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Highly Sensitive and Wide-Range Resonant Pressure Sensor Based on the Veering Phenomenon

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ABSTRACT

We report a highly sensitive wide-range resonant pressure sensor. The concept is based on tracking multiple modes of vibration of an electrothermally heated initially curved micro-beam experiencing the veering phenomenon between its first and third vibration modes. For low values of pressure, the third resonance frequency is very sensitive, and thus its variation with pressure is monitored and recorded. As increasing pressure, the resonance frequency of the third mode decreases until reaching the veering phenomenon. At that point, the first mode exchanges role with the third mode, becoming very sensitive, and hence its frequency is tracked afterward as varying pressure. We show that using this concept, the sensitivity of the resonant pressure micro-sensor is significantly enhanced. Finite element method (FEM) simulations and experimental data show that the proposed micro-sensor becomes highly sensitive for wide-range of pressure from 38 mTorr to 200 Torr. The effect of various parameters on the performance of the proposed pressure sensor is investigated including the thickness of the micro-beam, the vacuum chamber size, and the thermal actuation load.

1. Introduction

In recent years, miniaturized vacuum pressure sensors have received increasing attention, in addition to other environmental sensors, such as temperature [1], flow [2], gas [3][4][5][6], and mass sensors [7][8]. Pressure micro-sensors have been explored for various potential applications, such as industrial control, healthcare, medical testing, aerospace, meteorology, and environmental monitoring [9][10][11]. Different sensing mechanisms and designs have been used for the detection of air-pressure, such as capacitive, piezoelectric, piezoresistive, and resonant [12][13][14][15][16]. Resonant pressure micro-sensors have the advantage of digital frequency output, which can be measured with high precision using simple electronic circuits. Their principle of operation is based on tracking the resonant frequency shift, caused by the change of internal stress due to the change of the surrounding air pressure.

Compared to other sensing mechanisms, tracking the resonant frequency shift yields high accuracy, high stability, high sensitivity, and better immunity to noise. The resonant frequency tuning of silicon resonators can be achieved by electrostatic, magnetic, thermal, or electrothermal excitation [17][18][19]. Despite the higher power

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consumption, electrothermal excitation is simpler in fabrication compared to other methods, is more robust technique, and requires low actuation voltages.

In a previous work, we demonstrated a sensitive pressure-sensor based on the convective cooling of an electrothermally heated resonant straight micro-beam utilizing the fundamental mode operated near the buckling point [20]. Sensitivity up to 77081 ppm/Torr ($77081 \times 10^{-6}/\text{Torr}$) was demonstrated for a pressure range from 1 to 10 Torr. To alleviate the dip in frequency near the buckling instability, another sensor was demonstrated based on an initially curved arch micro-beam, which shows a sensitivity of 10482 ppm/Torr. The designs, however, were limited to a narrow range of pressure.

A device with enhanced sensitivity and wide pressure range, which is also simple in fabrication, operation, and sensing scheme, would be highly desirable. In this work, we present such a pressure sensor using an electrothermally heated initially curved micro-beam exhibiting the veering phenomenon among its first two symmetric vibration modes. This offers more continuity in frequency variations, and thus high sensitivity in wide range of pressure [21].

2. Background and Measurements Method

The concept is illustrated in Fig 1 (a). First, the resonant frequency of the third mode is monitored when the micro-beam is actuated with an electrothermal voltage V_{Th} . As increasing pressure, the axial load of the arch micro-beam decreases due to the cooling effect of the surrounding air, and hence its third resonant frequency keeps decreasing until reaching the veering zone (the transition point). After the transition point, the frequency tracking switches to the fundamental resonant frequency. The inset in Fig.1 (a) shows a scanning electron microscopic (SEM) image of the fabricated curved micro-beam resonator. The micro-beam resonator is fabricated from the SOIMUMPs process by MEMSCAP [20]. Fig.1 (b) shows a cross-sectional view of a device based on the SOIMUMPs. Compared to other pressure resonant sensors, the proposed sensor shows simplicity in fabrication with low-cost and size scalability. The tested curved micro-resonator is of length (L) 800 μm , width (b) 25 μm , thickness (h) 1.5 μm , and initial rise (b_0) 2.6 μm , where b_0 is the distance between the beam midpoint to its straight level. The transduction gap between the actuated electrode and the clamped end of the micro-beam is 12 μm (d). A schematic of the experimental setup used to test the proposed pressure sensor is shown in Fig. 1(c). The sensor is placed inside a controllable test chamber equipped with a pressure gauge. The pressure can vary from 38 mTorr to atmospheric pressure; thus the detection limit of the micro-sensor is 38 mTorr. The arch MEMS resonator is electrothermally tuned and electrostatically driven, Fig 1(c). We utilize a laser Doppler vibrometer from Polytec (MSA 500) [22] to measure the resonant frequencies of the micro-beam as driving the micro-beam electrostatically. A separate DC voltage source V_{Th} is used to induce a current flowing through the arch micro-beam, which heats it up by Joule's heating effect, and hence alters its stiffness and resonant frequencies.

Fig. 1. (a) The principle of operation of the proposed pressure micro-sensor based on an electrothermally heated clamped-clamped micro-beam (shown in the inset as an SEM image). The concept is based on tracking the resonant frequency of the third mode (black line) when the beam is actuated with an electrothermal voltage V_{Th} . Then, by increasing pressure, the axial load of the arch beam decreases due to the cooling effect of the surrounding air, and hence its third resonant frequency keeps decreasing until reaching the veering zone (the transition point). After the transition point, the frequency tracking switches to the fundamental resonant frequency (light-purple line). (b) Cross-sectional view of the fabricated structure by SOIMUMPs. (c) The experimental setup for the proposed pressure based on a clamped-clamped silicon arch micro-beam with dimensions: 800 μm length (L), 25 μm width (b), 1.5 μm thickness (h), and 2.6 μm initial rise (b_0), where b_0 is the distance between its midpoint to its straight beam level.

3. Results and Discussions

A. Experimental Results

The basic theory behind the frequency tuning comes from the effect of the induced compressive axial load, due to the heating of the arch from electrothermal actuation, which increases the curvature of the arch, and hence its stiffness. An analytical study of this effect was presented in [23]. In addition, we showed in [21] that by carefully choosing the geometrical parameters and the initial shape of the arch, the veering phenomenon (avoided-crossing) among the first two symmetric modes can be strongly activated [21]. Further, we studied experimentally and analytically the variation of the resonance frequencies of the micro-beam around the veering range (before, on, and after veering of the first two symmetric modes) while applying a constant DC electrothermal voltage V_{Th} [21].

Hence, in this work the curved micro-beam is designed deliberately to exhibit veering (near crossing) phenomenon among its first two symmetric vibration modes. Upon changing V_{Th} as maintaining pressure at low vacuum (38 mTorr), the first resonant frequency increases up to twice its fundamental value; due to the continuous increase in the arch curvature (stiffness). Also, the third resonance frequency (f_3) decreases. This continues until it approaches very close to the first resonance frequency (f_1); after which the curves of both the first and third resonance frequencies veer away from each other with high curvature, Fig. 2(a). Same behavior is shown as operating the arch micro-beam at atmospheric pressure but for higher V_{Th} due to the cooling effect at high pressure of the surrounding air, Fig. 2(b). Shown also on Fig. 2 simulations results, which indicate similar behavior to the experimental data, obtained using a FEM model using COMSOL Multiphysics.

The temperature of the Silicon (Si) beam has to be ensured to be below its melting point of 875 K while being actuated by V_{Th} . The inset schematic in Fig. 2(a) shows the FEM results of the maximum temperature and mid-point displacement at 38 mTorr of the tested arch micro-beam as varying V_{Th} . These results are important to choose the suitable electrothermal voltage to operate the micro-beam with a maximum displacement lower than 12 μm (the gap between the actuated electrode and the clamped end of the micro-beam) and a temperature lower than 875 K. Here, we choose $V_{Th} = 4$ V to analyze the proposed technique. The simulation indicates a maximum displacement of 7.3 μm and a temperature of 438 K with corresponding measured resonant frequency values near the first (at 1 atm) and third (at 38 mTorr) mode are 79 kHz and 169 kHz, respectively.

Fig. 2(c) shows experimental data of the relative frequency shift (Δf) with pressure as fixing V_{Th} at 4 V. Pressure was swept from 38 mTorr to atmospheric pressure. The relative frequency shift (Δf) is defined as $(f_0 - f)/f_0$, where f_0 and f are the frequency of the micro-beam at 38 mTorr and during the measurement with pressure, respectively. The results show five linear trends ((38 mTorr to 0.7 Torr), (0.7 to 3.3 Torr), (3.3 to 49 Torr), (49 to 125 Torr) and (125 Torr to 1 atm)). For each trend, the sensitivity of the micro-beam (S) is calculated using $\Delta f/(P_{\text{max}} - P_{\text{min}})$, where P_{max} and P_{min} are the maximum and minimum pressure, respectively. As shown in Fig. 2(c), the first linear regime shows the highest sensitivity against pressure (47473 ppm/Torr). As can be seen, the sensitivity is decreased with pressure. As listed in Table 1, the sensitivity of the proposed micro-sensor is significantly higher compared with other previously reported pressure sensors. Also, it is noted that the results show high sensitivity of 2689 ppm/Torr in wide pressure range until 200 Torr (detection limit), which is much higher than that of our previous work, that was limited to 30 Torr [20].

In general, the performance of a pressure sensor is related to the sensitivity (S) and the maximum detection limit (P). Thus the relative frequency shift (Δf) multiplied by the sensitivity can represent the performance of a pressure sensor (optimal value = $(S \times \Delta f) = (S^2 \times P)$) [28]. The optimal value of the proposed micro-sensor is 153170 ppm/Torr, which is much higher than the values reported in the literature and listed in Table 1.

In addition to having a wide range, low power consumption is also an important parameter. The power consumption is estimated based on resistive heating of the micro-beam $(V_{Th})^2/R$ where R is the resistance of the micro-beam, which is estimated to be 1.34 k Ω . Thus, increasing the resistance of the micro-beam will considerably reduce the power consumption. The proposed micro-sensor results in power consumption around 12 mW. Moreover, this value is much lower than the electrothermal actuated beams in the literature [29][30]. The sensitivity of the

device and its power consumption can be improved with a beam of a higher aspect ratio and using a material with a lower thermal conductivity. The thermal response time of the proposed arch micro-beam is equal to $162.8 \mu\text{s}$ [29]. Hence, to have faster response time, the sensor needs to be further miniaturized to smaller size, to the nano- and submicron-scale.

Fig. 2. (a),(b): Experimental data and finite element simulations of the first two symmetric resonant frequencies of the curved micro-beam while varying the electrothermal voltage V_{Th} , at (a) 38 mTorr pressure and (b) at atmospheric pressure. The first resonant frequency (f_1) increases while increasing V_{Th} and then slows down, almost flattens, as it gets close and passes the third resonant frequency. The third resonant frequency (f_3) decreases slightly with increasing V_{Th} then starts to increase when getting very close to f_1 . Inset in (a) shows finite element simulations of the temperature and static displacement at the center of the arch micro-beam by varying the applied electrothermal voltage V_{Th} , at 38 mTorr pressure. (c) Measured percentage relative shift of the resonant frequency with pressure for $V_{Th} = 4 \text{ V}$. The results show five linear trends with their sensitivities values.

Table 1: Summary of some of the reported pressure sensors.

Materials	Pressure range (Torr)	Maximum detectable pressure (Torr)	Sensitivity (Torr ⁻¹)	Optimal value (Torr ⁻¹)	References
Si/ZnO	[112- 6375]	6375	5.46 ppm	0.19 ppm	[17]
Si	[1-10]	30	10482 ppm	3296 ppm	[20]
p-Si	[0 – 0.75]	75	4341 ppm	1413 ppm	[24]
SiN	[0.02- 10]	10	6918 ppm	478 ppm	[25]
Graphene/SiO ₂ /Si	[150- 750]	750	3.95 ppm	0.0023 ppm	[26]
LRGO/DVD disk	[0.0075- 2.35]	2.35	12000 ppm	383 ppm	[27]
Si	[38 x 10 ⁻³ -10]	200	27674 ppm	153170 ppm	This work
Si	[38 x 10 ⁻³ -200]	200	2689 ppm	1446 ppm	This work

B. Finite Element Model Results

To further improve sensitivity, FEM simulation of the proposed sensor is conducted to evaluate the performance of the proposed micro-sensor and optimize its key parameters. To simulate the heat transfer between the solid and fluid domains, we coupled the Joule Heating and Thermal expansion module with the Conjugate Heat Transfer module. More details of the simulation steps can be found in [20]. The maximum temperature as shown in the inset schematic of Fig. 2(a) is calculated from the Joule's heating equation. One should note that the device sensitivity is dependent on the applied electrothermal voltage. A higher V_{Th} heats the beam more, and hence, more air volume (more pressure) is needed to cool down the beam. The performance of the micro-beam is simulated at two operating voltages, 4 V and 8.5 V, respectively. Fig. 3(a) shows the percentage of relative frequency shift as a function of pressure. Good agreement is shown compared to experimental data (Fig. 2(c)). The mismatch among the experimental and simulation results can be attributed to geometry imperfections. As shown in Fig. 3(b), the sensitivity decreases with the applied electrothermal voltage. This is because the micro-beam is cooled down before reaching the transition point, and thus the sensitivity is calculated from the third mode. The sensitivity of the proposed sensor at 1.2 Torr and at $V_{Th} = 4$ V is three times higher than the sensitivity at 8.5 V, which is equal to 127185 ppm/Torr. The sensor sensitivity is expected to improve as applying higher electrothermal voltage. However in this study, based on the veering phenomenon between two first symmetric modes, a lower voltage actuation shows higher sensitivity, while consuming lower power.

To further understand the effect of geometry on the veering phenomenon, and thus on sensitivity, we study the variation of sensitivity as varying pressure for the same micro-beam but with different thicknesses, Fig. 3(c). As can be seen, the transition point decreases with increasing thickness h . Below this pressure value the sensitivity decreases with increasing h and above it the sensitivity becomes higher for a thinner micro-beam. This suggests an optimum thickness for better sensitivity for low or high pressure depending on the targeted application. Also, the results show that for a specific thickness the third resonant frequency decreases until getting very close to the first resonant frequency. This presents a method to choose the geometric parameters of such curved micro-beams carefully to activate the veering phenomenon. The next step is to determine the optimal package size for optimal sensitivity. Fig. 3(d) shows that at low pressure, the sensitivity is much higher in the smaller volume. It is found that the sensitivity of the micro-beam at 2.35 Torr and for small package size of $1.5 \times 1.5 \times 1 \text{ mm}^3$ is 1.5 times higher compared to the large package size ($3.5 \times 1.5 \times 1 \text{ mm}^3$), which equals to 125919 ppm/Torr.

Fig. 3. (a) and (b) Finite element simulations of the percentage relative shift of resonant frequency and the sensitivity with pressure at two operating voltage $V_{Th} = 4 \text{ V}$ and 8.5 V , respectively. The insets show the first two symmetric resonance frequencies while varying V_{Th} of the curved micro-beams at 38 mTorr. (c) and (d) Finite element simulations of the sensitivity with pressure

for $V_{TH} = 4V$ at different thickness values and at different air volume surrounding the micro-beam. The insets show their corresponding percentage shift of resonance frequencies with pressure.

4. Conclusions

We proposed a wide-range and highly sensitive pressure micro-sensor based on an electrothermally heated initially curved micro-beam exhibiting veering phenomenon between its first two symmetric vibration modes. The proposed micro-sensor can exhibit a high sensitivity of 2689 ppm/Torr in wide-range of pressure 38 mTorr to 200 Torr, a pressure limit of 200 Torr, and an optimal value of 1446 ppm/Torr. In addition, we showed through FEM the significant effect of thickness of the micro-beam, the vacuum chamber size, and the thermal actuation load, on the sensitivity of the proposed pressure micro-sensor. For some pressure sensor applications, which require high sensitivity, these parameters need to be carefully optimized.

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6. References

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