

Modelling and characterisation of a micromachined resonant pressure sensor with piezoelectric excitation and sensing

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A resonant pressure sensor with piezoelectric excitation and sensing is presented, which is realised by combining a micromachined diaphragm and a quartz resonator. The sensor performance is improved by introducing double enhancement beams into the diaphragm. Finite element method is utilised to reveal the validity and optimise the structural dimensions. A self-excitation circuit is designed to drive the resonator into steady oscillation. The sensor chip is fabricated by bulk micromachining technologies and packaged in a metal shell in the inert gas environment for characterisation. The performance characteristics including the short-term drift, temperature characteristic and quality factor are investigated. The experimental results demonstrate that the sensor features a high sensitivity of 100.45 Hz/kPa and a short-term drift <14 ppm in the operating range of -10~10 kPa at room temperature. Owing to the excellent performance in sensitivity and accuracy, the sensor can be applied for micropressure measurement.

1. Introduction: Benefited from the quasi-digital output, resonant sensors gain major advantages over analogue output sensors in the aspect of accuracy, resolution and reliability [1–3]. With regard to this kind of sensors, they are basically required to drive the resonators into vibration to obtain the resonance frequency [4]. To achieve this goal, various excitation and detection techniques have been investigated in the literature. A typical method is piezoelectric actuation and sensing, which is remarkably distinguished from other electrostatic or thermal mechanisms for its linear behaviour, low-power consumption and short response time [5].

In the fields of resonant sensors, various types of piezoelectric resonators were managed to achieve high performance. Typically, these resonators were manufactured by depositing piezoelectric thin films such as AlN, ZnO or PZT on resonant beams or diaphragms [6, 7]. However, their piezoelectric coefficients were greatly affected by the crystal orientations. One of the major bottlenecks was to ensure the reproducibility and high orientation of the thin films in the process of deposition. Another unfavourable factor was that two separate piezoelectric patches had to be used for excitation and detection of the resonance frequency [8]. By contrast, quartz resonators could be mass-produced with low cost on the microscale, which were simultaneously used for actuation and sensing with a simple self-oscillation circuit [9]. So far, quartz resonators have already been employed in pressure sensing application. Typically, those resonant pressure sensors were implemented by incorporating quartz tuning forks with metal bellows and flexure hinge [10]. Another approach was an adoption of all-quartz structure that worked in the thickness-shear mode [11]. Though these innovations have achieved high accuracy and even been commercialised, the drawbacks such as large volume, high cost and low processing efficiency greatly restrict the application fields and somewhat hinder their development.

Considering the research status of the quartz resonator-based pressure sensors, a novel structure by combining micromachined diaphragm and quartz resonator is proposed in this Letter. Instead of using conventional metal bellows or corrugated diaphragms, the diaphragm is based on bulk micromachining technologies, which can be fabricated precisely and efficiently. Meanwhile, simple excitation and relatively high-quality factor can be achieved as a result of the favourable properties of the quartz resonator. By

incorporating enhancement beams into the diaphragm, the sensitivity and linearity are expected to be improved. To verify the scheme, structural optimisation and experiments are implemented.

2. Design

2.1. Design principle: The sensor is designed on the basis of the force-frequency characteristic of a quartz resonator: namely, the linear relationship between the resonance frequency and axial stress. This favourable property provides theoretical guidance for the sensor design. Owing to the symmetric construction, double-ended tuning fork (DETF) is recognised as an ideal structural type with high-quality factor. By taking this form, a quartz DETF is expected to achieve satisfactory performance. The fabrication can be effectively guaranteed by adopting the mature micromachining technologies of quartz crystal oscillators. Herein, quartz DETF is utilised as the sensitive element for pressure measurement in this Letter, as shown in Fig. 1.

For the clamped-clamped tines of the quartz DETF, the relationship between the resonance frequency and axial stress can be expressed by the following equation [12]

$$f = \frac{1.027w}{l^2} \sqrt{\frac{E}{\rho}} \left(1 + \frac{0.147l^2}{Ew^2} \cdot \sigma \right) \quad (1)$$

where w , l are the width and length of the tines, respectively; E is the elasticity modulus of quartz crystal; ρ is the density; and σ is the axial stress in the tines.

According to (1), the resonance frequency is highly subjected to the stress-frequency coefficient. Once the dimensions are determinate, the resonance frequency entirely depends on the internal stress of the quartz DETF. Thus, apart from the quartz DETF resonator, an elastic element is essential as well to convert the applied pressure into axial stress to generate frequency shift. In consideration of the excellent mechanical properties and high-accuracy microstructure, silicon diaphragm is employed for pressure sensing. To improve the frequency stability, it is better to constrain the resonator to motion only in one degree of freedom [13].

2.2. Structure design: The geometry model of the sensor chip is established, as schematically shown in Fig. 2. One end of the

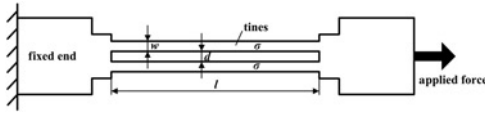


Fig. 1 Schematic diagram of the quartz DETF

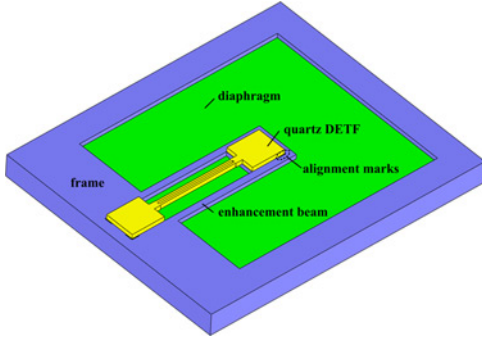


Fig. 2 Schematic diagram of the resonant pressure sensor

quartz DETF is anchored on the frame while the other end is vertically movable on the centre of the diaphragm. When external pressure is applied to the back side of the diaphragm, the quartz DETF is in compression with a linear frequency shift as a result of the vertical displacement.

To reduce the energy loss caused by gas damping, the quartz DETF is excited to resonate in anti-phase vibration through the inverse piezoelectric effect [14]. In this case, the resonator is under the effect of slide-film damping, where a high-quality factor is expected to be obtained because of the relatively small energy loss. The devised sensor is aimed at providing a cost-effective scheme for micropressure measurement with a range of $-10 \sim 10$ kPa. To enhance the sensitivity, the structural parameters such as width and length of the tines are optimised. The final dimensions are determined on the basis of the theoretical formula of (1) with the existing processing capacity taken into consideration simultaneously. The total length of the quartz DETF is determined as 7.5 mm, and the overall size of diaphragm is defined by $13 \times 11 \text{ mm}^2$ to fit with the dimensions.

As a key parameter that affects the resonance frequency and sensitivity, axial stress is selected as the evaluation index for structure optimisation. ANSYS software is utilised to optimise the dimensions through detecting the axial stress in the tines. The relationship between the absolute value of axial stress and the thickness of the diaphragm is depicted in Fig. 3. It can be observed that sensitivity can be typically enhanced by decreasing the thickness, but excessive thin diaphragm will deteriorate the linearity for the large

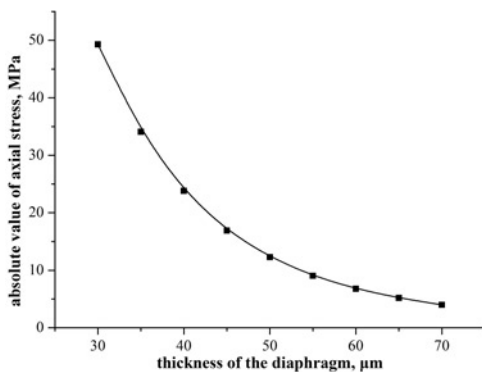


Fig. 3 Axial stress in the tines against thickness of the diaphragm

deflection. In this circumstance, two enhancement beams are introduced into the diaphragm to decrease the deformation for linearity improvement. The beams can configure on identical side of the quartz DETF or on the opposite side (dashed line), as shown in Fig. 4. To verify the validity and evaluate the effectiveness of these two cases, comparative analysis is carried out. The variation tendency of the absolute value of axial stress in the tines is shown in Fig. 5, where the stress is compressive on the same side and tensile on the opposite side. From these curves, all the stress increases evidently with the width and thickness of the beams (w_0 remains constant). The beams configured on the same side can achieve higher sensitivity. When the width of the beams exceeds 300 μm , the axial stress almost tends to be stable. The axial stress increases continuously from 3 to 18.5 MPa, whereas the thickness of the beams changes from 20 to 150 μm . Hence, by raising the width or thickness, sensor sensitivity can be enhanced; meanwhile, the gas damping will diminish greatly as a result of the larger spacing for vibration. In accordance with the expected measurement range and processing capability, the ultimate dimensions are determined and listed in Table 1.

2.3. Excitation circuit design: As a tuning-fork-type structure, the quartz DETF features similar characteristics with crystal oscillators in terms of mechanical and electrical properties. When the resonator is vibrating near the natural frequency, the mechanical resonance state is equivalent to a second-order series resonance circuit, as shown in the dashed box in Fig. 6. This means that the quartz DETF is not only a micromechanical

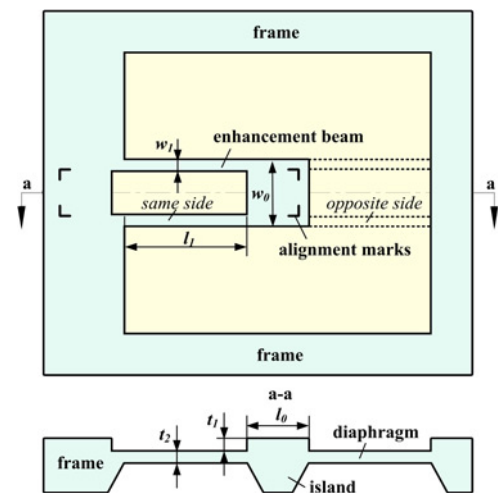


Fig. 4 Schematic diagram of the silicon diaphragm

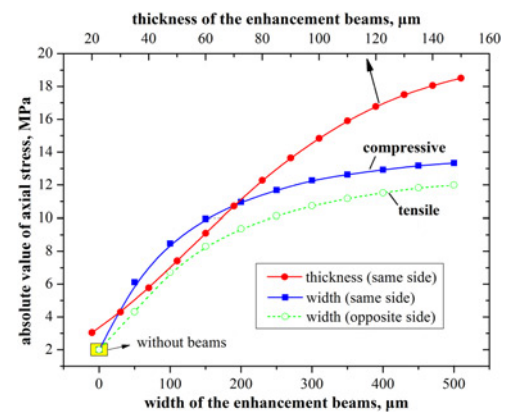
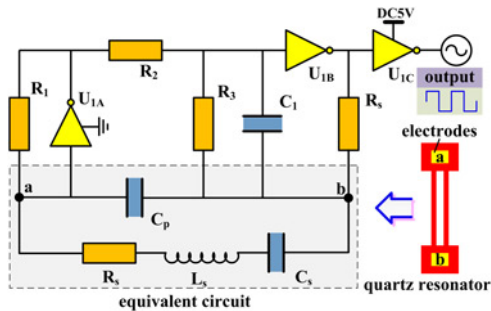


Fig. 5 Impacts of the enhancement beams on the axial stress in the tines

Table 1 Dimensions of the sensor chip

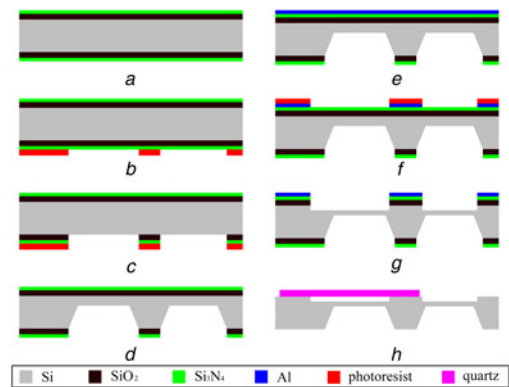
Parameter	Description	Value, μm
W	width of the tines	90
d	spacing between the tines	90
l	length of the tines	3700
w_1	width of the enhancement beams	300
t_1	thickness of the enhancement beams	100
t_2	thickness of the diaphragm	50
l_1	length of the enhancement beams	3780

**Fig. 6** Schematic diagram of the self-excitation circuit for testing

resonator, but also an electrical element as part of the resonant loop. In the electromechanical coupling system, the dynamic resistance (R_s), dynamic inductance (L_s) and dynamic capacity (C_s) of the circuit are corresponding to the mass, vibration damping and elasticity of the quartz DETF, respectively. C_p represents the static capacitance between the two electrodes configured on the tines. Accordingly, an excitation circuit is devised to constitute a resonant loop for sustained oscillation. The resonance frequency can be obtained by detecting the frequency of the circuit in steady state. To achieve self-excitation oscillation, the balance condition of phase and amplitude should meet certain criteria (*i.e.* Barkhausen conditions). Herein, two phase inverters are used to form a 360° phase shift to satisfy the requirement of phase. Feedback resistances are introduced to make the inverters work in the linear regions and function as amplifiers at the same time, thus the amplitude condition is satisfied as well. The schematic diagram of the self-excitation circuit is shown in Fig. 6, where the power supply is 5 V DC voltage without other incentive signals. An additional inverter (U_{1C}) is involved in this circuit for reshaping the output signals. Under the action of the phase inverters and resistors, the feedback loop can ensure stable oscillation in a specific frequency with steady square signal output.

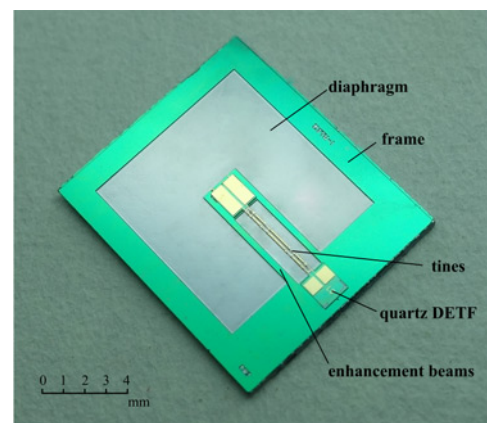
3. Experiment

3.1. Fabrication: The manufacturing method of the quartz DETF was quite similar to the crystal oscillators, where the standard fabrication processes such as wet etching and evaporation were adopted. Herein, the specific process flow was omitted [15]. The diaphragm was fabricated basing on the bulk micromachining technologies from an *n*-type (100) silicon wafer whose thickness was $450\ \mu\text{m}$, where two masks were required for patterning. The specific fabrication process flow of the sensor chip was illustrated in Fig. 7. (a) The $3000\ \text{\AA}$ thick SiO_2 layers were grown on both sides of the wafer by thermal oxidation, followed by the deposition of $1000\ \text{\AA}$ thick Si_3N_4 layers using low-pressure chemical vapour deposition. (b) Photolithography was implemented on the back side of the wafer to pattern the island, with subsequent exposure and development of the photoresist. (c) The passivation

**Fig. 7** Main fabrication process of the sensor chip

layers of Si_3N_4 and SiO_2 on the particular regions of back side were etched successively by means of inductively coupled plasma (ICP) technique. (d) For the purpose of creating a cavity and forming an island, KOH anisotropic etching was carried out on the back side with an etching rate of $1.0\ \mu\text{m}/\text{min}$. (e) Magnetron sputtering process was performed to deposit Al coating on the front side of the wafer as a protective layer. (f) After the procedures of photolithography and development, the exposed Al layer was etched with a corrosive liquid of phosphoric acid. (g) ICP etching technology was utilised to form the enhancement beams on the front side, where the diaphragm was simultaneously completed with an expected thickness of $50\ \mu\text{m}$. Then, the useless coatings on the surface such as Al layer, Si_3N_4 and SiO_2 were etched. (h) On a high-precision bonding machine, the prepared quartz DETF was gingerly attached to the diaphragm with special glue. In this step, the island on the back side of diaphragm can effectively prevent the resonator from being destroyed in the bonding process. With the aid of the alignment marks, the quartz DETF was adjusted to be aligned with the diaphragm through the microscope. Then, annealing was carried out to make the glue distribute evenly and eliminate the residual stress. The sensor chip was gradually heated to 200°C and cooled to room temperature inside a furnace, thus the fabrication process was finished. The photograph of the fabricated sensor chip was shown in Fig. 8.

3.2. Packaging: To reduce fabrication cost and avoid certain unreliability, the quartz DETF was encapsulated in the inert gas instead of vacuum packaging. The sensor chip was simply packaged in a metal shell for characterisation, as schematically shown in Fig. 9. For the purpose of reducing the influence of packaging stress, a substrate was involved to isolate the sensor

**Fig. 8** Photograph of the fabricated sensor chip

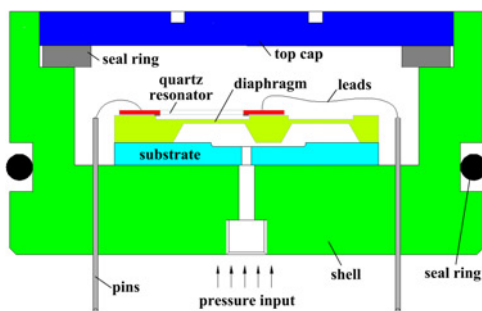


Fig. 9 Packaging scheme for testing

chip from the shell. On this substrate, a 40 μm thick groove was etched on the front side to avoid possible interference with the island. A tiny hole was processed as the pressure inlet. Two pins were fixed on the shell to constitute an electrical connection between the sensor chip and exterior excitation circuit. Metal leads were welded to the solder pads on the quartz resonator and the pins by using wire bonding technology. Finally, the top cap was bonded to the shell in inert gas environment, where a seal ring was utilised to maintain a hermetical cavity.

3.3. Experimental setup: To investigate the static performance of the sensor, an experimental setup was established for calibration by using the excitation circuit as shown in Fig. 10. During the course of experiments, atmospheric pressure provided by a miniature piston manometer is applied to the back of the diaphragm to generate axial stress in the tines. The standard pressure source was controlled to change with an interval of 1 kPa. The test was implemented at room temperature and the output signals were recorded on a high-accuracy frequency meter.

4. Results: The measured data were processed on the basis of least-square linear fitting as shown in Fig. 11, where the loading and unloading process showed satisfactory agreement. To observe more clearly, a partial enlarged drawing was given. From this curve, it could be found that the sensor performed well in terms of linearity and hysteresis. The resonance frequency varied from 39.6468 to 37.6557 kHz with the pressure ranging from -10 to 10 kPa, which showed fairly good agreement with the values obtained by the simulation calculation. The sensitivity of the sensor was calculated as 100.45 Hz/kPa. The nonlinearity was 0.028% in the range of $-8 \sim 8$ kPa, which increased to 0.041% from -10 to 10 kPa. The hysteresis was $\sim 0.039\%$ FS.

To investigate the anti-interference performance, vibration tests were carried out by hammering and shaking the package shell. The experimental results were shown in Fig. 12, where the maximum deviation of the resonance frequency was approximately

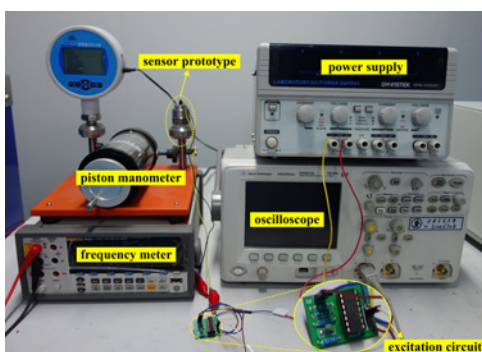


Fig. 10 Experimental setup for calibration

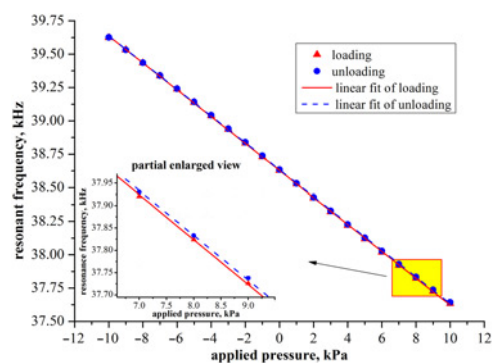


Fig. 11 Calibration results of output frequency against applied pressure

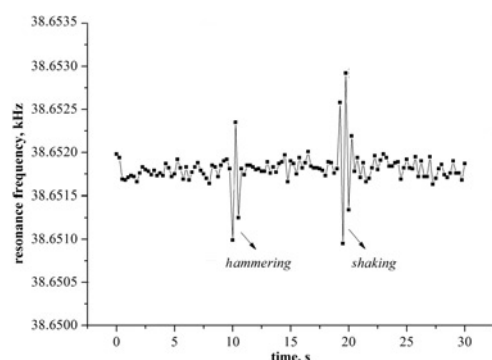


Fig. 12 Impact of the external vibration interference

equivalent to a pressure of 12 Pa. Testing results indicated that external vibration interference had relatively small influence on the sensor performance, mainly attributed to the introduction of the enhancement beams. Under the condition of non-vibration environment, the natural frequency was fluctuated within 14 ppm, which showed good short-term drift. In addition, the temperature characteristic of the sensor was also investigated, as shown in Fig. 13. The relation curve between the rate of frequency change and the testing temperature showed a steady increase trend within the range of $0 \sim 80^\circ\text{C}$. The relative change of natural frequency was $\sim 0.26\%$ when the temperature fluctuated 10°C .

The quality factor of the pressure sensor was measured by using an impedance analyser to obtain the equivalent electrical parameters. The measurement results of the dynamic resistance (R_s) and dynamic capacitance (C_s) were 1.42 M Ω and 1.8 fF, respectively. According to the formula of resonant circuit, the

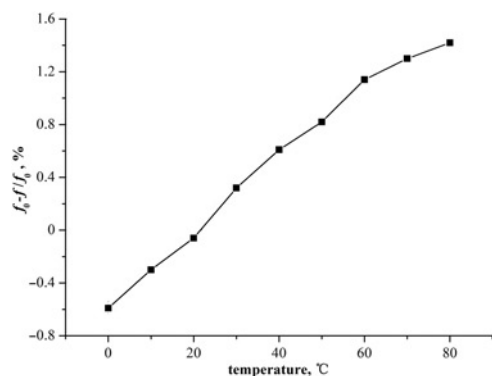


Fig. 13 Temperature characteristic of the pressure sensor

quality factor was calculated as

$$Q = \frac{1}{2\pi/R_s C_s} = 1612 \quad (2)$$

Both the experimental and simulation results of the frequency response curves were shown in Fig. 14. In the simulation process, only gas damping was taken into consideration. The simulation value and experimental value of quality factor were 5680 and 1612, respectively, which showed a relative error as high as 71.6%. The performance indicators of the devised pressure sensor were summarised and listed in Table 2.

A comprehensive comparison is made between the sensor of this work and the recent publications, as shown in Table 3. The comparison shows that the proposed sensor features relatively high performance regarding sensitivity and linearity.

5. Discussion: Owing to the favourable mechanical properties of the quartz DETF and the precise microstructure of the diaphragm, the proposed sensor has demonstrated high sensitivity and high linearity. Meanwhile, simple excitation and relatively high-quality factor are achieved. Nevertheless, the quality factors show significant inconsistency between the measured value and simulation value. The reason may be caused by having neglected the impacts of internal structural damping and practical processing in the simulation analysis. Moreover, in view of the temperature interference on the sensor performance, measures have to be taken for improving the accuracy in variable temperature conditions. A feasible solution is to establish a fitted curve equation between resonance frequency f and temperature T and adopt algorithm for temperature compensation. As both the applied pressure p and temperature T are related to the resonance frequency f , the temperature interference can be decoupled from the superposed equation $f(p, T)$. The second solution is to develop a differential approach for compensation, which can be achieved by introducing an additional sensor chip without

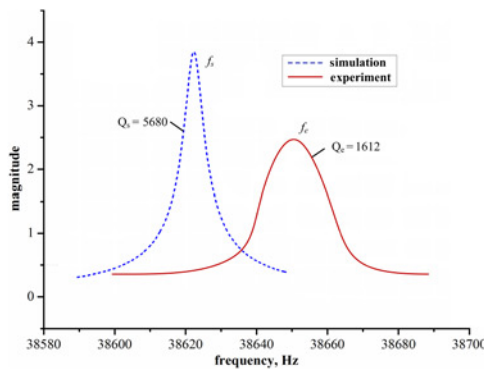


Fig. 14 Simulation and experimental results of frequency response (not to scale)

Table 2 Performance of the pressure sensor

Parameter	Value
reference temperature, °C	22
short-term drift, ppm	14
sensitivity, Hz/kPa	100.45
nonlinearity, %FS	0.041
hysteresis, %FS	0.039
quality factor	1612
frequency–temperature coefficient, %/°C	0.026

Table 3 Comparison with other resonant pressure sensors reported in the literature

Reference	Material of resonators	Sensitivity, Hz/kPa	Nonlinearity, %FS
this work	quartz crystal	100.45	0.041
[2]	silicon-on-insulator	180.1	0.2
[3]	silicon-on-insulator	20.77	0.045
[7]	PZT thick film	2.5–2.9	not given
[16]	silicon-on-insulator	34.8	not given

pressure inlet as a frequency reference. With both chips packaged in the same shell, the influences of external interferences such as temperature and vibration can be effectively eliminated. Alternatively, the diaphragm is fabricated using the same material of quartz crystal to avoid temperature drift caused by the mismatch of temperature coefficient. Currently, the deep etching process of quartz crystal is being studied in the hope of obtaining uniform quartz diaphragm. Future work will be focused on reducing the temperature sensitivity for improving the comprehensive performance.

6. Conclusion: In this Letter, a novel structure of quartz resonant pressure sensor is proposed by designing a micromachined silicon diaphragm as the elastic element. The sensor performance is improved by incorporating double beams into the bossed diaphragm, and the validity is verified by ANSYS simulation. The sensor chip is fabricated basing on standard micromachining technologies and necessary experiments are performed to characterise the sensor performance. A simple self-oscillation circuit is designed and proved to be effective for excitation. The sensitivity is 100.45 Hz/kPa and the nonlinearity is 0.041%FS. Testing results reveal the feasibility of the scheme, which provides an applicable solution for micropressure measurement.

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