Structured diaphragm with a centre boss and four peninsulas for high sensitivity and high linearity pressure sensors

Xian Huang[1,2], *Dacheng Zhang*[2]

[1]*Shenzhen Graduate School, Peking University, Shenzhen, Guangdong 518055, People's Republic of China*
[2]*Institute of Microelectronics, Peking University, Beijing 100871, People's Republic of China*
E-mail: dchzhang@ime.pku.edu.cn

Published in Micro & Nano Letters; Received on 17th March 2014; Revised on 24th May 2014; Accepted on 10th June 2014

Using the structured diaphragm with a centre boss and four peninsulas (CBP structure), a high sensitivity and high linearity pressure sensor for low pressure ranges was demonstrated. The finite element analysis indicated that the CBP structure could achieve a far better performance than other typical structures for low pressure applications. In accordance with the simulation, the fabricated pressure sensor showed a sensitivity of 21.0 mV/V full-scale output and a nonlinearity error of 0.15% full-scale span in the pressure range of 0–5 kPa. The sensors with the CBP structure are potentially a better choice for measuring low pressures.

1. Introduction: Micro-electro-mechanical system (MEMS) pressure sensors have been widely used in many fields, such as automobiles and process control. Recently, the rapid growth in demand for low pressure measurement in fields like aerodynamics [1], biomedical [2] and HVAC (heat ventilating and air conditioning) [3] has been a major driving force for the development of micro pressure sensors with ultra-high sensitivity and high linearity. Several types of micromachined pressure sensors with different transduction mechanisms (piezoresistive, capacitive and resonant) have been fabricated based on the MEMS technology. Among them, the sensors based on piezoresistive transduction are the most widely manufactured and used because of their low cost and good performance. Compared with capacitive sensing, piezoresistive sensing has the advantages of ease of differential pressure sensing configurations [4]. Resonant pressure sensors have been shown to exhibit better pressure sensitivity and lower temperature sensitivity [5], but the fabrication processes are normally more complicated compared with the alternative ones which limit their application for mass production.

Typically, a piezoresistive pressure sensor consists of a diaphragm to convert the loading pressure to the bending stress and four piezoresistors with the Wheatstone configuration to transduce the stress into an electrical signal. To apply for ultra-low pressure measurement, the ratio of diaphragm width to thickness should be increased to achieve high bending stress under relatively small pressure loading. Unfortunately, nonlinearity error increases at a much faster rate than sensitivity as the ratio increases. The trade-off between sensitivity and linearity has become a major problem in designing piezoresistive pressure sensors for low pressure ranges. Therefore, the development of high performance diaphragms capable of linear deflection and high sensitivity is very important for the successful realisation of sensors for low pressure measurements.

Many efforts have been made to address the nonlinearity and sensitivity problems for diaphragm-type pressure sensors for low pressure measurement. The stiffness of the diaphragm should be increased to avoid large deflection of the diaphragm, which is the major cause for nonlinearity errors. One commonly used method to stiffen the diaphragm is to add centre bosses on the backside of the flat diaphragm [6, 7]. Owing to the constraints imposed by processing methods, the centre boss is normally formed by selectively etching from the backside of a wafer with the sidewalls of 54.7°, in such a way that the centre boss may be taller or wider than required. As a result, large reduction of pressure sensitivity and a large increment of acceleration sensitivity often accompanied the sensor with centre-bossed diaphragms [8]. A second method is to use a partially structured diaphragm with beams and islands [9–11], which is formed by the topside ASE (advanced silicon etching) process. This process allows the freedom to customise the pattern and thickness of the structure to reduce nonlinear deflection and increase the stress concentration of the diaphragm. Recently, based on this principle,Tian *et al.* [12] proposed a novel front-side cross beam membrane (CBM) structure for the 5 kPa pressure measurement. The sensor exhibited perfect linearity performance with a relatively low sensitivity (7.081 mV/kPa). Yu *et al.* [13, 14] combined the CBM structure with a double-side centre boss for measuring absolute micro pressure lower than 500 Pa. High sensitivity was achieved, but the nonlinearity problem [3.046%FSS (full-scale span)] remained unsolved. Additional research and considerable progress are still needed to further improve the performances of the pressure sensors such as the increasing of sensor outputs and the decreasing of nonlinearity errors, chip size and fabrication cost.

In this Letter, a novel structured-diaphragm with a centre boss and four peninsulas (CBP structure) is proposed to achieve both high sensitivity and high linearity performance in pressure sensors for low pressure measurement. In the following Sections, the performance of the CBP structure is studied and compared with other typical structures by finite element analysis (FEA). A fabrication process for the proposed CBP structure is presented in detail. Finally, the fabricated sensors are tested and compared with the FEA results, which verify the accuracy of the FEM simulation.

2. Sensor design

2.1. Structure design: To solve the above-mentioned contradictions between the sensitivity and the linearity, a novel sensor structure featuring the CBP structure is proposed, as shown in Fig. 1. Four peninsulas were located near the diaphragm edges with narrow beams connecting to the Si pedestal. Four piezoresistors on the narrow beams were connected with each other to form the Wheatstone bride circuit. Local stiffening effect on the diaphragm was realised through the application of the CBP structure. Since the peninsula and centre boss regions were about two times thicker than the diaphragm, the stiffness of these regions would be eight times larger than the diaphragm. The bending stress induced by pressures on the diaphragm would be concentrated on the peninsula. Then, because of the difference in width between the peninsula and the narrow beam, the bending stress was

© The Institution of Engineering and Technology 2014

doi: 10.1049/mnl.2014.0154

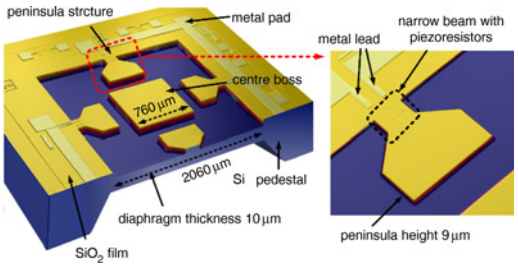


Figure 1 *Schematic diagram of proposed pressure sensor*

further concentrated at the narrow beam, where the piezoresistors were positioned. In addition, the deflection of the diaphragm under pressure loading could be reduced as well as the mechanical nonlinearity errors since the peninsulas and the centre boss have stiffened the diaphragm. Both high sensitivity and high linearity could be expected in the proposed sensor with the CBP structure.

The sensor was designed for 5 kPa pressure measurements with a full range voltage output higher than 100 mV and a terminal-based nonlinearity error (TBNL) lower than 0.2%FFS. Based on the considerations of the fabrication yield and the fabrication capability in terms of diaphragm thickness control accuracy, the diaphragm thickness was designed to be 10 μm. To obtain relatively high sensor outputs, the side length of the diaphragm was set to 2060 μm. Both the thickness of the peninsulas and the width of the centre boss were optimised to meet the design constraints of the nonlinearity errors. Based on the simulation results, the peninsula thickness was set to 9 μm and the width of the square centre boss was set to 760 μm.

2.2. Stress distribution characteristics for the CBP structure: Nonlinear static analysis by ANSYS™ was carried out to study sensor performance. A quarter finite element model of the pressure sensor is shown in Fig. 2*a* with the simulation parameters indicated. The stress intensity distributions for the CBP diaphragm under 5 kPa uniform pressure loading were investigated. High-level stress concentrations can be found at the narrow beams of the peninsulas, as expected (Fig. 2*b*). For maximisation of the sensitivity, the piezoresistors were positioned at the regions of the maximum stress, as shown in Fig. 2*c*.

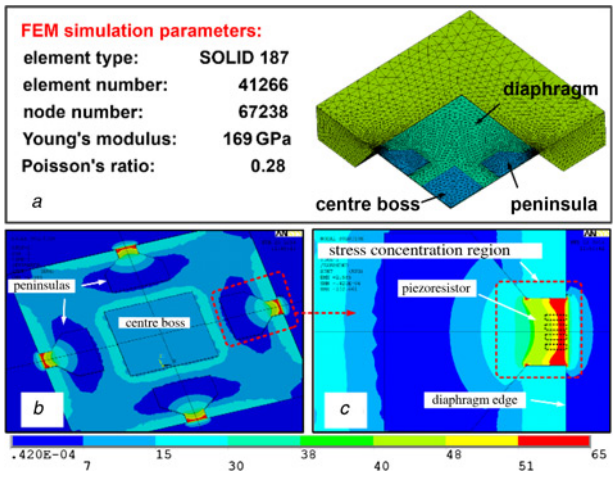


Figure 2 *FEM model and stress distributions*
a Quarter finite element model of pressure sensor
b Stress intensity distributions of diaphragm
c Stress intensity distributions of peninsula and positioning of piezoresistors

2.3. Comparisons with other typical structures: As a basic comparison, four sensors with different types of diaphragm were studied in detail. They were the C-type structure (sensor I) with a flat diaphragm, the E-type structure (sensor II) with a backside centre boss on the diaphragm, the P-type structure (sensor III) with a peninsula-structured diaphragm and the proposed CBP structure (sensor IV), as shown in the boxed region of Fig. 3*a*. All the diaphragms have the same side length of 2060 μm and thickness of 10 μm. The centre bosses in sensors II and IV have the same side length of 760 μm while the thickness in sensor II was 250 μm. The stress distribution characteristics, sensitivities and nonlinearity errors of these sensors were evaluated and compared.

For pressure sensors with ⟨110⟩ oriented and boron-doped piezoresistors, the sensitivities of the sensors are directly related to the stress differences of the longitudinal and transverse directions In this Letter, we use *Sx–Sy* to represent this stress difference. In Fig. 3*a*, the distributions of the stress *Sx–Sy* along the path that goes from the diaphragm centre to the middle of the diaphragm edge are plotted. It is evident that the mechanical stress for each diaphragm reached its maximum around the end of the path.

After obtaining the average stresses in the piezoresistors at different loading pressures of 0–5 kPa, the voltage outputs (V_{out}) and sensitivities (Sens) of these sensor structures can be calculated as follows

$$V_{out} = \frac{1}{2} V_{in} \times \pi_{44} \times \left[\frac{1}{4} \sum_{i=1}^{4} \left| \overline{Sx - Sy} \right|_i \right] \quad (1)$$

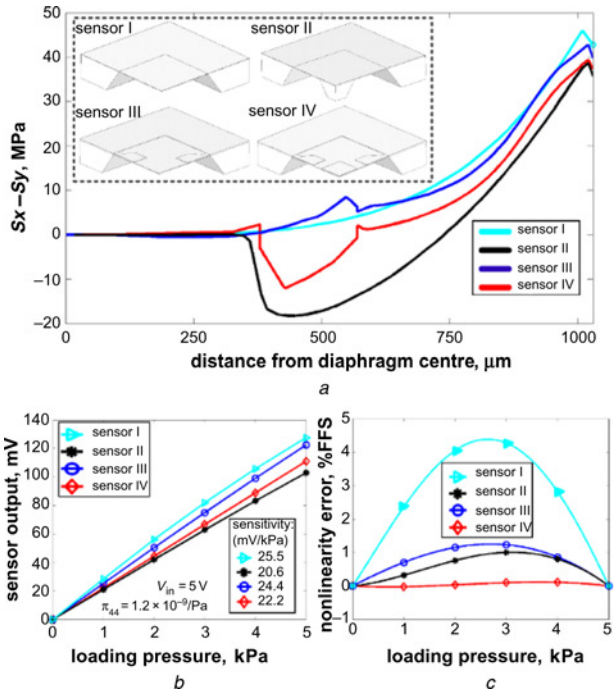


Figure 3 *Comparisons of four different sensors*
a Stress distributions along the path that goes from diaphragm centre to middle of diaphragm edge
b Voltage outputs against pressure loading (0–5 kPa)
c Nonlinearity errors against pressure loading (0–5 kPa)
Sensor I has a flat diaphragm (C-type structure); sensor II has a backside centre-bossed diaphragm (E-type structure); sensor III has a peninsula-structured diaphragm (P-type structure) and sensor IV has the CBP structure
All diaphragms have same side length of 2060 μm and thickness of 10 μm
Centre bosses in sensors II and IV have same side length of 760 μm

© The Institution of Engineering and Technology 2014

Table 1 Performance comparisons

No.	I	II	III	IV
Diaphragm types	C-type	E-type	P-type	CBP structure
Sensitivity, mV/kPa	25.5	20.6	24.4	22.2
TBNL (|%FFS|)	4.3	1.0	1.2	0.11

$$\text{Sens} = \frac{V_{\text{out}}}{P} \tag{2}$$

Where π_{44} represents the shear piezoresistance coefficient, the input voltage V_{in} is set to 5 V. The terms within the bracket of (1) represent the average absolute stress difference between the longitudinal and transverse directions of the four piezoresistors. Sens is the sensitivity of the sensor, and P is the loading pressure. Then, based on the sensor outputs, the TBNL of the pressure sensor was calculated as [15]

$$\text{TBNL} = \text{Delt/FSS} \times 100\% \tag{3}$$

where Delt is the voltage output difference between the real voltage output and the ideal linear output. The full-scale span (FSS) is the voltage range of the full pressure range.

The calculated voltage outputs and nonlinearity errors in the pressure range of 0–5 kPa are plotted in Figs. 3*b* and *c*, respectively. Detailed performance comparisons are listed in Table 1. The results indicated that the typical C-type structure presented the highest sensitivity of 25.5 mV/kPa; however, the worst nonlinearity error of larger than 4.3%FFS was also obtained. An improved nonlinearity error of nearly 1.0% FFS was achieved at the expense of the lowest sensitivity (20.6 mV/kPa) in the E-type structure. The P-type structure employed the peninsulas to stiffen the diaphragm. As a result, the sensor exhibited an improved nonlinearity of nearly 1.2% FFS, a reduction of nearly 72.1% compared with the C-type structure. Meanwhile, the sensor had a sensitivity of 24.4 mV/kPa, which has increased by 18.4% compared with the E-type structure and is only slightly lower than the highest sensitivity (25.5 mV/kPa) of the C-type structure. To further reduce the nonlinearity error, a centre boss was added to the P-type structure to form the CBP structure in sensor IV. The lowest nonlinearity error of 0.1%FSS and a sensitivity of 22.2 mV/kPa were achieved for the pressure range of 0–5 kPa. Compared with the typical E-type structure, a sensitivity increment of 7.8% and a nonlinearity error reduction of 90% were realised.

3. Fabrication process: An overview of the fabrication process for the proposed sensor is shown in Fig. 4. First, a 4-inch n-type (100) oriented Si wafer was chosen as the substrate; after the thermal oxidisation process, photolithography and boron implantation were employed to pattern and form the piezoresistors and the heavily doped contact sections on the front side of silicon wafer (Figs. 4*a* and *b*). After the final thermal activation process, a sheet resistance of 237 Ω/□ was achieved for the piezoresistors. Secondly, the passivation films of SiO_2 and Si_3N_4 were deposited by means of the low pressure chemical vapour deposition (LPCVD) process. After pattering for the backside cavity, KOH (potassium hydroxide) etching at 80°C was applied to fabricate the cavity and diaphragm. A diaphragm thickness of 19 µm was fabricated (Fig. 4*c*). Thirdly, the metallisation process was conducted (Fig. 4*d*). It began with the contact hole etching, followed by Al (aluminium) sputtering with a thickness of 1 µm. After lithography and the Al etching process, a sintering process was conducted to form the low resistance ohmic contact between the heavily doped section and the Al pad. Fourthly, the ASE process was carried out on the front side to form the boss and peninsula structures with a depth of 9 µm (Fig. 4*e*). The fabricated pressure sensor is shown in Fig. 5*a*, where the scanning electron microscope (SEM) images of the piezoresistors are displayed in detail.

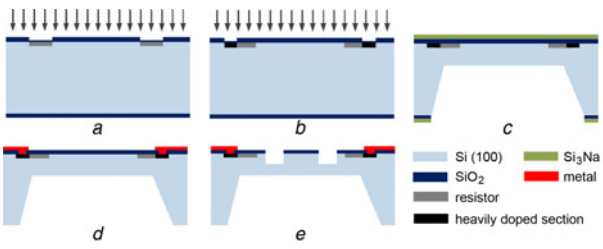


Figure 4 *Schematic of main process flow*
a, b Boron implantation and thermal annealing to form the piezoresistors and the heavily doped sections
c Cavity and diaphragm formation by KOH etching
d Contact hole etching and electrode deposition
e Top side ASE etching to form the boss and peninsula structures

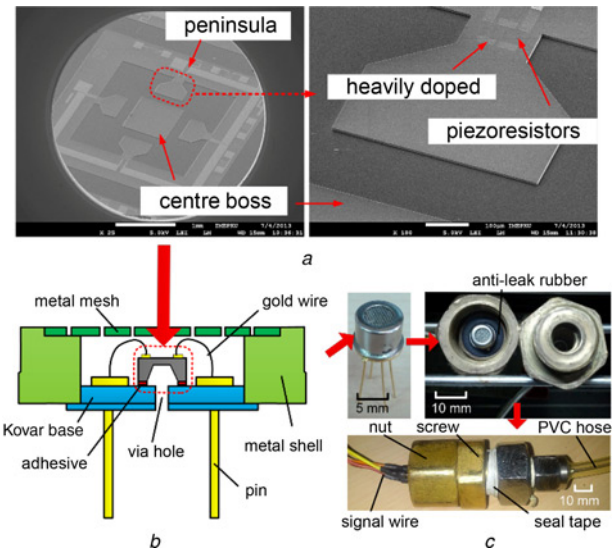


Figure 5 *SEM images of fabricated sensor and piezoresistors; schematic diagram of packaged sensor structure; packaged sensor and designed nut-screw structure for sensor measurement*
a SEM images of fabricated sensor and piezoresistors
b Schematic diagram of packaged sensor structure
c Packaged sensor and designed nut-screw structure for sensor measurement

4. Measurements and discussion: The schematic diagram of the packaged pressure sensor structure is shown in Fig. 5*b*. After dicing, the sensor chip was assembled on a gold-plated Kovar base. Through the wire bonding process, electrical connection between the sensor chip and the pins were realised. Differential pressures could be loaded on the sensor's diaphragm because of the existence of via hole at the middle of the Kovar base. A special nut-screw structure was designed for sensor measurement under pressure loadings, as shown in Fig. 5*c*. The packaged sensor was assembled in the nut with the pins of the sensor connected with the signal wire from the backside of the nut. Anti-leak rubber was used to prevent pressure leakage from the nut during the test. When the screw with a PVC hose and the nut with the packaged sensor were screwed together, pressure could be applied to the sensor chip from the PVC hose using the PPC2 + gas pressure controller.

Three sensor devices from the same wafer were measured. The voltage outputs and nonlinearity errors as well as the average value of the three devices are plotted in Fig. 6. The differences of the sensor outputs and TBNLs for the devices could be ascribed to the variations of the diaphragm thickness. The realistic sensitivity

© The Institution of Engineering and Technology 2014

doi: 10.1049/mnl.2014.0154

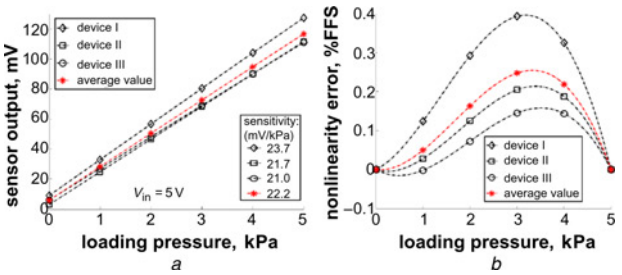


Figure 6 *Measured sensor outputs and nonlinearity errors against pressure loading for three sensor devices*
a Measured sensor outputs
b Nonlinearity errors

Table 2 Technical data of device III at 21°C

Full range pressure, kPa	5
Full range output, mV	105.1
Wheatstone bridge resistance, kΩ	3.9
Supply voltage, V	5
Zero output, mV	6.1
Sensitivity, mV/kPa	21.0
Nonlinearity error-TBNL, %FFS	0.15
Burst pressure, kPa	62
Die size, mm	3.6 × 3.6 × 0.4

performances of these sensors are well within the simulations with the diaphragm thicknesses in the range of 9.5–10.2 μm. The zero offset voltages for the three devices ranged between 3.2 and 10.1 mV. The detailed technical data of the device III at 21°C is listed in Table 2. The sensitivity of the device was 21.0 mV/V full-scale output with a maximum nonlinearity error of 0.15%FFS. In particular, the tested burst pressure was 62 kPa, a factor of 10 larger than the full pressure range (5 kPa).

5. Summary and conclusion: In this Letter, a novel CBP structure is proposed to address the contradictions between sensitivity and linearity of pressure sensors for low pressure ranges. FEM simulation results indicated that the proposed sensor could achieve an ideal nonlinearity error of 0.1%FFS and a sensitivity of 22.2 mV/kPa for the full pressure range of 0–5 kPa, far better than the typical sensors with C-type, E-type and the P-type structures. Utilising the mature technologies of KOH and ASE etching, pressure sensors with the CBP structure have been manufactured based on the cost-effective silicon wafer. In accordance with the FEM results, the fabricated pressure sensor showed that a sensitivity of 21.0 mV/V full-scale output and a TBNL of 0.15%FSS were achieved. It is concluded that the proposed sensor has excellent sensitivity, linearity and the most important feature of low cost. The proposed pressure sensor is potentially a better choice for applications of low pressure measurements.

6. Acknowledgments: This work was financed by the 863 Program (Grant no. 2011AA040401) and the 973 Program (Grant no. 2011CB309502). The sensor fabrication and measurement were supported by the National Key Laboratory of Science and Technology on Micro/Nano Fabrication, Institute of Microelectronics, Peking University.

7 References

[1] Berns A., Buder U., Obermeier E., Wolter A., Leder A.: 'AeroMEMS sensor array for high-resolution wall pressure measurements', *Sens. Actuators A*, 2006, **132**, (1), pp. 104–111
[2] Marco S., Samitier J., Ruiz O., Esteve J.: 'High-performance piezoresistive pressure sensors for biomedical applications using very thin structured membranes', *Meas. Sci. Technol.*, 1996, **7**, (9), pp. 1195–1203
[3] Patel S.N., Reynolds M.S., Abowd G.D.: 'Detecting human movement by differential air pressure sensing in HVAC system ductwork: an exploration in infrastructure mediated sensing', *IEEE Pervasive Comput.*, 2008, **5013**, pp. 1–18
[4] Barlian A.A., Park W.T., Mallon J.R., Rastegar A.J., Pruitt B.L.: 'Review: semiconductor piezoresistance for microsystems', *Proc. IEEE*, 2009, **97**, (3), pp. 513–552
[5] Eaton W.P., Smith J.H.: 'Micromachined pressure sensors: review and recent developments', *Smart Mater. Struct.*, 1997, **6**, pp. 530–539
[6] Yasukawa A., Shimazoe M., Matsuoka Y.: 'Simulation of circular silicon pressure sensor with a center boss for very low pressure measurement', *IEEE Trans. Electron Devices*, 1989, **36**, (7), pp. 1295–1302
[7] Sandmaier H., Kuhl K.: 'A square-diaphragm piezoresistive pressure sensor with a rectangular central boss for low-pressure ranges', *IEEE Trans. Electron Devices*, 1993, **40**, (10), pp. 1754–1759
[8] Kinnell P.K., King J., Lester M., Craddock R.: 'A hollow stiffening structure for low-pressure sensors', *Sens. Actuators A*, 2010, **160**, (1), pp. 35–41
[9] Bao M.H., Yu L.Z., Wang Y.: 'Stress concentration structure with front beam for pressure sensor', *Sens. Actuators A*, 1991, **28**, (2), pp. 105–122
[10] Johnson R.H., Karbassi S., Sridhar U., Speldrich B.: 'A high sensitivity ribbed and bossed pressure transducer', *Sens. Actuators A*, 1993, **35**, (2), pp. 93–99
[11] Hein S.: 'Piezoresistive silicon sensor for very low pressures based on the concept of stress concentration'. Solid State Sensors and Actuators Transducers'93 Conf., Yokohama, Japan, 1993, **93**, pp. 628–631
[12] Tian B., Zhao Y.L., Jiang Z.D., Hu B.: 'The design and analysis of beam-membrane structure sensors for micro-pressure measurement', *Rev. Sci. Instrum.*, 2012, **83**, (4), pp. 045003 (8 pages)
[13] Yu Z.L., Zhao Y.L., Sun L., Tian B., Jiang Z.D.: 'Incorporation of beams into bossed diaphragm for a high sensitivity and overload micro pressure sensor', *Rev. Sci. Instrum.*, 2013, **84**, (1), pp. 015004 (9 pages)
[14] Yu Z.L., Zhao Y.L., Meng X.W., Tian B., Jiang Z.D.: 'Absolute micro pressure measurements based on a high-overload-resistance sensor', *Micro Nano Lett.*, 2012, **7**, (12), pp. 1180–1183
[15] Chiou J.A., Chen S.: 'Pressure nonlinearity of micromachinedpiezoresistive pressure sensors with thin diaphragms under high residual stresses', *Sens. Actuators A*, 2008, **147**, (1), pp. 332–339

© The Institution of Engineering and Technology 2014