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A CMOS-MEMS cantilever sensor for capnometric applications

Asif Mirza[1a)], **N. H. Hamid**[1], **M. H. Md. Khir**[1], **J. O. Dennis**[2], **Khalid Ashraf**[1], **Muhammad Shoaib**[1], **and Mohammad Tariq Jan**[1]

[1] *Department of Electrical and Electronic Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750, Perak, Malaysia*

[2] *Department of Fundamental and Applied Sciences, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750, Perak, Malaysia*

a) *assffg@gmail.com*

Abstract: Capnometers monitor the concentration of CO_2 in exhaled breath, which can be a life saving modality. High cost, big size and high power consumption of the conventional capnometers limit their scope and adaption. To overcome these issues, a CMOS MEMS microcantilever based CO_2 sensor is proposed for capnometric applications. The microcantilever is manufactured using CMOS MEMS technology and its critical parameters are analytically investigated. The optimized microcantilever has a quality factor, sensitivity and resolution of 3116, 16 mHz/ppm and 0.31 ppb, respectively.

Keywords: capnometers, CMOS-MEMS, CO_2 sensor, quality factor, microcantilever

Classification: Micro- or nano-electromechanical systems

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1 Introduction

Life-threatening conditions could be very well detected by the fast and dependable method of capnometry, whereby the concentration of CO_2 in the exhaled breath is monitored. Capnometry could in turn help to avoid potentially irreversible injuries to patients [1]. A few uses of capnometry include the observation of the breathing of patients suffering from cardiac arrest, dyspnea, asthma, pediatric trauma and receiving mechanical ventilation through an endotracheal tube. The conventional capnometers are based on the simplest form of spectroscopic sensors — the non-dispersive infrared (NDIR) sensors. However, the physical size, cost, complicated calibration procedures and the power consumption of these sensors restrict the technology considerably [2]. An alternative technology is therefore highly desirable to ensure adaption of the technique on a large scale in ambulatory services and home applications.

A microcantilever is a simple beam like structure whose one end is fixed and the other end is free to move [3]. A polymer layer coated on the microcantilever surface selectively adsorbs the target gas molecules. In the resonant mode of operation, the microcantilever is actuated at its resonance frequency and its frequency is monitored. The amount of gas adsorbed by the polymer layer can be detected as a shift in the resonance frequency.

In this paper, a COMS-MEMS microcantilever is investigated for its application as a capnometer. The fabrication, post-CMOS processing, analytical modeling and simulation based investigations of the resonance frequency and the mass sensitivity of our proposed microcantilever based sensor are discussed in our previous publications [4, 5, 6]. This paper focuses on the analytical modeling of the dependence of quality factor on the geometrical parameters of the microcantilever and the effect of the polymer thickness on the sensor gas sensitivity and resolution.

2 Design and fabrication of the microcantilever sensor

The microcantilever sensor is fabricated in 0.35 µm CMOS technology allowing two poly-silicon and three metal layers in MIMOS foundry, Malaysia. A coil of 36 turns is created in the metal-two layer in order to actuate the microcantilever electromagnetically using the Lorentz force. For vibration sensing, there are two types of integrated mechanisms, capacitive with comb fingers at the free end and piezoresistive with a fully differential Wheatstone bridge at the fixed end of the microcantilever. The final layout of the microcantilever sensor drawn in Cadence software and submitted to the foundry for fabrication is shown in Fig. 1(a) and the design parameters of the CMOS-

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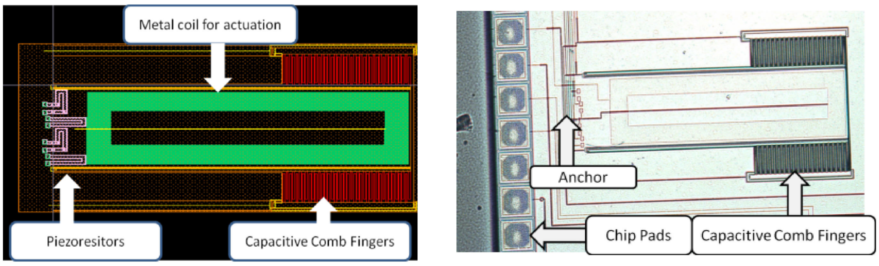
Table I. Device design parameters

Parameter	Microcantilever			Comb finger			
	Thickness	Length	Width	Length	Width	Spacing	Overlapping
Value (μm)	45	1000	300	100	6	3	90



(a) (b)

Fig. 1. The microcantilever sensor: (a) Layout in Cadence software, (b) optical image of the fabricated sensor.

MEMS microcantilever sensor are given in Table I. A photograph of the fabricated microcantilever obtained through an optical microscope is depicted in Fig. 1(b). Although a microcantilever can be fabricated in the top thin metal/oxide layers of the CMOS process, the residual stress mismatch between the different layers causes the released structure to curl. Curling of the structure not only offer challenges in polymer layer deposition, but also disturb the sensing and actuating mechanism. To avoid the undesirable curling of the structure, a thick layer of 40 μm silicon is attached underneath the microcantilever by using deep reactive ion etching (DRIE) technique [7]. The total thickness of the microcantilever including the thin metal/oxide layers is 45 μm.

3 Analytical modeling

In order to functionalize the microcantilever, it is coated with a thin layer of polymer [3]. The ratio of the equilibrium concentration of the analyte in the polymer (C_{poly}) and that in the ambient (C_{gas}) is represented by the partition coefficient K of the polymer, given as

$$K = \frac{C_{Poly}}{C_{gas}} \tag{1}$$

Using the above equation, the total mass loaded in a given coating volume of the polymer V_{poly}, can be written as

$$\Delta m = K C_{gas} V_{poly}. \tag{2}$$

The shift in the resonance frequency of a microcantilever due to mass loading can be expressed as

$$\Delta f = -\frac{1}{2}\frac{f_o}{m_{eff}}\Delta m \tag{3}$$

where m_{eff} is the effective mass of the microcantilever and the coated polymer

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layer, f_o is the initial resonance frequency with polymer coating. Using Eq. (2), the above equation can be rearranged as

$$\Delta f = -\frac{1}{2}\frac{f_o K V_{poly}}{m_{eff}} C_{gas} \tag{4}$$

where C_{gas} is the concentration (in the units of mass/volume) of the gas in the ambient. Using the general gas equation ($PV = nRT$), Eq. (4) can be modified as

$$S_{gas} = \left|\frac{\Delta f}{\Delta C_{ppm}}\right| = \frac{1}{2}\frac{f_o K V_{poly}}{m_{eff}}\frac{PM}{10^6 RT} \tag{5}$$

where S_{gas} represents the sensitivity of the sensor in the units of Hz/ppm, P is the pressure, n is moles of gas and R is the ideal gas law constant ($8.314\,\mathrm{Pa.m^3}$). T is the temperature in kelvins and M is the molar mass of the gas. The above equation gives sensitivity of the sensor and actual detectable minimum concentration of the analyte is further limited by mechanical and electrical noises. The mechanical noise floor depends upon the quality factor of the resonator, which measures its damping. The damping results in broadening of the resonance peak and hence the minimum detectable change in frequency is increased. Dissipation of energy in a resonator is associated with several mechanisms that are either intrinsic to the resonator or due to extrinsic processes. The quality factor of a resonator is given as [8]

$$Q = \frac{1}{2\zeta} \tag{6}$$

where ζ is the damping ratio. For a cantilever, the damping ratio can be expressed as

$$\zeta = \frac{\left(3\pi\mu b + \left(\frac{3}{4}\right)\pi b^2\sqrt{2\rho_a\mu\omega_n}\right)}{2\rho_b b^2 h\omega_n} + \frac{\mu b^2}{2\rho_b g_o^3 h\omega_n} + \frac{\eta}{2} + \frac{0.23h^3}{l^3} \tag{7}$$

where ρ_b is the density of the cantilever material, b is the width, h is the thickness, ω_n is the natural frequency of the cantilever, g_0 is the distance between the cantilever and any nearby rigid wall. In the packaged form, this distance is 350 µm. μ is the viscosity of air (1.8×10^{-5} Pas at STP) and η is the structural damping coefficient for silicon (5×10^{-6}).

Knowing the resonance frequency and the quality factor, the minimum detectable shift in the resonance frequency of the microcantilever can be expressed as [9]

$$\Delta f_{\min} = \frac{1}{X_o}\sqrt{\frac{f_o k_B T}{kQ^2}}. \tag{8}$$

Where $k_B = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant, k is the spring constant, X_o is the amplitude of oscillation, Q is the quality factor and T is temperature. The dynamic amplitude can be expressed as

$$X_0 = Q\frac{F}{k} \tag{9}$$

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where F is the force applied by the actuation mechanism and k is the spring constant of the microcantilever.

4 Results and discussion

As mentioned in Section 2, a 40 µm thick silicon is attached under the thin CMOS layers ($\approx 5\,\mu m$) using DRIE in order to control curling of the beam due to residual stress mismatches. The CMOS thin film layer is very small as compared to the thickness of the silicon. The material of the whole cantilever can be considered as silicon for modeling and optimization purposes [10]. For the beam thickness of 45 µm, MATLAB is used to optimize the corresponding length and width using Eq. (6). Initially, the microcantilever length is varied from 400 µm to 4000 µm, keeping the width at 300 µm. Whereas, in the second case, a surface area of $0.3\,mm^2$ is kept the same and the length is increased from 400 µm to 4000 µm. Finally, the length is fixed at 1000 µm while the width is changed from 50 µm to 4000 µm. For the first two cases, as shown in Fig. 2, the quality factor changes in quite a similar pattern. The quality factor increases from 1304 to 3289 for a length sweep from 400 µm to 820 µm. After a length of 820 µm, the quality factor starts to decrease gradually to reach its value of 795 at a length of 4000 µm. In shorter lengths ($l < 820\,\mu m$), support losses are dominant, whereas, at larger lengths ($> 820\,\mu m$) airflow forces are the cause of lowering the quality factor. In the third case, the quality factor is 2136 at width of 50 µm and it increases sharply to the highest value of 3116 for a width of 300 µm and then decreases to 1990 at a width of 4000 µm. The quality factor has a highest value of 3289 at the length to width ratio of 2.7:1 and length to thickness ratio of 18:1. For the currently fabricated microcantilever with a length and width of 1000 µm and 300 µm respectively, the quality factor is 3116. The resonance frequency of the fabricated microcantilever sensor is 57 kHz and effective mass is 7.5492 µg.

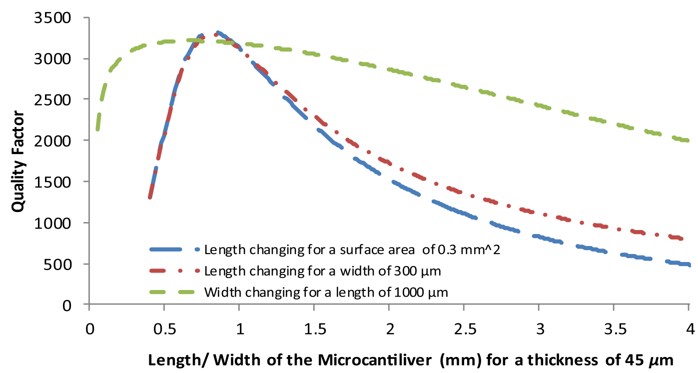

Fig. 2. Variation in quality factor with the change in length and width of the microcantilever.

Polyallyalamine is selected as the absorbent layer whose partition coefficient K is 3000 [11] and density is $0.7630\,g/cm^3$. Considering that the sensor works at the room temperature of 298 K, CO_2 with molar mass of 44 g as the analyte, the shift in resonance frequency is calculated for different polymer

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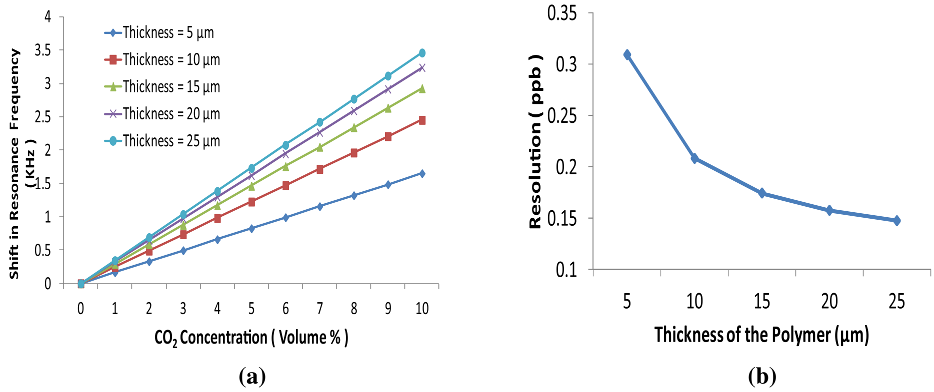

Fig. 3. **(a)** Resonance frequency shift with CO_2 concentration at different polymer thickness, **(b)** Resolution of the sensor with variation in thickness of the polymer.

thicknesses using Eq. (5). As shown in Fig. 3(a), the sensor response to gas concentration is linear and the shift in resonant frequency for polymer thicknesses of 5 µm, 10 µm, 15 µm, 20 µm and 25 µm are 1.6 kHz, 2.4 kHz, 2.9 kHz, 3.2 kHz and 3.4 kHz, respectively at 10% V of CO_2. The gas sensitivity of the sensor on these polymer thicknesses are 16 mHz/ppm, 24 mHz/ppm, 29 mHz/ppm, 32 mHz/ppm and 34 mHz/ppm, respectively. It may be noted that the gas concentration range used in this study (0–10% V) is the normal sensor measuring range for commercial capnometers [1].

From Eq. (8), the minimum detectable shift in the resonance frequency is found to be 5.1 µHz. It may be noted that the dynamic amplitude is calculated to be 2.7 µm using Eq. (9) for an achievable electromagnetic force of 1 µN [6]. The values of the minimum detectable shift in the resonance frequency and sensitivity are used to find the senor gas resolution. Fig. 3(b) shows the resolution of the sensor for different polymer thicknesses. The sensor gas resolution values change from 0.31 ppb to 0.15 ppb when the polymer layer thickness is varied from 5 µm to 25 µm. In the tested range, a larger thickness of the polymer gives a better resolution. However, viscoelastic losses in the polymer layer may affect the quality factor of the resonator and hence limit the actual resolution of the sensor for large polymers thicknesses. The resolution of 0.31 ppb achieved at a very small thickness of 5 µm (giving a ratio of 1:9 for polymer layer thickness to silicon layer thickness) is sufficient for capnometric applications.

5 Conclusion

A CMOS-MEMS microcantilever is proposed for capnometric applications. The microcantilever with a length of 1000 µm, a width of 300 µm and thickness of 45 µm has a quality factor of 3116. With a polymer layer thickness of 5 µm deposited as the active material, and a dynamic force of 1 µN acting at the resonance frequency of the sensor, the proposed sensor has a gas sensitivity of 16 mHz/ppm and resolution of 0.31 ppb. The achieved resolution and sensitivity are appropriate for capnometric applications.

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