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Polymer-coated QCM Sensor Leveraging Energy Trapping Effect for Enhanced Detection of Volatile Organic Compounds

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Summary:

This work presents a novel QCM sensor with a unique topology design, developed based on distribution of area for improving mass sensitivity (DAIS), for the VOC detection at parts per million (ppm) levels. A polymer sensing layer is applied to facilitate the adsorption of target analyte molecules during experimentational phase. The DAIS-QCM sensor exhibits superior mass sensitivity when exposed to various concentrations of VOC target analyte, showcasing an enhancement of over 10% in comparison to a conventional QCM sensor used as a reference.

Keywords: energy trapping effect, gas detection, mass sensitivity, polymer sensing layer, quartz crystal microbalance

Introduction

The detection of volatile organic compounds (VOCs) has gained interest due to its various applications domains, including environmental monitoring, industrial safety, and public health. The quartz crystal microbalance (QCM), a resonator sensor, is a widely used device for mass sensing application, owing to its capability to detect mass changes in nanogram range [1]. Through this paper we present a comparative analysis and experimental evaluation of a polymer-coated QCM sensor, leveraging a novel approach based on the utilization of energy trapping effect regions for mass loading area (MLA) for improved mass sensitivity [2]. The DAIS-QCM, as shown in Fig. 1, is derived from a finite elements analysis (FEA) on the impact of MLA on QCM sensor mass sensitivity. The findings reveal that the DAIS topology, featuring an array of circular electrodes with a radius of 0.62 mm and outer radius of 2.96 mm, outperforms the conventional QCM design, which features a conventional single electrode with radius of 4.25 mm. Despite the conventional QCM having a larger sensing electrode, which accommodates a greater mass loading area for more adsorption of target analyte molecules, the DAIS-QCM with an MLA of 21 mm², ~38% of the MLA of the conventional QCM, shows improved mass sensitivity by ~ 25% compared to the conventional QCM. This is attributed to the presence of the phenomena of energy trapping effect caused by the natural structure of quartz crystal substrate.

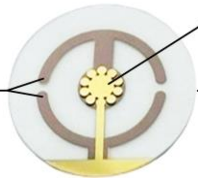

Fig. 1. A 5 MHz AT-cut QCM sensor, featuring a novel topology termed DAIS based on maximizing the energy trapping effect region by replacing the conventional single circular electrode with an array of smaller circular electrodes with 0.62 radii.

This paper further presents the maintained experimental setup and the materials used during the characterization process. both the DAIS-QCM and the conventional QCM are coated with polymer sensing layer and then subjected to identical concentrations of Ethanol to evaluate their sensing performance by observing the shift in their resonant frequencies. This paper introduces the DAIS-QCM as a promising avenue for enhanced VOC detection for various application domains.

Experimental Setup and Materials

To establish a basis for comparison, and validate the enhancement in sensing performance, DAIS-QCM is fabricated by Angstrom Engineering Inc., using eBeam evaporation technique. A 5 MHz QCM with a conventional topology serves as a reference device during the experimental process. The QCM sensors are then coated with Polyvinylpyrrolidone (PVP), a polymer reported for its efficacy in VOC detection through the adsorption of its molecules [3]. A sensing material solution is prepared by dissolving 100 mg of PVP, from Polysciences, Inc. (catalog# 01052-250), in 10 mL of methanol, yielding a 0.1 weight percent (Wt.%) solution. The solution undergoes sonication for 20 minutes to ensure complete dissolution of the polymer. The deposition of the polymer is achieved through spin coating, depositing 100 µL of the solution, resulting in an approximate thickness of 0.1 µm. Both the DAIS and conventional polymer-based QCM sensors are tested under controlled conditions using a Plasmionique FLO07-TSV system to ensure consistency. Ethanol, a volatile organic compound, is introduced into the chamber through NI 5.0UH-T, a 5.0 ultra-high purity Nitrogen, selected as a carrier gas due to its non-reactive properties. The target analyte is exposed, commencing with a baseline of pure N_2 gas at a flow rate of 100 SCCM, followed by exposure to a mixture of N_2 and Ethanol-saturated vapors with concentrations listed in Tab. 1, while maintaining the total flow rate at 100 SCCM. This distinct pattern of exposure process is iterated thrice to ensure data reliability.

Tab. 1: Ethanol flow rates and corresponding concentrations

Flow rate (%)	Concentration (ppm)
2	1100
4	2300
6	3400
8	4600
10	5700

Results and Discussion

The QCM mass sensitivity (S) of the QCM is defined as the ratio of the change in resonant frequency (Δf) resulting from added mass (Δm) [2]. It serves as a key metric for the QCM's ability to detect mass changes, thereby reflecting its sensing performance. During the experiment, both sensors are exposed to same concentration of Ethanol. Therefore, the observed Δf indicates the sensing performance of the sensors, as the added mass (Δm) remains consistent for both sensors. The resonant frequency values over time, responding to identical concentrations of Ethanol, are plotted for both DAIS and conventional QCMs in Fig. 2(a). Despite the conventional QCM having a larger MLA, the unique design of DAIS-QCM enables it to achieve a higher resonant frequency shift, showcasing superior mass sensitivity. Additionally, the frequency shift slope of DAIS-QCM is more uniform compared to the conventional design, as presented in Fig. 2(b). The DAIS design, where the single circular electrode is replaced by an array of smaller electrodes to maximize the energy trapping effect region, yields enhancements in sensor mass sensitivity and its uniformity. Therefore, the unique design of DAIS is presented as a promising approach for enhanced detection of VOCs in various applications.

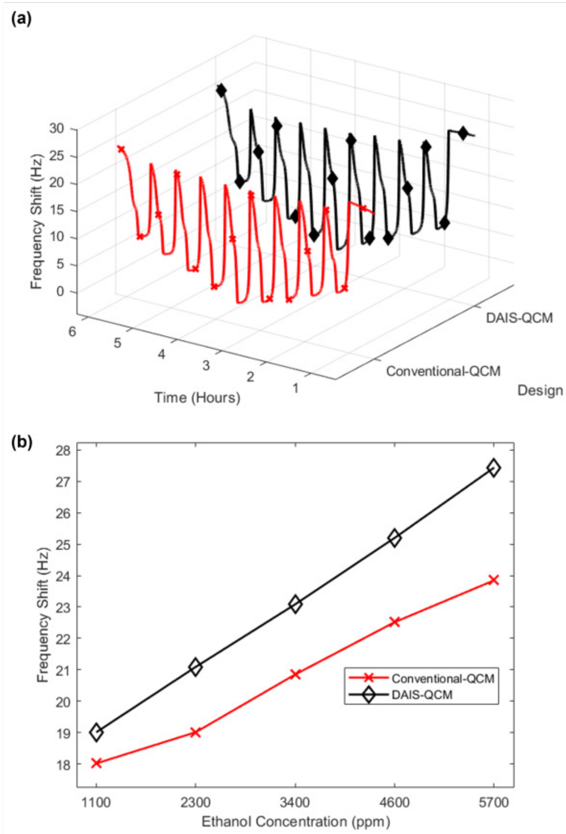

Fig. 2. (a) The graph from the experiment results illustrates the response of both DAIS-QCM and conventional QCM to variation in VOC target analyte Ethanol. (b) Comparative frequency shift characterization for Ethanol concentrations 1100, 2300, 3400, 4600, and 5700 ppm.

References

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