

ZnO@ZIF-8 Doubly Clamped Microbeam Resonator for Detection of VOCs

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Summary:

This paper reports the fabrication and characterization of a doubly clamped ZnO@ZIF-8 microbeam resonator for the detection of volatile organic compounds (VOCs), in which a single heterostructure material provides both actuation and gas sensing functionality. The ZIF-8 layer, with its tuneable porosity and molecular sieving capability, enables selective adsorption of VOC molecules, while the ZnO core ensures efficient piezoelectric actuation. The ZnO@ZIF-8 device exhibits a resonance frequency of 4.5 MHz with a quality factor (Q) of 204. Upon exposure to 300 ppm ethanol, a frequency shift (Δf) of 732 Hz is observed, demonstrating the potential of the proposed structure for VOC sensing applications.

Keywords: ZnO@ZIF-8, microbeam resonator, MOF-based sensor, gas sensing, piezoelectric resonator

Background

Sensitive and selective detection of volatile organic compounds (VOCs) is important for indoor air monitoring and non-invasive diagnostics such as breath analysis. Metal-organic frameworks (MOFs), particularly ZIF-8, are widely studied due to their tuneable porosity and selective adsorption, enabling differentiation between VOC species [1]. These materials operate at room temperature and release adsorbates upon mild heating, making them suitable for low-power sensing.

In contrast, conventional chemiresistive sensors require elevated temperatures ($>150\text{ }^{\circ}\text{C}$) [2], limiting portability. MEMS piezoelectric resonators functionalized with ZIF-8 offer a promising alternative, combining room-temperature operation with high sensitivity. A ZnO@ZIF-8 doubly clamped resonator provides a simpler and more stable platform compared to coupled or multi-degree-of-freedom designs. This work builds on previous studies of ZnO nanowire oscillators [3] and ZnO@ZIF-8 surface conversion techniques [4].

Description of the New Method

This work introduces a ZnO@ZIF-8 microbeam resonator in which a single heterostructure

material provides both piezoelectric actuation and gas sensing. The use of tetrapodal ZnO arms with a single-crystalline structure enables efficient charge transport and enhanced piezoelectric performance compared to conventional ZnO nanowires. In this approach, the entire surface of the microbeam is converted into ZnO@ZIF-8, increasing the effective surface area for gas adsorption, while the porous ZIF-8 layer provides molecular sieving capability for selective VOC adsorption. This selectivity is demonstrated through comparative adsorption behaviour of ethanol and toluene in ZnO and ZnO@ZIF-8 devices.

Experimental Procedure

The fabrication sequence is illustrated in Fig. 1. A p-doped Si (100) wafer with a 200 nm thermally grown SiO_2 layer was used as the substrate. Au/Cr electrodes were patterned using UV lithography, RF sputtering, and lift-off, with a gap of 20 μm between pads.

Tetrapodal ZnO (t-ZnO) was synthesized and converted into ZnO@ZIF-8 via surface chemical transformation [4]. The material was dispersed in DI water, drop-cast onto the substrate, and dried at 100 $^{\circ}\text{C}$ for 30s. Individual ZnO@ZIF-8 arms were then positioned across the electrodes using an Omniprobe micromanipulator, dual-beam

SEM/FIB system and fixed by Pt deposition, forming a doubly clamped resonator (Fig. 2). The device was excited using an AC voltage ($V_{sd}^{ac} = 0.8$ V), and the resonant response was measured using a laser Doppler vibrometer.

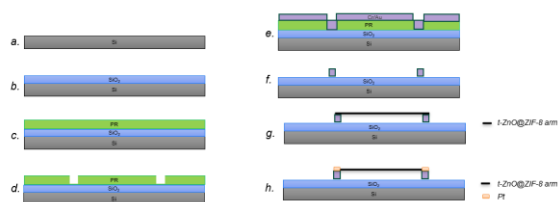


Fig. 1. Fabrication process flow of a single ZnO@ZIF-8 doubly clamped microbeam a. substrate preparation, b. thermal oxidation, c. photoresist (PR) spincoating, d. UV exposure and development, e. RF sputtering, f. lift-off photolithography, g. ZnO@ZIF-8 arm pick and placement using Omniprobe micromanipulator, h. Pt deposition for fixing ZnO@ZIF-8 arm.

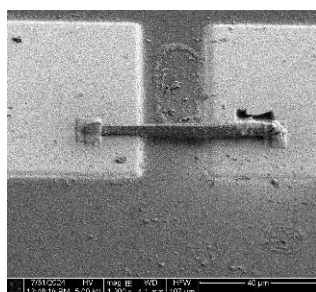


Fig. 2. SEM Image of ZnO@ZIF-8 doubly clamped microbeam

Results

The ZnO@ZIF-8 microbeam resonator exhibited a resonance frequency of approximately 4.5 MHz with a quality factor (Q) of 204 under piezoelectric excitation ($V_{sd}^{ac} = 0.8$ V). The resonance response was recorded at three stages: t_0 (baseline at room temperature), t_1 (after activation by heating at 100 °C overnight followed by 2 h storage in N_2), and t_2 (after gas exposure for 20 min in a 1.4 L chamber with 1 μ L of 99% ethanol). Compared to the bare ZnO device, the ZnO@ZIF-8 microbeam shows $\sim 2\times$ higher response to ethanol than toluene. Upon exposure to 300 ppm ethanol, a frequency shift (Δf) of +1709 Hz and +732 Hz and an amplitude shift of +8E-05 m/s and +40E-05 m/s were observed in bare ZnO and ZnO@ZIF-8 respectively. Notably, the frequency increases upon gas adsorption, which deviates from the conventional mass-loading behaviour of resonant sensors. This suggests that adsorption-induced changes in effective stiffness and surface stress is dominant over the mass loading effect in doubly clamped single crystalline ZnO-based microbeam.

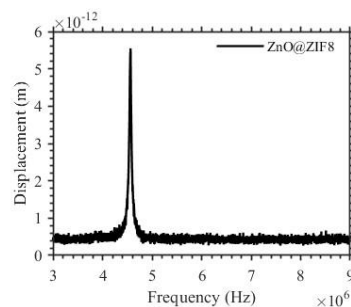


Fig. 3. Resonance spectrum of the ZnO@ZIF-8 doubly clamped microbeam resonator under piezoelectric excitation ($V_{sd}^{ac} = 0.8$ V), showing a resonance frequency of 4.56 MHz and a quality factor of $Q = 204$

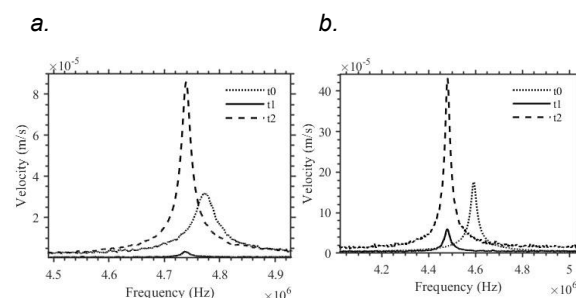


Fig. 4. Resonance response of microbeam resonators under exposure to 300 ppm ethanol in a. Bare ZnO microbeam resonator, b. ZnO@ZIF-8 microbeam resonator. Curves correspond to t_0 (before activation), t_1 (after activation), and t_2 (after exposure).

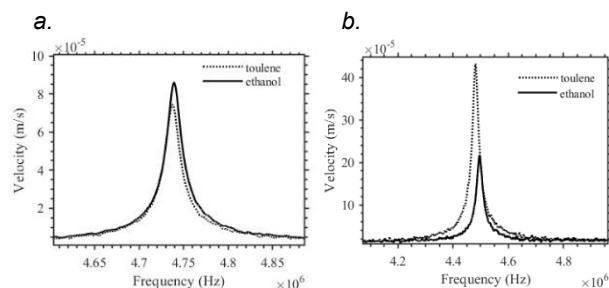


Fig. 5. Gas adsorption characteristics of ethanol and toluene in a. ZnO microbeam resonator, b. ZnO@ZIF-8 microbeam resonator

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