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Design and Experiment of a Laterally Driven Micromachined Resonant Pressure Sensor for Barometers

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Abstract

A novel resonant pressure sensor based on electromagnetically driven and sensed H-type lateral beam resonators is described and FEA simulation is carried out on the analysis of the sensitivity, linearity and temperature drift of the pressure sensor. The resonant elements consist of four clamped-clamped boron diffused silicon beams (30 µm in thickness) organized along the diagonal direction suspended on a silicon square diaphragm, the differential output of two of which provides the sensor reading. The beams and the diaphragm are fabricated by bulk micromachining techniques in one wafer, which is then bonded to another supporting silicon wafer in vacuum, leaving the resonant beams exposed to the pressure media. The cleaved sensor die is mounted to the metal package by fixing the die only at a corner through stacks of small silicon dies with epoxy. The proposed pressure sensor has advantages such as low cost, ease of fabrication and high performance, making it suitable for barometers.

Keywords: Resonant pressure sensor ; Electromagnetical exitation ; Lateral beam resonator; Barometers

1. Introduction

Silicon resonant pressure sensors have been well development and widely used in the automotive industry, medical, aerospace, military, and industry control application due to their high sensitivity, high linearity, high long term stability and ease of signal processing. However, to achieve these merits, resonant pressure sensors are commonly isolated from the environment by vacuum sealing and require careful packaging to prevent undesirable external influences. For vacuum packaging, complex process, electrical feedthroughs to the outside and stress-relieving packaging designs become a challenge problem, which adds the cost and complexity of packaging [1-5]. Our previous works adopt tri-resonator structures [6, 7], exhibiting poor nonlinearity and large temperature drift due to unbalance of the sensitivities of the central beam and the side beams and the package induced stress.

To improve the performance and simplify the fabrication and packaging process, this paper proposes a novel design and provides the fabrication and packaging methods. The boron diffused silicon layer and the bulk silicon are used as the resonant beam and pressure membrane respectively. Electromagnetic excitation and detection are used for the sensor to drive the resonant beam to enhance the signal of the sensor, which can make the close-looped

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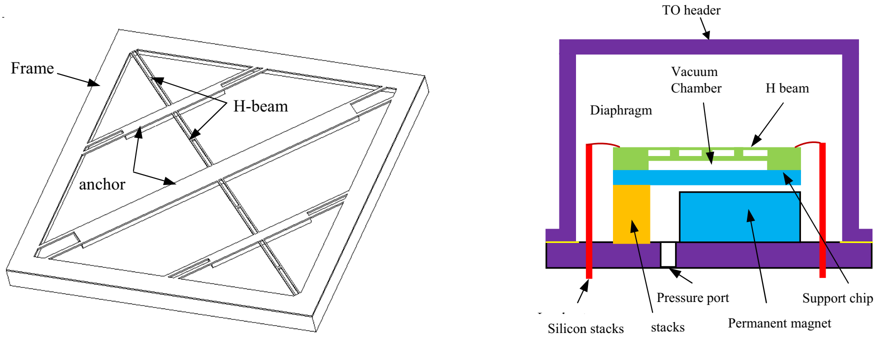
control for the sensor easily. The proposed sensor is successfully made by bulk micromachining and BCB adhesive bonding techniques and the experimental results indicate improved sensitivity, linearity, and temperature stability.

2. Device design



(a) sensor chip

(b) Package design

Fig. 1. Schematic of a novel design with the beam exposed to pressure media. (a) sensor chip; (b) package design

The schematic diagram of the new resonant pressure sensor is shown in Fig. 1. Fig.1 (a) is the schematic of a sensor chip. The resonant elements consist of four clamped-clamped beams suspended on a silicon square diaphragm by three anchors and a silicon rectangular frame, which are organized symmetrically along the diagonal direction. The two beams located near the center of the diaphragm are called central beams and the other two near the silicon frame are called side beams. Both central beams and side beams have almost identical sizes, and are expected to have nearly equal resonant frequencies at zero pressure loads. When a pressure is applied on the diaphragm, the central beams induces an axial tensile stress which increases the resonant frequency while the side beams an axial compressive stress leading to decrease of the resonant frequency. In work, only one pair of beams (consisting of a central beam and a side beam) is needed to be exited into resonance to measure the applied pressure by working out the difference of the two resonant frequencies of the pair. Because the measurement is based on the frequency difference, if there is ambient temperature influence, the frequency drift induced on both beams will be the same. The frequency difference will be unchanged, guaranteeing a temperature independent pressure sensing. Thick boron diffused silicon (30 μm in thickness) H-type beams are used as resonators so that they can work in a lateral mode to minimize the mechanical coupling between the diaphragm and resonator as their fundamental resonant modes are perpendicular. Fig.1 (b) is the schematic of the novel overall package design. The sensor chip is bonded to a supporting silicon wafer by wafer-level adhesive bonding in a vacuum to form a sealed chamber for a zero-pressure reference, with the resonant beams exposed to the pressure media rather than working in vacuum, and the chip die is mounted to the metal package by fixing the die only at a corner through stacks of small silicon dies with epoxy to release package stress. By FEA simulation Several design aspects of the sensor are analyzed, including the pressure induced stress distribution, damping effects and the influence of geometrical structure on the pressure performance. Fig.2 gives the plot of the FEA simulated resonant frequency versus applied pressure. Differential output (f_1-f_2) with nearly balanced sensitivities of two beams improves nonlinearity.

3. Experiments

The device is fabricated in one piece from single crystal silicon by MEMS technology and the boron diffused silicon beams are released by undercutting in KOH etching solution. The fabrication process is shown in Fig.3. The starting materials are 3 inch <100> 300μm silicon wafers, with boron diffused silicon 30 μm in thickness.

First, a thin silicon oxide (100nm) and a thin SiN film (100nm) are grown on both side of the wafer by thermal oxidation and LPCVD methods respectively. Using thick positive photoresist as the mask, Si_3N_4 and SiO_2 on the reverse side are removed by RIE etching selectively to define the pressure diaphragm, then, ICP deep etching is performed to etch silicon to the depth of 80μm.

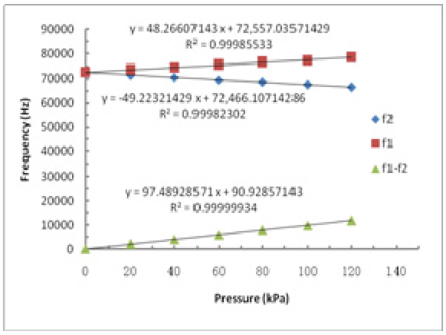


Fig.2: Plot of the FEA simulated resonant frequency versus applied pressure.

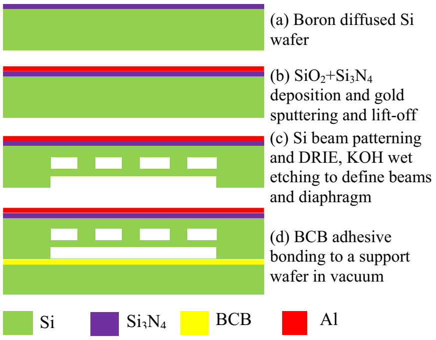


Fig.3: Fabrication process of the sensor by bulk micromachining and bonding techniques.

Second, by means of lift-off technology, Cr / Au electrodes, current conducting leads have been deposited on the film of Si_3N_4 on the front side of the wafer. Then, using thick positive photoresist as the mask, Si_3N_4 is removed by RIE etching selectively to define the beams, and using the same mask, ICP deep etching is conducted to etch silicon to the depth of 60μm.

Third, the wafer is immersed in hot KOH solution, and the same etch is performed from the front and back sides of the wafer. The pressure diaphragms are formed by time-controlled etching in KOH and the Si beams are released by undercutting.

Next, the sensor chip is bonded to a supporting silicon wafer by wafer-level BCB adhesive bonding in a vacuum to form a sealed chamber for a zero-pressure reference and then diced into sensor dies.

Finally, a SmCo permanent magnet is glued on the seat of the metal package, and the sensor die is mounted to the metal package by fixing the die only at a corner through stacks of small silicon dies with epoxy. Fig. 4 shows the photograph of the pressure sensor, and Fig.5 is the SEM picture of a corner of the silicon H-type beam.

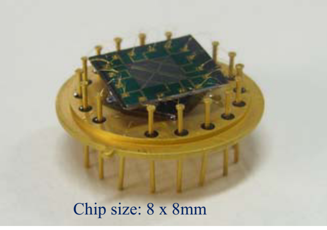


Fig. 4: Photograph of the pressure sensor without cap.

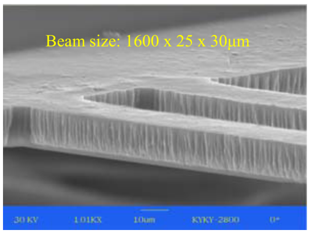


Fig. 5: SEM image of a corner of the silicon H-type beam.

Fig. 6: Photograph of the packaged resonant pressure senor with a circuit.

The frequency response of the silicon beam resonator is measured by an open loop scanning method with help of the HP3562A dynamic systems analyzer. The resonant frequencies of the beams are about 50 kHz in air at nearly zero pressure loads, and the Q factor is nearly 1200 in 1atm air and reaches 2600 in 1kPa pressure.

Static sensitivity measurements are performed in closed loop operation by a self-oscillating circuit shown in Fig.6. Fig. 7 plots the output frequency versus applied pressure. The differential output (f_1-f_2) sensitivity of this sensor is about112Hz / kPa over the range 0~120kPa with improved sensitivity and linearity. The resolution is 10Pa, the nonlinearity is lower than 0.03%, and the maximum hysteresis error of the packaged pressure sensor is 0.06% span. Fig.8 demonstrates the measured output frequency shift (relative to T=25℃) of the packaged pressure sensor associated with the temperature variation at 1atm, the temperature coefficient of the sensor is less than 0.05% span/ ℃ in the range of -40℃ to 70℃ without any temperature compensation.

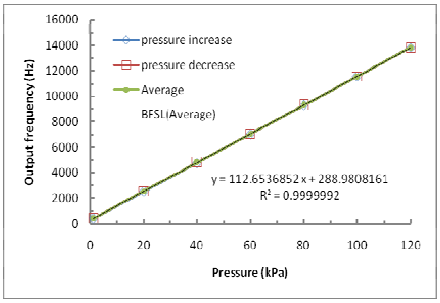


Fig.7: Measured static sensitivity of the pressure sensor.

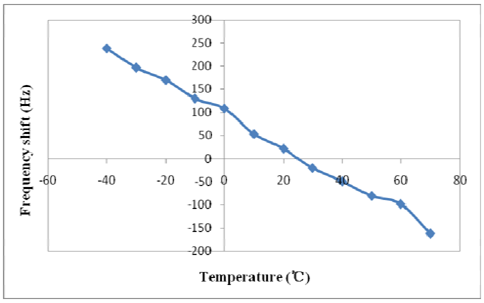


Fig.8: Measured frequency shift with the temperature variation at 1atm.

4. Conclusions

A resonant pressure sensor with novel microstructures is presented and several design aspects of the sensor are analyzed, including the pressure induced stress distribution, damping effects and the influence of geometrical structure on the pressure performance. The proposed sensor is successfully made by bulk micromachining and BCB adhesive bonding techniques. Open-loop electrical measurements of the beams reveal quality factor 1200 in 1atm air and 2600 in 1kPa. With closed loop self-oscillating circuit, measurements of the static behavior of the sensor are conducted. Over the pressure range 0~120kPa, the resolution is 10Pa, with the nonlinearity lower than 0.03%, and the temperature drift is less than 0.05%/℃ in the range of -40℃ to 70℃.

Acknowledgements

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