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Monolithic bridge-on-diaphragm structure for pressure sensor applications

H.-J. Wagner, A. Schumacher, M. Alavi, T. Fabula, B. Schmidt

Abstract Monolithically clamped bridge-on-diaphragm (BOD) structures for pressure sensor applications were fabricated by means of Nd:YAG-laser micromachining and anisotropic KOH-etching techniques. The pressure/frequency-dependence of the BOD structures was measured by acoustical resonance excitation and optical detection of the microbridge and applying an external pressure between −0.8 bar and +1 bar to the diaphragm. In this vacuum/atmospheric pressure range the pressure/frequency-characteristic is quite linear with a sensitivity of about 4.5 kHz/bar and a fundamental bridge resonance frequency of 82 kHz. Extensive finite-element modelling has been carried out to optimize the geometrical dimensions of the BOD structures with respect to maximum sensitivity and pressure range. Using the same BOD structure layout it is possible to realize pressure sensors with applications ranging from 0.5 to 12 bar by only varying the thickness of the diaphragm. Varying the BOD structure layout to smaller dimensions the pressure sensors can be operated up to 100 bar with sensitivities of about 141 Hz/bar.

1
Introduction

Resonant microsensors fabricated from single crystalline quartz or silicon exhibit many applications in the field of precision measurement technique because of their special benefits like large gauge factors, high resolution, and semidigital output [Tilmans et al. (1992)]. One key aspect in the design of resonant sensor devices is a high mechanical quality factor, achieved by placing the resonator in an evacuated cavity [Ikeda et al. (1990)] and/or by using a special resonator design [Greenwood and Satchell (1988)]. Resonant beams are well suited for the detection of forces, as the resonance frequency depends on the mechanical stress which is induced by an applied axial force [Fabula et al. (1994)]. For the realization of pressure sensors a bridge-on-diaphragm (BOD) structure, i.e. a resonating beam connected to a diaphragm at both ends, is preferred. In this case the resonator element (bridge) is functionally separated from the pressure sensitive element (diaphragm). The microbridge is clamped between two pillars connected directly to the diaphragm. A pressure applied to the BOD structure leads to a deformation of the diaphragm and therefore via the knee leverage principle to an axial stress in the microbridge.

In recent years several BOD pressure sensors were realized. Greenwood and Satchell (1988) have produced 6 μm thin resonating structures on a 6 μm thin diaphragm of highly boron doped silicon by selective and anisotropic etching techniques. Thornton et al. (1990) fabricated 2 μm thin boron-doped silicon resonator structures on a 30 μm thick silicon diaphragm. Due to these fabrication techniques the thickness of the resonator is limited to a few microns. Furthermore, the high dopant concentration causes intrinsic stresses which determines the sensor characteristics. Buser et al. (1991) used Silicon-to-Silicon bonding techniques to produce beams with higher thicknesses (top silicon wafer) on diaphragms with mesa structured pillars (bottom silicon wafer). However, for the bonding procedure high temperatures are necessary. Furthermore, the resonator bridge has to be separated manually from the supporting frame, so that batch processing is not feasible. In addition, any electrical contact of the beam is difficult to realize.

Another way to realize BOD microstructures in silicon is by the use of laser machining and anisotropic etching techniques [Schumacher et al. (1994)]. With this method BOD structures have been fabricated monolithically in silicon without any use of bonding or doping techniques. For pressure sensor applications, the BOD structure can be operated either statically by piezoresistors on the bridge surface, for example, to obtain analog output signals, or alternatively, the microbridge can be excited to resonant vibrations by additional piezoelectric thin films, for example, and the change of the resonance frequency induced by the axial stress can be detected. Electrical interconnection lines between the microbridge and external metallization pads can easily be established on the supporting piers (see Fig. 1).

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Fabrication technology

The monolithic BOD microstructure has been fabricated by combination of laser micromachining and anisotropic etching

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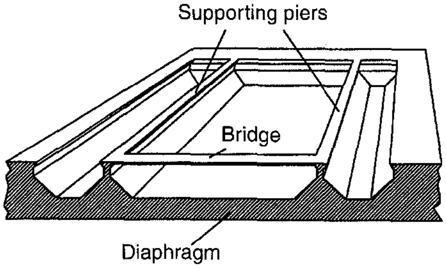

Fig. 1. Scheme of the monolithically clamped BOD structure

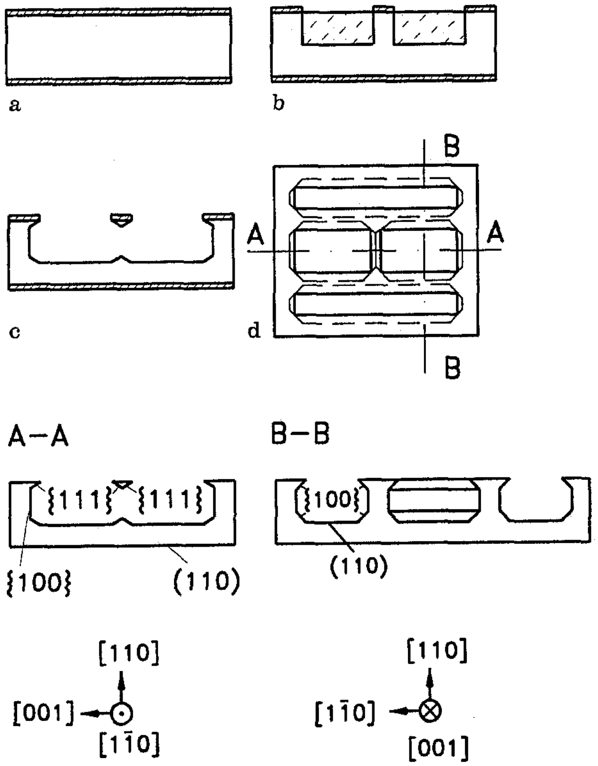

Fig. 2a–d. Fabrication sequence of the monolithic BOD microstructure using laser micromachining and anisotropic etching techniques. **a** SiO$_2$ masked silicon wafer; **b** Lokal destruction of the $\{1\,1\,1\}$ crystal planes by a laser beam; **c** Anisotropic etching of the $\langle 1\,1\,0 \rangle$ oriented microbridges; **d** top view with mask design and two perpendicular side views

techniques [Alavi et al. (1991)]. The principle of this fabrication method is based on the local destruction of $\{1\,1\,1\}$ crystal planes by a laser beam. In $\langle 1\,1\,0 \rangle$ oriented silicon wafers following anisotropic etching in KOH solution leads to the formation of microbridges with triangular cross sections [Alavi et al. (1993)]. For the fabrication three inch $\langle 1\,1\,0 \rangle$ silicon wafers with a thickness of 380 µm covered with a thermally-grown 1.5 µm SiO$_2$ layer were used (Fig. 2a). In a standard photolithographic process the SiO$_2$ layer was patterned to define the dimensions of the microbridge, the supporting piers and the diaphragm, respectively (Fig. 2b, d). In a second step the crystal structure of the silicon substrate was locally disordered down to a defined depth by scanning the focused beam of a Nd:YAG laser across the wafer surface (Fig. 2b). During the following anisotropic etching in KOH solution the monolithic BOD microstructure was formed (Fig. 2c).

The SEM micrograph of Fig. 3 shows the total view of an etched BOD microstructure. The dimensions of the diaphragm are 5 mm × 5 mm with a thickness of 150 µm. The microbridge with a length of approximately 2 mm is oriented parallel to the $[1\,\bar{1}\,0]$ direction of the silicon wafer. Its sidewalls are consisting of $\{1\,1\,1\}$ planes with an angle of 35° to the $(1\,1\,0)$ wafer surface resulting in a triangular cross section (width $= 120$ µm, thickness ≈ 37 µm). Figure 4 shows the clamping region of the microbridge with one supporting pillar (left) and the end of the bridge. At both ends of the bridge $\{1\,1\,1\}$ silicon planes vertical to the substrate surface were additionally designed by the masking layer to minimize the mechanical stress in the clamping region of the bridge if the pressure sensor is loaded.

For applying the BOD structure as a resonant sensor element an excitation/detection mechanism is needed. Piezoelectric thin-film ZnO is a promising and widely used material for the excitation and detection mechanism of resonating beams [Prak et al. (1994)]. A schematic cross-sectional view demonstrating

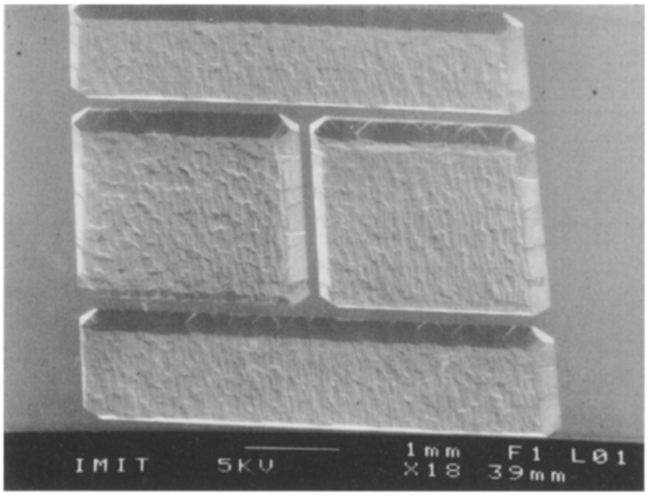

Fig. 3. SEM micrograph of a monolithically clamped BOD structure

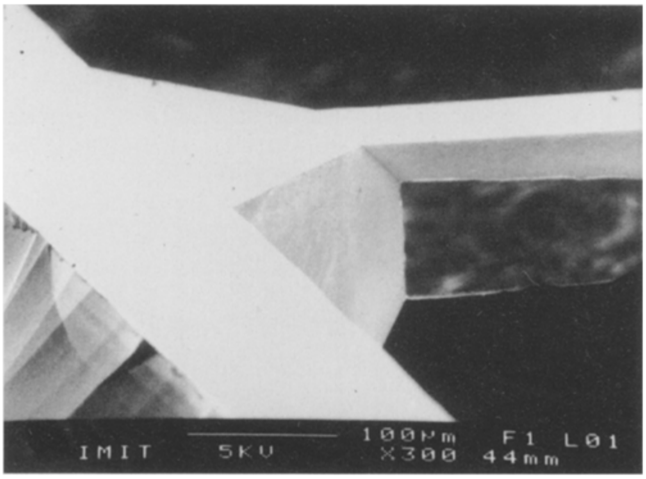

Fig. 4. SEM micrograph showing the clamping region of the microbridge

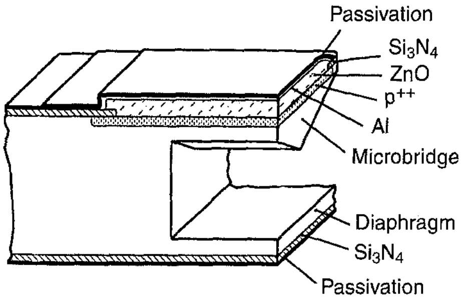

Fig. 5. Schematic cross-sectional view demonstrating a thin-film multilayer structure for excitation and detection of BOD structures

the convenient thin-film multilayer structure and the contacts to the electrodes of the BOD is shown in Fig. 5.

3
Design and simulation

Theoretical investigations have been carried out to optimize the sensor geometry with respect to the pressure sensor characteristics, relating sensitivity, and maximal load. Due to the detecting principle it is evident, that the pressure sensitivity will be enhanced if the stress in the microbridge is increased at constant pressure difference. As there are no analytical formulas available concerning the dynamic behaviour of this complex sensor structure, finite-element analysis (FEA) was used to predict the sensor characteristics and to analyse geometric modifications on the sensor performance.

A three dimensional FE model of the sensor structure was created with the simulation program I-DEAS (SDRC), and FE simulations were carried out with the simulation tool ANSYS considering anisotropic material properties of single crystal silicon. For these calculations a bridge length of 1.95 mm and a beam thickness of 42.4 μm were assumed. By applying a pressure difference of 1 bar the maximum displacement of the diaphragm is about 1 μm. Due to the knee leverage principle a stress concentration occurs in the microbridge resulting in a maximum tensile stress of about 24.7 MPa. The finite-element mesh was refined in the bridge and in the clamping region to get a better stress resolution. Due to the complex geometry the BOD structure vibrates in several different flexure modes. For real applications only the first fundamental flexure mode of the bridge is considered.

As a strong influence on the pressure sensitivity is expected, the diaphragm thickness was varied in the range between 50 and 300 μm while the remaining geometrical dimensions were kept constant. The corresponding resonance frequencies of the diaphragm ($f_{diaphragm}$) and the bridge (f_{bridge}) were calculated. While the frequency of the first fundamental flexure mode of the bridge is nearly independent of the diaphragm thickness, the frequency of the diaphragm is approximately linearly dependent to its thickness as shown in Fig. 6. At a thickness of about 130 μm a cross-over of the resonance frequencies exists. This geometrical configuration should be avoided, because due to mode coupling the vibration energy of the bridge will be transferred into the diaphragm leading to a reduction of the Q-factor. Additionally, the unimodality of the BOD sensor structure is drastically decreased.

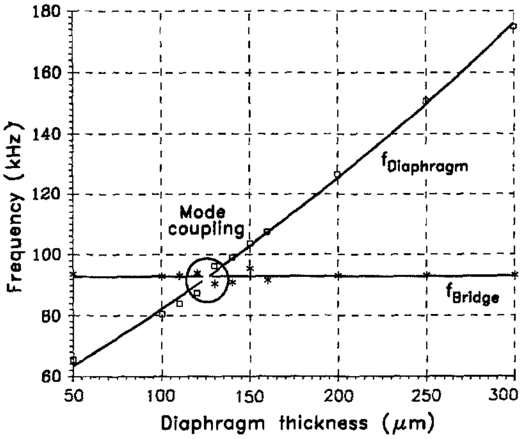

Fig. 6. Calculated resonance frequencies of bridge and diaphragm, respectively, depending on the diaphragm thickness

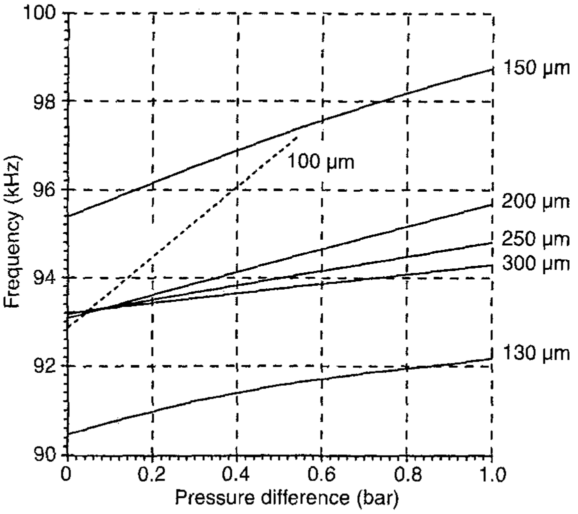

Fig. 7. Frequency/pressure-characteristics of BOD sensors with different diaphragm thicknesses [μm]

The resonance frequencies of the microbridges were calculated in dependence of the pressure difference in the region between 0.0 and 1.0 bar for different diaphragm thicknesses. The pressure/frequency-characteristic for the first fundamental bridge flexure mode is shown in Fig. 7. The pressure difference p_{max}, where the stress σ_{max} in the bridge amounts to a quarter of the break stress of single crystal silicon, had not been exceeded. For diaphragm thicknesses below 130 μm the reduced stiffness of the diaphragm results in a weakening of the leverage mechanism, accompanied with a decrease of the resonance frequency. With this geometric configuration and identical mask layout it is possible to realize BOD pressure sensors with application ranges from 0.5 to 12 bar only by varying the diaphragm thickness. By reducing the diaphragm side length higher pressures can be detected. FE calculations were carried out for several diaphragm side length and thickness configurations. Calculated pressure/frequency-characteristics are shown in Fig. 8. An additional FE-calculation example exhibits that for a 2 mm × 2 mm × 300 μm diaphragm in combination with a 1 mm × 120 μm ×

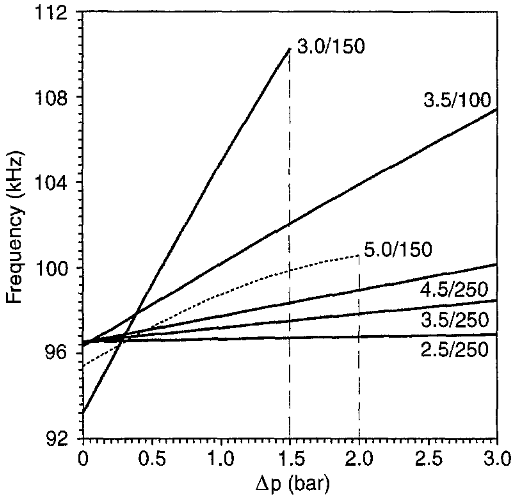

Fig. 8. Calculated pressure/frequency characteristics of different diaphragm lengths/thicknesses

42.4 µm microbridge the fundamental resonance frequency amounts to 386 kHz and a pressure sensitivity of 141 Hz/bar in the range between 0 and 100 bar. At the maximum pressure difference p_{max}= 100 bar a tensile stress of $\sigma_{max} \approx$ 60 MPa will occur in the microbridge.

4
Experimental results

The dynamic behaviour of unlayered BOD prototype structures have been characterized by acoustical excitation of the resonator bridge with a piezoelectric ceramic disk and optical detection with a laser vibrometer unit (POLYTEC OFV 1102 HR). The output signal of the vibrometer is fed to a computer-controlled spectrum analyzer (HEWLETT-PACKARD 3588A) with a personal computer data acquisition system which directly displays the frequency spectrum.

For measuring the pressure/frequency characteristic the BOD structures were mounted on a test chuck, ensuring an overpressure or vacuum application to the reverse side of the diaphragm while the front side including the microbridge remains at atmospheric pressure. The frequency of the first fundamental bridge flexure mode was measured in dependence of the pressure difference (reverse side to front side) ranging from −0.8 bar to 1.0 bar (see Fig. 9). The unloaded resonance frequency has been determined to 82.08 kHz, and the pressure sensitivity is measured to approx. 4.5 kHz/bar, related to the investigated pressure range. The calculated fundamental bridge resonance frequency of 95.4 kHz differs from the measured value caused by the fact, that an ideal triangular bridge with a thickness of 42.4 µm and a length of 1.95 mm has been assumed for FE simulations. However, the length of the fabricated bridge was (1.99 ± 0.04) mm and the thickness was (37 ± 5) µm, due to the convex edge which has been attacked by the etchant at the bottom of the triangular beam. At atmospheric pressure the Q-factor is about 500.

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Conclusions and outlook

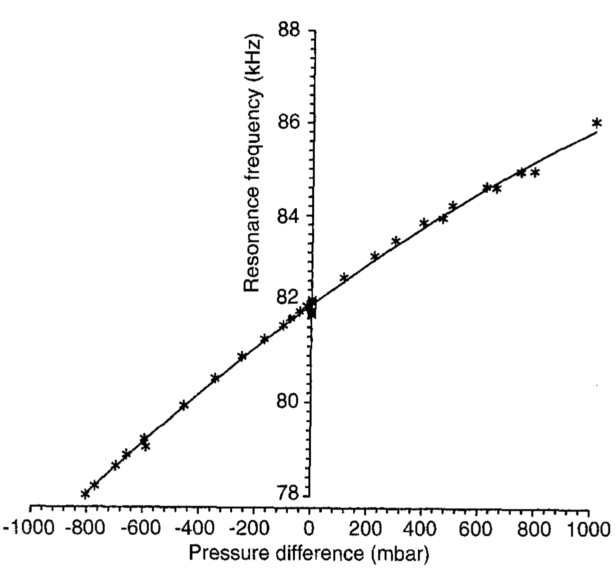

Fig. 9. Measured pressure/frequency characteristic of a monolithic BOD microstructure

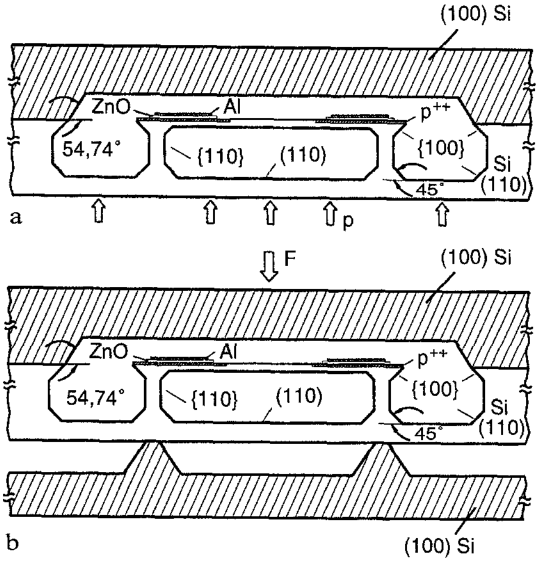

Fig. 10a, b. Schematic cross-sectional views of vacuum encapsulated BOD pressure (a) and force sensor (b) by means of bonding techniques

Monolithic BOD microstructures for pressure sensor applications were fabricated by means of laser machining and anisotropic etching techniques. This fabrication method is suited for batch processing. As the excellent mechanical properties of the single crystal silicon material are preserved, pressure sensors based on this BOD structure principle exhibit high sensitivities combined with high linearity. Furthermore, high Q-factors can be achieved by vacuum encapsulation of the BOD resonator schematically shown in Fig. 10. By varying the geometrical dimensions of the BOD structure sensors can be fabricated for a wide range of pressure and forces.

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