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Multimode Excitation of a Metal Organics Frameworks Coated Microbeam for Smart Gas Sensing and Actuation

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Highlights

- The purpose of this study to demonstrate a smart sensor that is capable of performing simultaneous sensing and actuation using a single device which reduce the device size, power requirement, and cost.
- The concept is based on tracking the frequency shift due to external physical stimuli in the first and third modes of vibration of an electrostatically actuated clamped-clamped microbeam.
- The microbeam is uniformly functionalized with metal organic frameworks (MOFs) to enhance the sensitivity and selectivity of the proposed sensor.
- Optimizing the resonator design to excite higher order modes will open the door for simultaneously measuring multiple physical stimuli using a single resonator, which leads to smarter generation of sensors.

ABSTRACT

Smart sensing systems suffer complexity requiring interface circuits, microcontrollers, switches, and actuators to detect and sense, process the signal and take a decision, and trigger an action upon demand. This increases the device footprint and boosts significantly the power required to actuate the system. Here, we present a hybrid sensor and switch device, which is capable of accurately measuring gas concentration and perform switching when the concentration exceeds specific (safe)

threshold. The device is based on a clamped-clamped microbeam coated with metal-organic frameworks (MOFs). Using the electrostatic harmonic voltage, we employ dynamic multi-modal actuation in which the microbeam is simultaneously excited at the first mode of vibration, near the pull-in band, and at the third mode. We demonstrate experimentally the effectiveness of this technique in measuring the concentration of water vapor and achieving switching when the concentration exceeds a threshold value. In contrast to the first mode operation, we show that monitoring the third mode enhances sensitivity, improves accuracy, and lowers the sensor sensitivity to noise.

1. Introduction

Smart gas sensing systems are under increasing interest for gas leakage detection and alarming for domestic and industrial applications. Developing smart sensors that can selectively detect low concentrations of a particular gas and perform an action if the concentration exceeds a threshold value is of crucial importance in a wide range of applications including health and environmental monitoring [1,2], gas hazards detection and warnings [3], and aerospace systems [4]. Conventionally, smart gas sensing systems are composed of the sensing element to detect the gas concentration, a microcontroller to process the signal, a display for the measurements, and an actuator or a switch to perform an action upon demand [5]. However, the needs for complicated circuits, several electronic components, and a microcontroller increase the device size and the power requirement to operate the system.

Micro/nano electromechanical systems based resonators have been utilized to detect minute mass and low gas concentrations [6-14]. These mainly employ electrostatic actuation, which is the most common method due to the unique advantages of low power consumptions and compatibility with CMOS circuits [15, 16]. Various dynamical principles have been used to enhance sensitivity, such as higher order modes of vibrations [17, 18], bifurcation points, and the pull-in instability [19-23]. Since the pull-in instability was first reported [24], many studies have been dedicated to the understanding of this phenomenon with various developed analytical and finite elements models [25, 26]. The pull-in instability occurs when the electrostatic force overcomes the mechanical

restoring force. It can be classified into a static pull-in, due to the DC bias, and a dynamic pull-in, which can be triggered when the structure is dynamically actuated near the resonance frequency. Under certain operating conditions, the movable electrode can have sufficient energy to escape the stable potential well and collapse into the stationary electrode. The pull-instability is commonly considered undesirable and should be controlled and predicted accurately [16]. On the other hand, several MEMS devices make use of this phenomenon, such as MEMS switches [27] and threshold inertia switches [28]. Also, the static pull-in is utilized to extract the structure properties experimentally, such as the flexural rigidity [17].

Recently, the simultaneous actuation and tracking of the frequency shift of multiple vibrational modes of a single resonator has been utilized to enhance the resonator stability [29], reveal the spatial distribution of adsorbed particles [30], measure the mass, position, and velocity of a particle flowing inside a microchannel [6], and also measure the evaporation rate of Polyethylene Glycol [31]. The collective information from different modes of vibrations of a single resonator enable the detection of multiple physical stimuli using a single device. This reduces the power required to operate the sensor and the overall device size, cost, and complexity [6].

Functionalizing the resonator surface with thin materials that have an affinity to a particular type of gas enhances the sensitivity by orders of magnitudes. Examples of such materials include palladium coating for hydrogen sensing [32], gold for mercury detection [33], and zeolitic imidazolate framework (ZIF) for CO₂ detection [34]. Recently, metal-organic frameworks (MOFs) have gained significant attention due to their large surface area, tunable pore size, and exposed inner functionalities [35-39]. These materials can be engineered and designed to selectively detect particular gases, such as Hydrogen Sulfide H₂S [40], Carbon dioxide CO₂ [41], volatile organic compounds (VOCs) [42], and humidity [43].

In previous works [21, 23], we utilized the pull-in band near the first mode to enhance the sensitivity of the sensor and perform switching when the concentration exceeds a certain threshold. As higher order modes are known to boost sensitivity in resonant sensors, exciting the resonator near the pull-in bands of the higher order modes should lead in principle to more sensitive switching. However, this requires special designs and impractical high actuation voltages [17]. Also, the robustness and accuracy of the bifurcation based sensing need to be ensured. In close

proximity of the bifurcation point, the basin of attraction gets eroded, and the noise effect becomes significant, which reduce the reliability and accuracy of the sensor measurements [19, 22].

Despite the previous efforts in realizing smart sensors and switches based on the first mode, the low sensitivity of the first mode and the reduced accuracy near the bifurcation point remain main issues. To resolve these issues, we demonstrate here the employment of two modes of vibration of a clamped-clamped microbeam coated with MOFs and operated in air to selectively detect and accurately measure the concentration of particular gas and perform switching, at reduced voltage, when the concentration exceeds the threshold value. As a case study, we demonstrate the concept based on detecting water vapor concentrations.

2. Fabrication

Color	Material	Thickness (nm)	Modulus Of Elasticity (GPa)	Density (kg/m ³)
Silicon Dioxide (SiO ₂)	3000	85	2300
Chrome (Cr)	50	279	7190
Gold (Au)	200	79	19300
Polyimide (Pi)	4300	8.5	1400

(b)

(c)

(d)

Fig. 1. (a) Schematic of the fabrication steps. (b) Schematic of the microbeam with the two-third lower electrode showing the material types, properties, and thicknesses. (c) An SEM image of the fabricated microbeam with MOFs functionalization. (d) XRD pattern of Cu(bdc).xH₂O thin film on microbeam (blue) and calculated (black).

The proposed device is based on a clamped-clamped microbeam resonator functionalized with MOFs for sensitive and selective detection. The resonator is electrostatically actuated using two-third lower electrode configuration, which as shown in [17], reduces the voltage values required to excite the third mode of vibration to one-third compared with the full electrode configuration. The microbeam is fabricated on 4" silicon wafer covered with 3 μm of silicon dioxide (SiO₂) layer, which insulates the device layers from the conductive silicon layer. The fabrication steps are shown in Fig. 1a. The lower electrode and on-chip connections are formed by sputtering and patterning Cr/Au layer of 50/200 nm thicknesses. The Cr is used to enhance the adhesion of gold with other materials. The upper electrode is formed by spinning and curing a 4.3 μm polyimide coated from the bottom with Cr/Au/Cr layer of thicknesses of 50/200/50 nm. Also, it is coated from the top with Cr/Au layer of a thickness of 50/200 nm, which acts as a hard mask to protect the microbeam during the etching process of the polyimide. The two electrodes are separated by a 3.3 μm sacrificial layer of amorphous silicon (α -Si), which will be etched in the final release process to form the air gap. This microbeam is functionalized with a COOH-terminated layer by immersing the chip in ethanolic solution of 16-mercaptohexadecanoic acid for 24 hours [44, 45]. Using the layer-by-layer approach, a uniform 2D periodic porous structure based on the assembly of copper ions and benzene dicarboxylate ligands (Cu(bdc).xH₂O) MOF layer is grown by dipping the chip

in metal precursor (copper acetate) ethanolic solution and organic ligand (1,4-benzenedicarboxylic acid (bdc)) ethanolic solution for five and ten minutes, respectively, with a washing step with pure solvent in between, which is considered as one growth cycle [46]. The process is repeated for ten cycles to grow and increase the thickness of the $\text{Cu(bdc)} \cdot x\text{H}_2\text{O}$ MOF thin film [43]. Figure 1b shows a schematic of the microbeam design and dimensions; which are length (l) $500\ \mu\text{m}$, width (w) $20\ \mu\text{m}$, and gap (g) $3.3\ \mu\text{m}$. These dimensions are selected to minimize the squeeze film damping in accordance with the fabrication process rules [47]. Figure 1c shows an SEM image of the clamped-clamped resonator. The XRD pattern depicted in Fig. 1d shows high intense peaks at 37 degrees that correspond mainly to the substrate and another peak at ~ 8.2 degrees, which corresponds to the highest intensity peak of the MOFs simulated pattern. This confirms the formation of the targeted MOFs thin film on the microbeam. The other peaks are hard to detect due to the low thickness of the MOFs film and the limitation of the measurement tool.

3. Experimental setup

Fig. 2. Schematic of the experimental setup used for testing the device.

The experimental setup is shown in Fig. 2. We utilize a laser Doppler vibrometer to measure the resonance frequency values and their corresponding mode shapes, record the frequency response curves, and track the change in the amplitude of vibration due to water vapor exposure. A data acquisition card (DAQ) connected to an amplifier is used to actuate the microbeam with a wide range of frequencies and voltage amplitudes. Using the LabVIEW software, the measured real-time data were post-processed to generate the frequency response curves and the amplitude shift due to water vapor exposure. The microbeam is placed inside the test chamber, which is equipped

with ports to provide the actuation signals. The water vapor is generated by flowing the nitrogen inside a bubbler placed in a controlled temperature bath. The vapor concentration is governed by controlling the flow of the dry nitrogen line and bubbler line.

4. Results

4.1 Frequency response

The resonance frequency values are experimentally extracted by actuating the microbeam with white noise signal while scanning the response at different points along the microbeam length. The test is conducted under vacuum conditions where the chamber pressure is fixed at 4 mTorr . Figure 3a shows the measured frequency values near the first (79.26 kHz) and third (345.4 kHz) vibration modes. The corresponding mode shapes, shown in the insets of Fig. 3a, match the clamped-clamped microbeam mode shapes, which confirms the uniformity of the MOFs coating; nonuniform coating generates distorted mode shapes.

Next, we actuate the microbeam with a harmonic AC signal superimposed to a DC voltage, where the frequency of the AC signal is swept around the mode of interest while using the laser to monitor the microbeam amplitude at the microbeam midpoint. The frequency response curves are generated by taking the maximum steady state amplitude W_{max} at each frequency step. Figures 3b and 3c show the results for $V_{DC} = 30\text{ V}$ and at atmospheric pressure near the first and third modes for different V_{AC} values. The reported results help in selecting the appropriate actuating voltages to obtain a large signal-to-noise ratio. Also, we employ the frequency response curve in converting the measured amplitude change due to water vapor adsorption into frequency values. The frequency values are important in quantifying the amount of adsorbed mass and characterizing the MOFs coating material [39]. Figure 3d shows the microbeam response to the multifrequency excitation signal. The signal is composed of two AC signals, V_{AC1} and V_{AC2} , superimposed to a DC voltage source V_{DC} . The first source frequency Ω_1 is fixed near the first mode (75 kHz) while the second source frequency Ω_2 is swept around the third mode. The reported results show the significance of the multimodal excitation in raising the floor of the third mode above the noise level using low actuation voltages compared with the single harmonic excitation, which facilitates detecting the response near the higher order modes of vibration. It is worth to mention that exciting the microbeam with a single frequency near the third mode with voltage load $V_{DC} = 30\text{ V}$ and V_{AC}

= 50 V has resulted in $0.5 \mu\text{m}$ maximum amplitude of vibration, Fig. 3c, which is around 15% of the air gap. Hence, under practical voltage loads, it is almost impossible to realize a pull-in band using a single excitation source at the third mode.

Fig. 3 Frequency response curves of the microbeam when subjected to (a) a white noise excitation at $V_{DC}=10$ V, $V_{AC} = 10$ V, and at chamber pressure $P= 4$ mTorr. Insets: the corresponding mode shapes acquired by recording the response at different points along the beam length. Response of the microbeam at $V_{DC} = 30$ V and at atmospheric chamber pressure for different AC voltages (b) near the first mode and (c) near the third mode. The open curve in (b) shows a pull-in band. (d) The response to a multifrequency excitation signal, V_{AC1} as shown, $\Omega_1 = 75$ kHz, $V_{AC2} = 40$ V, $\Omega_2 = \text{swept}$ near the third mode, and $V_{DC} = 30$ V at atmospheric pressure.

4.2 Noise analysis

To experimentally study the sensor stability, we monitor the microbeam response over time due to a multifrequency excitation. The actuation signal is composed of two AC signals of frequencies $\Omega_1 = 75 \text{ kHz}$ and $\Omega_2 = 340 \text{ kHz}$ near the first and third modes, respectively. We employ a LabVIEW software to convert the real-time data of the microbeam into frequency spectra. From the resulting frequency spectra, the amplitude of each mode is recorded over the duration of the experiment as shown in Fig. 4a. Hence, the measured noise response, Fig. 4a, accounts for all the noise sources in the experiment, which include the instrumentation noise, thermal drift, and adsorption-desorption noise [48-50]. As shown in Fig. 4a, the measured response demonstrates the enhanced stability near the third mode indicating amplitude fluctuation less than 3 nm compared with 20 nm near the first mode. To further investigate the stability of the device, we calculate the Allan deviation $\sigma_f(\tau)$. Hence, we convert the measured amplitude fluctuation at each mode into frequency by utilizing the suitable frequency response curves for the first and third modes, depicted in Fig. 3b and Fig. 3c, respectively. Considering that the noise test is conducted at $V_{DC} = 30 \text{ V}$, $V_{AC1} = 20 \text{ V}$ and $V_{AC2} = 40 \text{ V}$, we utilize the red triangles curve in Fig. 3b (1st mode) and the green square curve in Fig. 3c (3rd mode) to convert the amplitude fluctuation into frequency. The Allan deviation can be expressed as [48]

$$\sigma_f(\tau) = \sqrt{\frac{1}{2(N-1)} \sum_{i=1}^{N-1} (\bar{f}_{i+1}^\tau - \bar{f}_i^\tau)^2} \quad (1)$$

where N is the sample size and $\bar{f}_i^\tau$ is the average frequency fluctuation over the i th time interval τ defined as

$$\bar{f}_i(\tau) = \frac{f(i) - f_0}{f_0} \quad (2)$$

where $f(i)$ is the measured frequency at the time step i , and f_0 is the resonator nominal frequency.

The calculated Allan deviation curves are used in identifying the type of noise in the measurement data. As shown in Fig 4b, at low integration time at which the slope is negative, the fluctuation is dominated by the Gaussian noise whereas for higher integration time, where the slope is positive, the fluctuation increases due to random walk and steady drift [49, 50]. Also, the reported Allan

deviation values at $\tau=100s$ demonstrate the improved stability near the third mode $\sigma_{f_3}(100)=21.1ppm$ compared with $\sigma_{f_1}(100)=557ppm$ near the first mode. Hence, the corresponding frequency fluctuations near the first mode and third mode are $\Delta f_1=42Hz$ and $\Delta f_3=7Hz$.

Fig. 4. (a) Amplitude fluctuation of the microbeam over 15 minutes to a multifrequency excitation signal $V_{AC1}=20V$, $\Omega_1=75kHz$, $V_{AC2}=40V$, $\Omega_2=340kHz$, and $V_{DC}=30V$ at atmospheric pressure. (b) The corresponding Allan deviation near the first and third modes.

4.3 Operating point selection

The different modes of vibration of a single resonator are coupled through the nonlinear mid-plane stretching, which generates axial stress that tunes the frequency of the excited mode and the other modes of vibration [51, 52]. To simplify our study, we select the operating frequencies such that the frequency shift due to the intermodal coupling is negligible. To experimentally determine these frequencies, two tests are conducted. Figure 5a shows the result of fixing one source frequency near the third mode ($344kHz$) while sweeping the frequency of the other source near the first mode. The recorded change in the third mode amplitude is maximum near the first mode peak due to the mode cross-tuning. However, moving away from the third mode peak, the measured amplitude fluctuation is minimal and can be attributed to the different noise sources, inset of Fig 5a. In the second test, Fig. 5b, the frequency of one source is fixed near the first mode ($75kHz$) while sweeping the other source frequency near the third mode. As shown in the inset of Fig 5b,

the multimodal interaction is minimal up to a frequency value of 347 kHz . In our experiments, we fix the operating points at 75 kHz near the first mode and 344 kHz near the third mode. These values give a working range up to 3 kHz near the first mode and the third mode where the effect of multimode interaction is negligible. As the water molecules get adsorbed on the resonator surface, the amplitude of vibration increases following the left branch of the frequency response curve. Using the frequency response curves in Fig 3b and 3c, the recorded amplitude changes are transformed into frequency shifts.

Fig. 5. Frequency response of the microbeam to a multifrequency excitation for $V_{DC} = 30\text{ V}$ at atmospheric pressure (a) $V_{AC1} = 20\text{ V}$, $\Omega_1 = \text{swept}$, $V_{AC2} = 40\text{ V}$, and $\Omega_2 = 344\text{ kHz}$. Inset: amplitude fluctuation near the third mode while sweeping around the first mode, (b) $V_{AC1} = 20\text{ V}$, $\Omega_1 = 75\text{ kHz}$, $V_{AC2} = 20\text{ V}$, and $\Omega_2 = \text{swept}$. Inset: amplitude fluctuation near the first mode while sweeping around the third mode.

4.4 Sensitivity

Before exposing the device to water vapor, we flush the testing chamber with Nitrogen at a flow rate of 2 L/min for an extended period of time. Then, we expose the resonator to water vapor while monitoring the change in the amplitude of vibration. As water molecules get adsorbed on the device surface, the amplitude of vibration at the selected operating points increases following the left branch of the frequency response curves. The water vapor concentration is controlled by controlling the flow ratio between the bubbler line and the dry nitrogen line. The vapor concentration values are calculated following the procedure in [23]. The repeatability is demonstrated by replacing the water vapor flow with nitrogen to flush the resonator and return to the original state; this process is repeated for two cycles as shown in Fig 6a. Figure 6b shows the device response to the different levels of water vapor concentrations. The frequency shift rises linearly as we increase the water vapor concentration, Fig. 6c. Also, we ensure the reversibility by completely flushing the device after each exposure cycle. The experimentally calculated

responsivity near the first mode $\Re_{C_{wv}}^{1st} = 0.43 \text{ Hz/ppm}$ and third mode $\Re_{C_{wv}}^{3rd} = 0.65 \text{ Hz/ppm}$ demonstrate the enhanced sensitivity near the higher order modes of vibration. From the noise analysis, the minimum detectable gas concentration is 11 ppm near the third mode.

To study the dynamic of adsorption, we fit an exponential function decay of the form $f(t) = a \exp(-t/\tau)$ to the experimentally recorded data at 4990 ppm depicted in Fig. 6a. The calculated adsorption τ_{Response} and recovery τ_{Recovery} time constants are 5.2 min , 12.8 min , respectively. These are higher than those reported in the literature, for example [43, 53-55]. Although the time constants are governed by the nature of the surface coating, the current experimental setup limits our ability to accurately measure these parameters due to the long time required to fully humidify and dehumidify the chamber. In our study, the chamber volume is $3L$, and the maximum flow rate is 2.5 l/min , which indicates that a longer transient time is required to reach the final concentration value. Using smaller chamber will improve and lower these time constants.

Fig. 6. Real time measurement of the frequency shift near the first (75 kHz) and third (344 kHz) mode due to vapor exposures. (a) Repeatability of the response at fixed water vapor concentration $C_{wv} = 4990 \text{ ppm}$. (b) Linearity of the

response at different water vapor concentrations. (c) Experimentally calculated sensor responsivity near the first and third modes, which demonstrates the enhanced sensitivity near the higher order mode of vibration.

4.5 Multi-modal smart switching

It is desirable to realize a smart switch that can be utilized to perform an action when the gas concentration exceeds a certain threshold while accurately measuring the concentration. Although, the concept can be employed in principle to detect any harmful gas, in our experiment we utilize water vapor for safety reasons. The idea is based on actuating the device with a harmonic signal that has two frequencies Ω_1 and Ω_2 with AC amplitudes V_{AC1} and V_{AC2} superimposed to a DC voltage. V_{AC1} is selected such that the frequency response near the first mode shows a nonlinear response with dynamic pull-in band, Fig. 7a, while Ω_1 is tuned close to the dynamic pull-in band of the first mode. The difference between Ω_1 and the bifurcation frequency defines the threshold concentration value after which the microbeam collapses due to dynamic pull-in, hence, can be realized as an electrical switch. V_{AC2} is chosen such that a linear response is realized near the third mode as shown in Fig. 7b. Ω_2 is set close to the third mode. The advantage of measuring the shift in the frequency of the third mode that it provides an independent, noise tolerant, and sensitive probe for accurately measuring the gas concentration compared to the first mode bifurcation-based sensing, which is less sensitive and more affected by noise thereby dramatically reducing the accuracy of the sensor readings [22].

It is worth to mention that the dynamic pull-in band, Fig. 7a, is obtained by slowly sweeping the excitation frequency around the first mode (quasi-static sweep rate of 500 Hz/s). When exposing the resonator to mass (vapor) loading, these quasi-static loading conditions may not apply. Hence, the boundaries of stabilities reported in Fig. 7a represent idealized scenarios; the actual instability boundaries are in general dependent on the noise level and dynamic disturbances in the system. This may lead for instance to earlier instability threshold on the left branch of the figure. Nevertheless, such an experiment gives a close enough idea of when to expect the actual dynamic pull-in to occur in actual mass loading experiments.

Next, we illustrate the mass loading experiment. As water molecules get adsorbed on the resonator, the resonance frequencies decrease, and the corresponding amplitudes at each excitation frequency increase following the left branch of the frequency response curves shown in Fig. 7a and Fig. 7b. As a case study, a vapor concentration of 3260 ppm is considered as the threshold value. As shown in Fig. 6c, when operating the resonator in the linear regime, a concentration of 3260 ppm shifts

the first mode frequency by 1.78 kHz and the third mode by 2.455 kHz . To experimentally demonstrate the concept of smart switching, we fix the first source frequency at $\Omega_1=68 \text{ kHz}$ (first mode) and voltage amplitude $V_{AC1} = 50 \text{ V}$, the second source frequency at $\Omega_2=344 \text{ kHz}$ (third mode) and voltage amplitude $V_{AC2} = 40 \text{ V}$, and use $V_{DC} = 30 \text{ V}$. Ruzziconi *et al.* [56] demonstrated that the stability of the resonator at a particular operating frequency depends on the size of the safe basin of attraction. As the driving frequency approaches the bifurcation frequency, the safe basin of attraction gets eroded and shrinks in size. To ensure the stability of the resonator at the operating points, we monitor the amplitude fluctuation over time due to noise as shown in the inset of Fig. 7d. The calculated Allan deviation near the first and third mode of vibrations are $\sigma_{f_1}(100) = 388 \text{ ppm}$ and $\sigma_{f_3}(100) = 6 \text{ ppm}$, which correspond to frequency fluctuation of $\Delta f_1 = 26 \text{ Hz}$ and $\Delta f_3 = 2 \text{ Hz}$. Hence, the minimum detectable water vapor concentration is theoretically (and based on linear analysis [11, 12]) 3 ppm . However, in the case of realizing a switch, the minimum detectable concentration will be influenced by not only the frequency fluctuation but also by the erosion of the basin of attraction near the bifurcation point. Hence the minimum detectable concentration for such switches depends on the setup and experimental conditions and needs to be determined experimentally. By monitoring the amplitude fluctuation shown in the inset of Fig. 7d, one can note that the minimum detectable concentration is 58 ppm . Then, the microbeam is exposed to water vapor at the threshold concentration of 3260 ppm . As shown in Fig. 7c and Fig. 7d, when the frequency shift near the first mode exceeds the threshold value ($\sim 1.8 \text{ kHz}$), the upper electrode collapses into the lower electrode (simulating a switching action). However, the measured frequency shift near the third mode is 1.6 kHz , which is less than the expected value at this concentration, 2.455 kHz , reported in Fig. 6c. In the vicinity of the bifurcation frequency, the noise influence becomes significant, hence, the measured frequency shift near the first mode can be attributed to the combined effect of noise and water adsorption on the resonator surface [19, 22]. In our case study, although the threshold concentration is set at 3260 ppm , the measured frequency shift near the third mode indicates that the switching occurs at 1924 ppm , Fig. 7d. This proves the importance of using the third mode as an independent channel of information to accurately measure the concentration at which pull in occurs.

The reported results show the significance of this technique in accurately measuring the concentration of water vapor while still being able to switch if the concentration exceeds beyond

a certain safe value. The reported noise effect can be used as safety factor, which ensures that the switching action will take place at a gas concentration equal or less than the estimated threshold value based on the idealized curve (based on slow sweeping) of Fig. 7a. Analytically, the robustness of bifurcation based gas sensors can be investigated by conducting a global dynamics analysis on the stable solution before pull-in, which can be used to identify the range of stable solutions. In contrast to previous works using a single mode to demonstrate smart sensor, at which the noise effect in the vicinity of the bifurcation frequency significantly reduces the accuracy of the measurement, we show a noise immune technique that can accurately measure the gas concentration by utilizing the higher order modes of vibrations of the same resonators, while still being able to switch upon exceeding a safe concentration value. Also, utilizing the third mode improves the sensor sensitivity and resolution. The reported findings can be easily extended to measure the change in other physical stimuli, such as temperature, and switch upon exceeding the critical limit. Furthermore, employing higher number of modes opens the door for simultaneous measurement of multiple physical parameters using the same resonator, which reduces the power consumption, fabrication cost, and size of the sensor.

Fig. 7 Frequency response curves at $V_{DC} = 30$ V and at atmospheric pressure (a) near the first mode at $V_{AC1} = 50$ V showing the softening behavior and the dynamic pull-in band, (b) near the third mode at $V_{AC2} = 40$ V. Real time measurement of the frequency change and the water vapor concentration until pull in. The vapor exposure started at time = 9 minutes. (c) Near the first mode, (d) near the third mode. Inset: the fluctuation due to noise.

5. Conclusions

We demonstrated a smart sensor that is capable of accurately measuring the concentration of a particular gas and performing switching upon exceeding a certain threshold value. This is in contrast to a single mode operation, in which the noise effect in the vicinity of the bifurcation reduces the accuracy and reliability of the sensor readings. The method is based on simultaneously actuating the resonator near the pull-in band of the first mode and the linear response of the third mode. As a case study, we utilized this concept to measure the environmental humidity. Based on the theoretical analysis Allan deviation results, and assuming linear operation of the resonator based on frequency shifts, a minimum detectable water vapor concentration of 3 ppm has been reported near the third mode. This concept can be easily employed to detect more harmful gases by functionalizing the microbeam with a selective coating material. Also, it can be utilized and extended to independently detect other physical stimuli, such as temperature. Optimizing the resonator design to excite higher order modes will open the door for simultaneously measuring

multiple physical stimuli using a single resonator, which reduces the power consumption, device size, and cost.

6. Acknowledgment

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7. Conflict of interest

The authors declare no conflict of interest.

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