadband dielectric spectroscopy, while the electric modulus $M^*(\omega) = 1/\epsilon^*(\omega)$ is employed to isolate intrinsic MWS

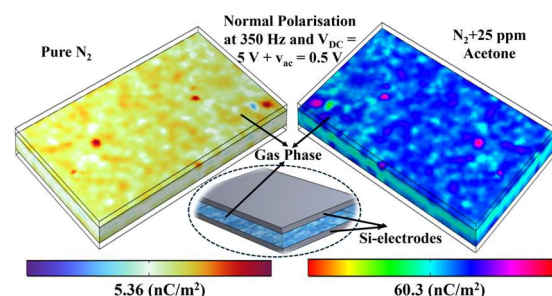


Fig. 2. Simulated normal polarization in the gas region at 350 Hz for N_2 and N_2+25 ppm acetone.

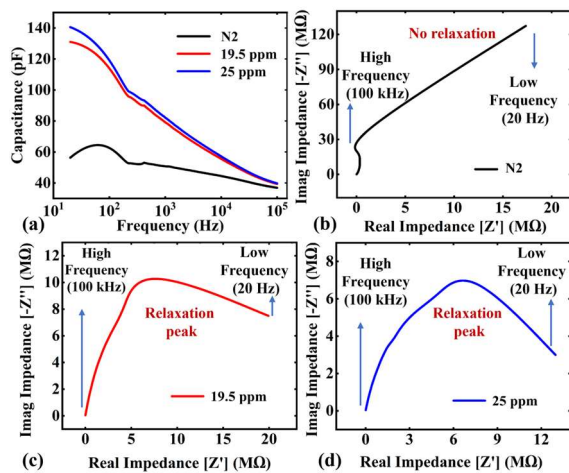


Fig. 3. (a) Measured capacitance vs. frequency at ambient conditions for various gas concentrations. Nyquist responses for (b) N₂, (c) 19.5 ppm acetone, and (d) 25 ppm acetone, showing semi-arc relaxation.

relaxation from electrode polarization and parasitic conductance artifacts. COMSOL based finite element analysis show that normal polarization between the electrodes increases from 5.36 nC/m² (in N₂) to 60.3 nC/m² (N₂ + 25 ppm acetone) at 350 Hz under V = 5 V DC + 0.5 V AC, confirming the dielectric contrast induced by acetone vapor as shown in Fig. 2.

Detection Performance

The sensor performance is evaluated in N₂ and N₂-acetone mixtures. Fig. 3a shows that the static capacitance increases from 60 pF in N₂ to 140 pF at 25 ppm acetone, reflecting an enhancement in the effective permittivity of the gas mixture. In contrast to the featureless Nyquist response of pure N₂ (Fig. 3b), Figs. 3c-d reveal semicircular arcs of progressively reduced diameter with increasing acetone concentration, indicating a polarization-driven relaxation process.

Fig. 4a demonstrates an asserted dispersion in the real permittivity (ϵ') between N₂ and the acetone mixture, consistent with enhanced polarizability of the analyte. The imaginary permittivity (ϵ'') spectra in Fig. 4b exhibit a loss peak near 353 Hz for the acetone mixture, absent in N₂, confirming the presence of a dielectric relaxation mechanism. The peak amplitude scales from 0.28 at 19.5 ppm to 0.319 at 25 ppm acetone, reflecting a concentration-dependent response with signal-to-noise (SNR) ratio ~20.3 dB for 25 ppm. Moreover, the electric modulus formalism decouples the bulk conductivity contributions. The real (M') and imaginary (M'') components (Figs. 4c-d) reproduce the 353 Hz peak, corroborating the relaxation signature independently of ohmic effects. Cole-Cole plots provide further insight. The $\epsilon'-\epsilon''$ arc (Fig. 5a) appears only for acetone mixtures. The $M'-M''$ plot (Fig. 5b) yields a characteristic relaxation time $\tau \approx 0.45$ ms.

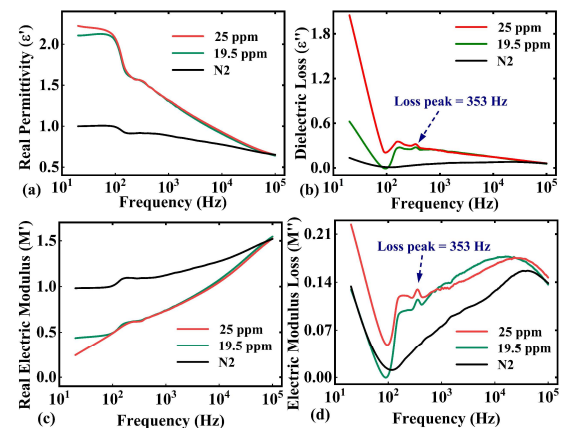


Fig. 4. Measured: (a) ϵ' , (b) ϵ'' (loss), (c) M' , and (d) M'' spectra for various gas concentrations.

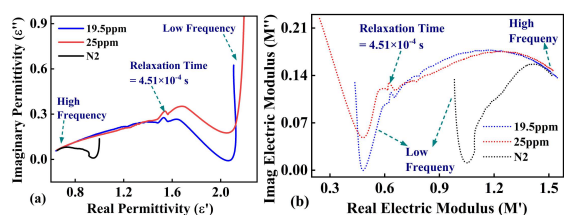


Fig. 5. Cole-Cole plots of: (a) ϵ' vs. ϵ'' and (b) M' vs. M'' for various gas concentrations.

Collectively, these results confirm interfacial polarization-driven relaxation within the gas-electrode system. The sensor power consumption is ~6 μ W below 1 kHz.

Conclusion

This work demonstrates a functionalization-free, low-power acetone vapor detector using MEMS parallel Si-electrodes. High field (>1 MV/m) induced MWS polarization yields a concentration-scalable, acetone-specific distinct dielectric loss peak at 353 Hz with 20.3 dB SNR at 25 ppm. At ~6 μ W below 1 kHz, the platform is inherently compatible with battery-operated and MEMS-integrated deployment, offering a route toward portable, label-free VOC sensing.

References

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