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A Double-Ended Tuning Fork Based Resonant Pressure Micro-Sensor Relying on Electrostatic Excitation and Piezoresistive Detection †

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† Presented at the Eurosensors 2018 Conference, Graz, Austria, 9–12 September 2018.

Published: 27 November 2018

Abstract: This study proposes a microfabricated resonant pressure sensor based on electrostatic excitation and low-impedance piezoresistive detection in which a pair of double-ended tuning forks were utilized as resonators for differential outputs. In operations, targeted pressures deforms the pressure-sensitive membrane, resulting in stress variations of two resonators, leading to shifts of the intrinsic resonant frequencies, which were then measured piezoresistively. The developed microfabricated resonant pressure sensor was fabricated using simple SOI-MEMS processes and quantified in both open-loop and closed-loop manners, where the quality factor, differential sensitivity and linear correlation coefficient were quantified as higher than 10,000, 79.4 Hz/kPa and 0.99999, respectively. Compared to previous resonant piezoresistive sensors, the developed device leveraged single-crystal silicon as the piezoresistor, with advantages in simple sensing structures and fabrication steps. Furthermore, the differential setup was adopted in this study which can further improve the performances of the developed sensors.

Keywords: double-ended tuning fork; resonant pressure micro-sensor; electrostatic excitation; piezoresistive detection; differential resonators

1. Introduction

Resonant pressure micro-sensors are featured with quasi-digital outputs, which rely on electrostatic/electromagenetic/electrothermal excitations and capacitive and piezoresistive detections [1]. The electrostatic excitation can be realized easily without the requirement of magnets, and is convenient for integrations while piezoresistive sensing reduces influences from parasitic capacitors and increases the ratios of signal to noise in comparison to capacitive detections [2]. However, previously reported resonant sensors based on electrostatic excitation and piezoresistive detection suffered from complicated structures and fabrication processes due to the limitations in the structure of the piezoresistor [3].

In order to address this issue, in this study, the resonators of the proposed pressure micro-sensor were electrostatically driven into oscillation and sensed by low-impedance piezoresistive detection where single-crystal silicon was used as the piezoresistor, which is featured with low DC biased voltages, simple sensing structures (see Figure 1) and fabrication steps. The proposed device was fabricated by SOI MEMS where a wafer-level vacuum packaging with silicon-to-glass anodic bonding was utilized to form a sealed vacuum chamber, and through-silicon-vias were formed for electrical feed-through. The fabrication flow of the developed resonant pressure micro-sensor is shown in Figure 2. Figure 3 shows the open-loop and closed-loop characterization results of the fabricated resonant pressure micro-sensors producing a quality factor higher than 10,000, a sensitivity of 79.4 Hz/kPa and a non-linearity error less than 0.01%.

2. Device Design and Fabrication

Figure 1a,b show the schematic of the resonant pressure sensor which mainly consists of a pressure-sensitive membrane, double resonators featured with double-ended tuning forks and several electrodes. The function of the pressure-sensitive membrane is to sense the outside pressure under measurement and transfer to the stress distributions of the resonators. The thickness of the pressure-sensitive membrane contributes reversely to the sensitivity of the sensor chip. Two resonators clamped on the membrane are positioned on the central and side areas of the membrane respectively, which are named as "central resonator" and "side resonator". In individual resonator, double-ended tuning forks are used as resonators, which are driven to vibrate due to electrostatic forces generated by the driving electrodes and the resonant beams. The piezoresistors are positioned at the end of the resonant beams to sense the buildup of the stress.

The working principle of the resonant pressure micro sensor relying on electrostatic excitation and piezoresistive detection is that pressure under measurement causes the deformation of the pressure-sensitive membrane, leading to stress buildup of the resonator with corresponding shift of the resonant frequency, which was detected by both open-loop and closed-loop circuits. Note that a differential design was used in this study, which can further increase the sensitivity and linearity of the pressure sensor.

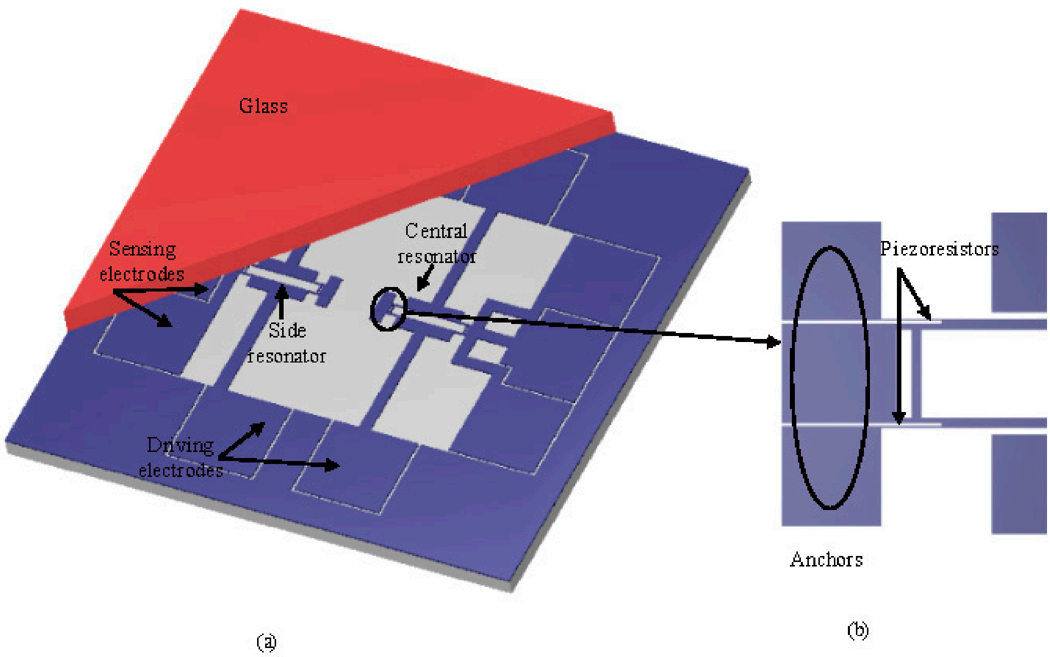

Figure 1. Schematic of the resonant pressure micro-sensor (**a**) relying on electrostatic excitation and piezoresistive detection (**b**) where double-ended tuning forks were used as resonators.

The sensor chips were fabricated by conventional SOI-MEMS processes based on a 4-inch SOI wafer. Figure 2 shows the fabrication flow of the developed resonant pressure micro-sensor. In the first step, the pressure-sensitive membrane and through-silicon vias were etched by DRIE (Deep Reactive Ion Etching). Next, DRIE was also used to pattern the resonators. Then, the resonators were released using an HF buffer. In the fourth step, a getter material was sputtered into glass covers. In the next step, silicon-to-glass anodic bonding was realized to form a vacuum chamber for resonators.

In the end, Al was sputtered into through-silicon vias to form electrical connection with the surrounding circuits

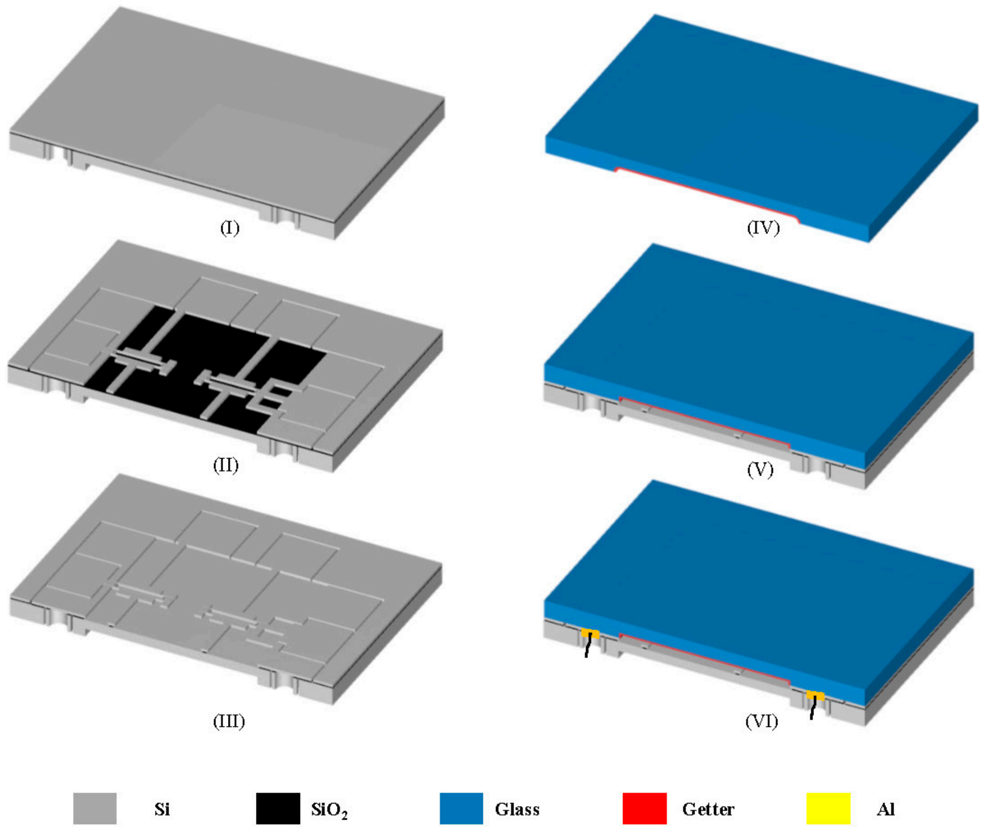

Figure 2. The fabrication flow chart of the proposed resonant pressure micro-sensor includes key steps of (**I**) formation of the pressure-sensitive membrane and through-silicon vias by DRIE; (**II**) patterning of the resonator by DRIE; (**III**) release of the resonator using an HF buffer; (**IV**) deposition of getter material on glass covers, (**V**) silicon-to-glass anodic bonding; (**VI**) formation of electrical connections.

3. Device Characterization

The fundamental frequency and the quality factor of the proposed resonant pressure sensors were tested using E5601B Network Analyzer (Agilent, Santa Clara, CA, USA) in an open-loop manner. Figure 3a shows the open-loop results of a typical resonant pressure micro-sensor where its quality factor was quantified higher than 10,000, suggesting that the fabrication process can produce an environment of high vacuum for the resonators. Figure 3b shows the closed-loop results of a resonant pressure micro sensor where the resonant frequencies of the central and side resonator were observed to increase and decrease, respectively, in response to an increase in pressure under measurement. The sensitivities of the central and side resonators are 44.34 Hz/kPa and 35.11 Hz/kPa respectively The differential output of the resonant pressure micro sensor, was characterized to produce a sensitivity of 79.45 Hz/kPa, a non-linearity error less than 0.01%, and a pressure detection range of 10–150 kPa.

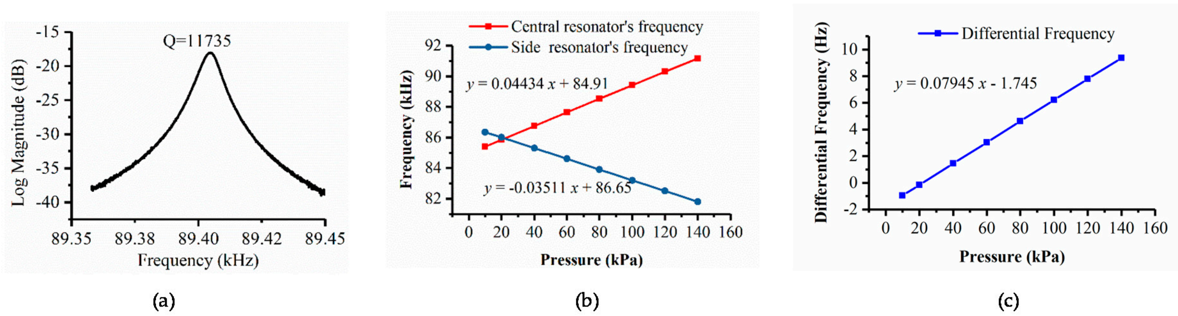

Figure 3. (**a**) The open-loop result of a typical resonant pressure micro-sensor where the quality factor was quantified as 11735, validating the fabrication process, which can produce an environment of high vacuum for the resonators; (**b**) The closed-loop result of a resonant pressure micro-sensor where the resonant frequencies of the central and side resonator were observed to increase and decrease, respectively, in response to an increase in the pressure under measurement; (**c**) The differential output of the resonant pressure micro-sensor, producing a sensitivity of 79.45 Hz/kPa, a linearity less than 0.01%, and a detection range of 10–150 kPa.

4. Conclusions

A resonant pressure micro-sensor based on electrostatic excitation/piezoresistive detection was developed where a differential mode of positing two resonators on the central and side areas of the pressure-sensitive membrane was adopted to increase the performance of the sensors. In each resonator, the piezoresistors are positioned at the end of the resonant beams to sense the buildup of the stress. Conventional SOI-MEMS processes were used to fabricate the sensor chips. The open-loop test indicated the quality factor of the prototype sensor was higher than 10,000. Furthermore, the closed-loop test characterized the sensitivity of the central resonator, the side resonator and the differential mode, which were 44.34 Hz/kPa, 35.11 Hz/kPa and 79.45 Hz/kPa respectively with a pressure range of 10 kPa–150 kPa. The linear correlation coefficient of the prototype sensor was 0.99999.

Acknowledgments: The authors acknowledge financial supports from National key research and development plan (Grant No. 2018YFF01010401), National Basic Research Program of China (Grant No. 2014CB744600), National Natural Science Foundation of China (Grant No. 61431019, 61372054), National Key Foundation for Exploring Scientific Instrument (No. 2013Y12035703), and Natural Science Foundation of Beijing (4152056).

Conflicts of Interest: The authors declare no conflict of interest.

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