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SCALABLE PRESSURE SENSOR BASED ON ELECTROTHERMALLY OPERATED RESONATOR

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ABSTRACT

We experimentally demonstrate a new pressure sensor that offers the flexibility of being scalable to small sizes up to the nano regime. Unlike conventional pressure sensors that rely on large diaphragms and big-surface structures, the principle of operation here relies on convective cooling of the air surrounding an electrothermally heated resonant structure, which can be a beam or a bridge. This concept is demonstrated using an electrothermally tuned and electrostatically driven MEMS resonator, which is designed to be deliberately curved. We show that the variation of pressure can be tracked accurately by monitoring the change in the resonance frequency of the resonator at a constant electrothermal voltage. We show that the range of the sensed pressure and the sensitivity of detection are controllable by the amount of the applied electrothermal voltage. Theoretically, we verify the device concept using a multi-physics nonlinear finite element model. The proposed pressure sensor is simple in principle and design and offers the possibility of further miniaturization to the nanoscale.

Keywords: Pressure Sensor, Resonator, Electrothermal Actuation, Cooling effect.

1. INTRODUCTION

The growth of the use of the micro/nanoelectromechanical systems (MESM/NEMS) has been a key driver for the development of the sensor technology thanks to their low mass, low power losses, and high reliability. MEMS structures demonstrate a great capability for sensing applications, such as force sensors [1], mass/gas sensors [2], flow sensor [3], and pressure sensors [4].

Pressure sensors have been used to provide an accurate monitoring of the surrounding pressure in both domestic and industrial applications. The quest for miniaturized systems and low-cost deployable sensors have sparked interest recently to seek alternative approaches for pressure sensing; other than the conventional [5] and bulkier strain-gauge [6], capacitive [7], and piezoresistive [8] pressure sensors. Several studies have explored different techniques and designs to realize pressure sensors and improve their sensitivity based on micro-sized diaphragms [9], carbon nanotubes sensors [10], micromechanical drumhead resonators [11], microcantilever sensors [12], and bridge resonator [13]. Khan et al. [9] presented a microchannel string resonator that has a resonance frequency modulated by the internal gauge pressure of microchannels sitting on the strings. Southworthet al [11] investigated the sensitivity of a pressure sensor based on the variation of the resonance frequency due to the squeeze damping effect of a drum-type resonator. One of the recent studies, Kim et al. [13] presented a pressure-sensing technique based on the variation of the resonance frequency of a miniaturized beam resonator due to the local photothermal effect, controlled by an external laser source, which induces compressive stresses.

Here, we demonstrate a new pressure sensor that offers the flexibility of being scalable to small sizes. The principle of operation relies on convective cooling of the air surrounding an electrothermally heated structure. Here we use an initially curved structure in which the resonance frequency is tuned by applying an electrothermal voltage across the beam. In recent works [14-15], we showed that by controlling the electrothermal voltage of either straight or initially curved structures a large tunability could be realized while operating the system electrostatically. The main advantage of the extensive use of thermal actuation for bistablity is that it offers a large axial force by low applied voltages. In this work, we show that the variation of pressure can be tracked accurately by monitoring the change in the resonance frequency of the resonator at a constant applied electrothermal voltage. We show that the range of the sensed pressure and the sensitivity of detection are controllable by the amount of the applied electrothermal voltage.

The rest of the paper is organized as follows. The device operation system and experimental setup are presented in Sec. 2. The results showing the response and the sensitivity of the proposed sensor is described in Sec. 3. Finally, the main conclusions are summarized in Sec. 4.

2. DEVICE OPERATION SYSTEM

An intentionally curved arc in-plane silicon microresonator is fabricated on a highly conductive Si device layer of a 30 µm-silicon-on-insulator wafer by a two-mask process using standard photo-lithography, electron beam evaporation for metal layer deposition for actuating pad, deep reactive ion etch for silicon device layer etching, and vapor hydrofluoric acid etch to remove the oxide layer underneath the resonating structure [16]. The device, Fig.1, consists of a clamped-clamped curved beam (arc) and drive and sense electrodes. Different case studies are used with different lengths to compare the sensitivity of the proposed device. The geometric characterizations of the two systems under consideration are given in Table 1. The curved beam is sandwiched between two adjacent electrodes, Fig. 1, to induce the vibration by exciting it electrostatically. For both cases, the gap between the actuating/sensing electrode and the arc resonator is 8µm at the clamped ends.

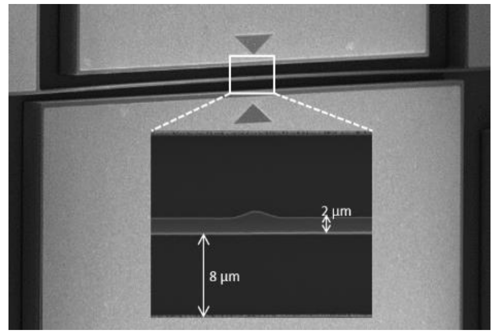


Figure 1. An SEM image of the fabricated curved beam microresonator (Arc beam 1).

TABLE 1. GEOMETRICAL PROPERTIES OF THE MICROBEAM MADE OF DOPED SILICON.

Quantity	***Arc beam 1***	***Arc beam 1***
Length (*µm*)	800	500
Thickness (*µm*)	2	3
Width (*µm*)	30	30
Initial curvature (*µm*)	2.6	3

Figure. 2 shows the experimental setup used to test the proposed pressure sensing technique. The figure shows a two-port electrical transmission measurement configuration for electrostatic actuation and capacitive sensing. The drive electrode is provided with an AC actuation signal, and the arc beam is biased with a DC voltage source. The output current induced at the sense electrode is coupled with a low-noise amplifier whose output is coupled to the network analyzer input port. A voltage source, V_{TH} is connected across the arc beam anchors to induce a current flowing through the structure and to heat up the beam by joule's heating effect. This current causes thermal expansion and controls the internally induced axial stress of the arc beam that causes an increase in its curvature, and hence increases its stiffness. Then, upon changing the pressure while maintaining V_{TH} constant, the cooling of the beam from the surrounding air changes, hence changing its compressive stresses, and thus its resonance frequency. This presents a way to monitor the surrounding pressure by means of the cooling effect.

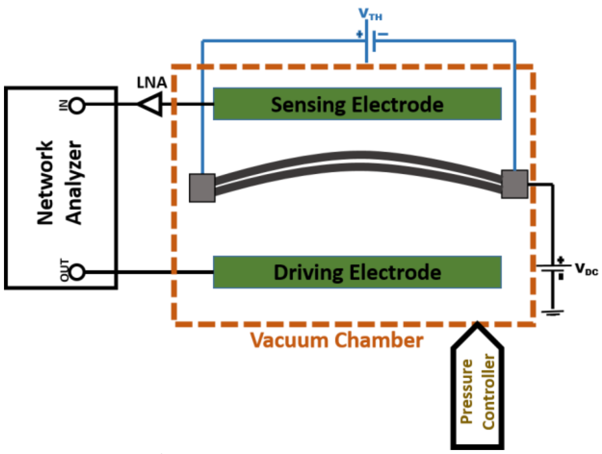


Figure 2. Schematic of the used setup and the sensing and detection scheme.

3. RESULTS AND DISCUSSIONS

One should mention that the time associated with the electrothermal cooling and heating is much longer than the time associated to the vibration of the studied arc. The associated thermal time coefficient is defined by $\tau = \left[\frac{\pi^2 K_{Si}}{c\rho l^2} + \frac{F_S K_{air}}{gbc\rho} \right]^{-1}$ [17], where l, b, g, ρ, c, K_{Si} and K_{air} present the length, width of the arc beam and the gap between the arc beam and the substrate, the silicon density, the silicon heat capacitance and the thermal conductivity of the silicone and the air, respectively. F_s is the beam shape factor that presents the correction term calculated based on the geometry of the arc beam using the formula given by $F_S = \frac{b}{h}\left(\frac{2g}{b}+1\right)+1$ [18], where h is the thickness of the arc beam. Thus, the associated thermal time constant for arc beam 1 and 2 is equal to 162.833 µs and 152 µs, respectively.

Figure. 3(a) shows the variation of the fundamental resonance frequency of arc beam 1 as varying the applied electrothermal voltage V_{TH}, in air. Figure. 3(a) shows that the first resonance frequency increases while tuning the electrothermal voltage until reaching values as high as twice the initial value at zero electrothermal voltage [15]. While tuning the electrothermal voltage, the temperature along the beam increases as well by joule's heating effect. Referring to the Fourier's heating equation [14], we simulate in Fig. 3(b) the variation of the corresponding maximum temperature at the midpoint and average temperature along arc beam 1. Figure. 3(b) demonstrates that the temperature variation is much lower than the melting point of the silicon, which is equal 1414^{o}C.

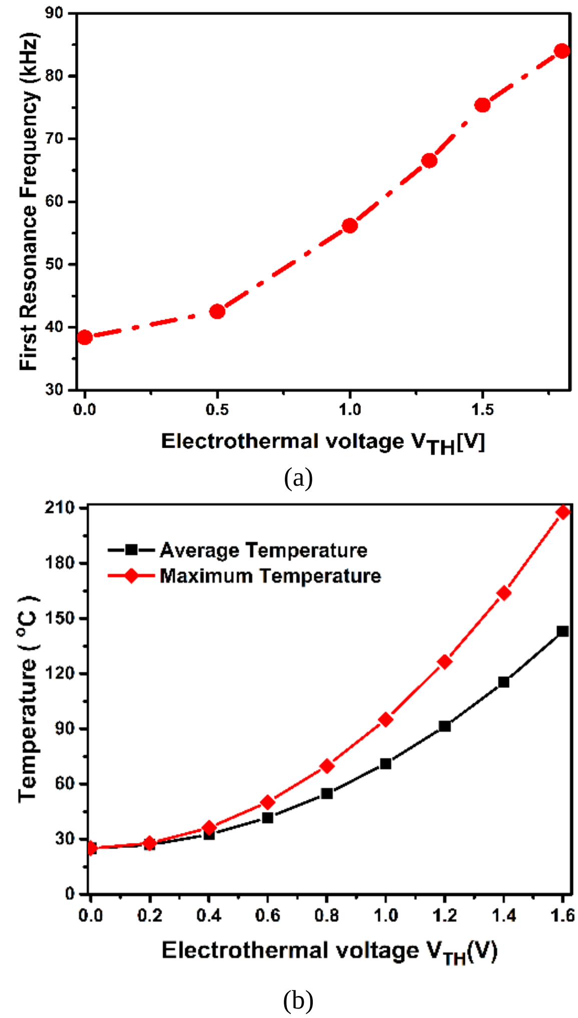
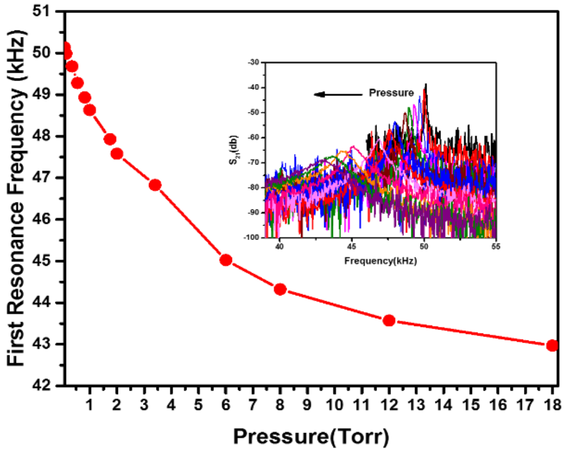
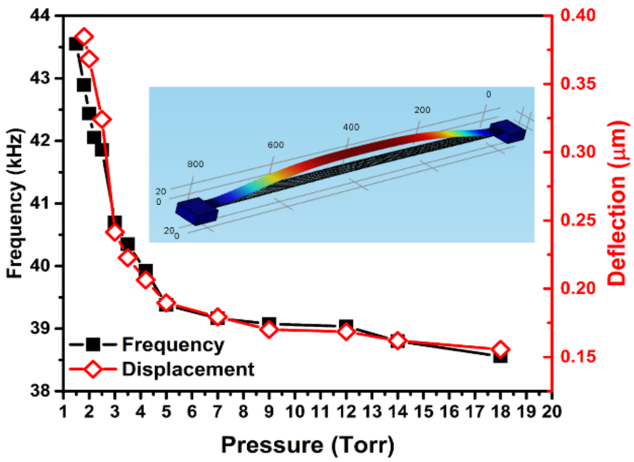


Figure 3: (a) The fundamental resonance frequency of arc beam 1 while varying the applied electrothermal voltage, in air, using optical measurements (stroboscopic microscope) [15]. (b) The calculated maximum and average temperatures at the midpoint of arc beam 1 versus the applied electrothermal voltage.

Upon changing the pressure while maintaining V_{TH} constant, the cooling of the beam from the surrounding air changes, hence changing its compressive stresses, and thus its resonance frequency. Figure. 4.a shows that the resonance frequency of arc 1, for V_{TH} =0.3V, drops exponentially with pressure due to the enhancement of the air convective cooling (effectively means less axial thermal stresses). Theoretically, using a multi-physics nonlinear finite element model, we show in Fig. 4.b that the resonance frequency, as well as the static deflection of the beam, decreases with pressure due to the convective cooling. This further demonstrates the impact of convective cooling of the air on the curvature of the arc beam, and hence on its resonance frequency and stiffness.



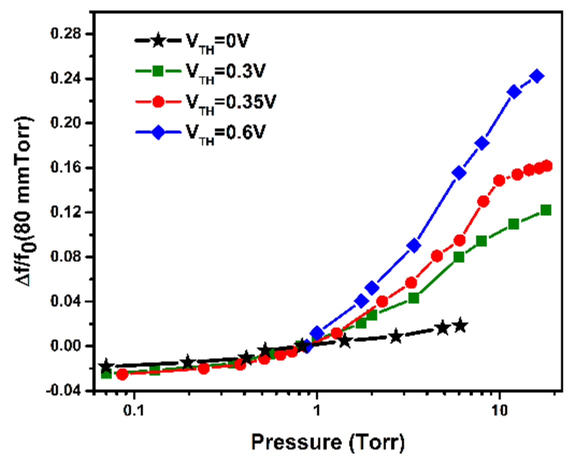
(a)



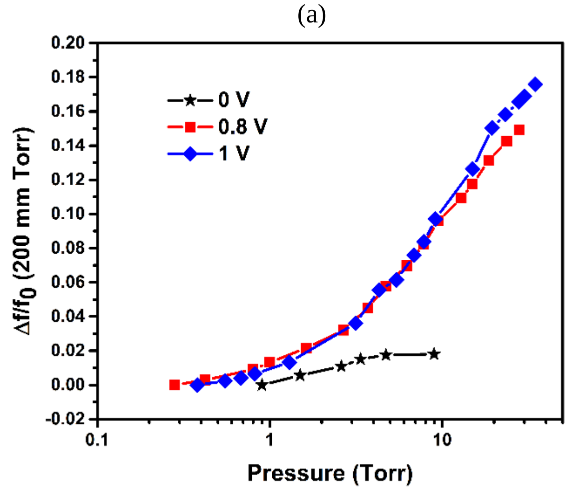
(b)

Figure 4: (a) Fundamental resonance frequency of arc beam 1, for V_{TH} =0.3V, as varying the pressure. The inset shows the electrical frequency sweep as varying the pressure.(b) Finite element simulation of the resonance frequency and the static deflection of arc beam 1, for V_{TH} =0.3V, as varying the pressure. The inset describes the first mode shape of the studied resonator.

Increasing V_{TH} heats the beam further causing more axial compressive stresses, which increase the arc curvature and stiffness (and hence its resonance frequency). Also, since the beam is heated more; its sensitivity to pressure variation increases. Figure. 5 shows that the normalized shift of the frequency with pressure for both case studies is highly dependent and sensitive to the applied V_{TH}. As increasing the pressure, the volume of air surrounding the arc beam provides sufficient cooling power to reduce the temperature along the beam and then its stiffness leading to lower resonant frequency. This could be explained as well y the linear dependence of the heat coefficient of the air with the pressure. At constant electrothermal voltage, once the volume of air surrounding the beam is enough to cool down the beam (i.e. at specific pressure), the arc beam reaches the equilibrium temperature and then no more variation as increasing the pressure. For the arc beam 1, the sensitivity in the range of pressure from 1 to 10 Torr increases from 12655 ppm/mbar to 24634ppm/mbar while increasing V_{TH} from 0.3 to 0.6V. For V_{TH} =0.6V, the frequency changes from 1 to 10 Torr is 2.5kHz/Torr that is higher than the resolution proposed in [11] that was equal to 2kHz/Torr. Moreover, the sensitivity of the proposed sensor at V_{TH} =0.6V is 8 times higher than the normalized sensitivity of the microdiaphraghm-based pressure sensor which was equal to 3256 ppm/mbar [19]. However, this sensitivity is two order lower than the proposed sensor in [13] that was equal to 51888ppm/mbar. This difference in sensitivity is due to the difference in scale since they are proposed a nanoscale beam [13]. Also, the pressure range is dependent on the applied electrothermal voltage. The variation of the frequency in different pressure zones seem to be linear with the logarithm of the pressure. For instance, if we take the case of arc beam 2 at V_{TH} =1V, Fig. 5(a) displays two zones in which we have a linear variation of the frequency with different slopes: the regime of milli-Torre and above the milli-Torre. The slope of the curve from 1 to 10 Torr is highest, which means a higher sensitivity in that zone. This result could be improved by scaling down the dimension of the beam.



(a)



(b)

Figure 5: Normalized shift of the resonance frequency of the arc beams for different V_{TH} while varying pressure. (a) Arc beam 1. (b) Arc beam 2.

4. CONCLUSIONS

In this paper, we investigated experimentally a pressure sensor relying on convective cooling of the air surrounding a heated arc MEMS resonator. The initially curved beams were electrothermally tuned and electrostatically driven. The resonance frequency increases up to twice its initial value while tuning the electrothermal voltage. While maintaining a constant electrothermal voltage, the pressure could be tracked by the cooling effect. We prove theoretically the concept of cooling using a multi-physics nonlinear finite element model. For higher electrothermal voltage, we demonstrated an increase in sensor sensitivity and a way to control the range of the sensed pressure. The range of sensing is showed to be from milli-Torres to 25 Torr. We demonstrated a sensitivity of 24634ppm/mbar that could be improved by scaling sown the device. In conclusion, we demonstrated a prototype of a pressure sensor that is simple in principle and design and offers the possibility of further miniaturization to the nanoscale. We expect also that by convenient thermal and electrical material properties, the sensitivity of the proposed pressure sensor could be improved.

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