第29卷 第3期
2008年3月

半 导 体 学 报
JOURNAL OF SEMICONDUCTORS

Vol.29 No.3
Mar.,2008

A Novel Capacitive Pressure Sensor*

Huang Xiaodong, Huang Jianqiu, Qin Ming†, and Huang Qing'an

(Key Laboratory of MEMS of the Ministry of Education, Southeast University, Nanjing 210096, *China)*

Abstract: A novel capacitive pressure sensor is presented, whose sensing structure is a solid-state capacitor consisting of three square membranes with Al/SiO_2/n-type silicon. It was fabricated using pn junction self-stop etching combined with adhesive bonding, and only three masks were used during the process. Sensors with side lengths of 1000, 1200, and 1400μm were fabricated, showing sensitivity of 1.8, 2.3, and 3.6fF/hPa over the range of 410～1010hPa, respectively. The sensitivity of the sensor with a side length of 1500μm is 4.6fF/hPa, the nonlinearity is 6.4%, and the max hysteresis is 3.6%. The results show that permittivity change plays an important part in the capacitance change.

Key words: capacitive pressure senor; electrostriction; pn junction self-stop etching; adhesive bonding; linearity
EEACC: 2575; 8460
CLC number: TP212.12 **Document code**: A **Article ID**: 0253-4177(2008)03-0428-05

1 Introduction

Capacitive pressure sensors are widely used in many fields such as industrial control, biomedical instruments, and environmental monitoring. Compared with the piezoresistive sensor, this kind of sensor has advantages that include low power dissipation, low temperature drift, good hysteresis, and stability. According to $C = \varepsilon A/d$, the capacitive sensor changes primarily due to variation in displacement, variation, and permittivity. A normal sensor based on displacement variation usually has severe nonlinearity since the capacitance is inversely proportional to the displacement between the electrodes as well as the nonlinearity due to large load-deflection bending[1]. In addition, feed through of the electrode in the sealed cavity leads to complex fabrication[2]. A sensor based on area variation has also been reported[3]. We have presented a new capacitive pressure sensor[4,5], a solid-state capacitor that consists of Au/Si_3N_4/SiO_2/p^{++}-type silicon. Different from the above structures, the capacitance changes under pressure applied due to the variation of the permittivity, area, and displacement between the electrodes. The sensor was fabricated by heavily doped self-stop etching. However, heavy doping may induce large stress, and it is difficult to fabricate electronic devices on the p^{++}-type layer. The mechanism leading to the variation of the capacitance also needs to be further analyzed. Thus, we redesign the sensor, which consists of three square layers of Al/SiO_2/n-type silicon. This paper gives the design, fabrication steps, and test results of the sensor. The analysis results indicate that the capacitance changes mainly due to the permittivity variation under pressure applied.

2 Design and fabrication

A cross section of the proposed sensor is shown in Fig.1. This sensor consists of Al/SiO_2/n-type silicon, where Al and n-type silicon are used as top and bottom electrodes, respectively, while SiO_2 is the dielectric layer. The membranes are deformed under pressure, causing a load-deflection bending, and hence leading to changes of the area and displacement between the electrodes. According to electrostriction effects[6,7], the permittivity also changes due to the induced stress under applied pressure.

The sensor was fabricated by pn junction self-stop etching[8] combined with adhesive bonding. The pn junction self-stop etching was used to define the cavity and control the thickness of the membrane

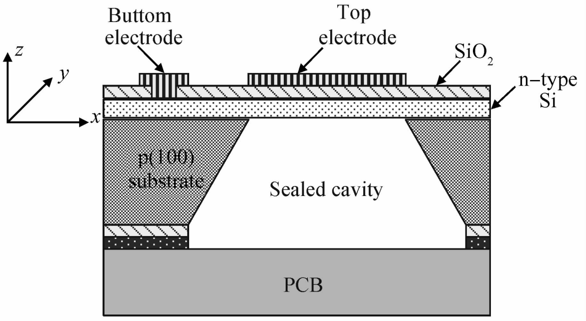

Fig.1 Cross-section of the capacitive pressure sensor

---

* Project supported by the Key Program of the National Natural Science Foundation of China (No.90607002)

† Corresponding author. Email: mqin@seu.edu.cn

Received 1 September 2007, revised manuscript received 9 November 2007

©2008 Chinese Institute of Electronics

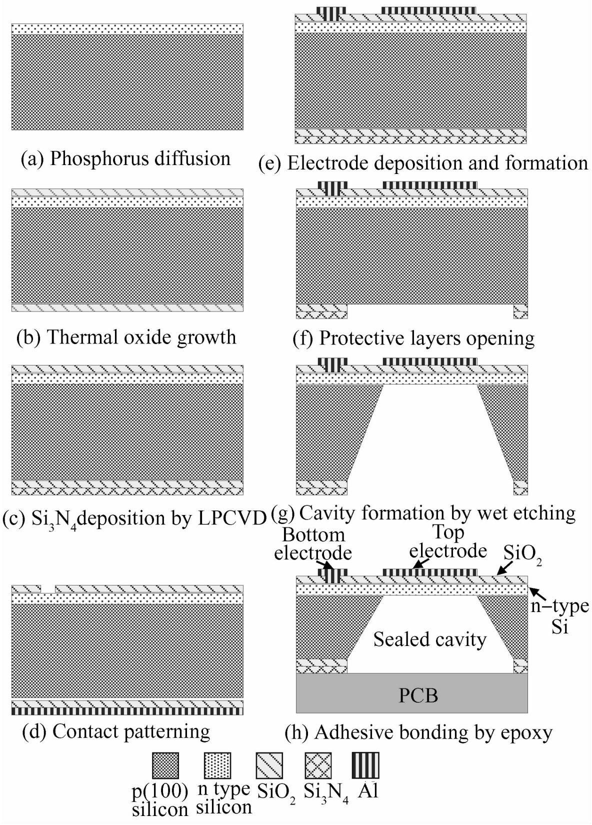

Fig. 2 Fabrication process of the sensor

accurately, and adhesive bonding was used to form the sealed cavity. The detailed process flow shown in Fig. 2, is listed as follows.

(a) Diffuse phosphor on the p-type (100) oriented silicon to form an n-type layer, which is used not only as the bottom electrode of the sensor, but also the self-stop layer. The thickness of the n-type layer is about 3μm, and the square resistor is 8Ω/□.

(b) Grow thermal oxide on the wafer by the dry method, which is used as a dielectric layer, and the thickness is about 0.2μm.

(c) Deposit Si_3N_4 (about 100nm) on the back side of the wafer using LPCVD (low pressure chemical vapor deposition) as a protective layer during bulk silicon etching.

(d) Lithography contact.

(e) Deposit and pattern Al (about 200nm) as electrodes.

(f) Define the window in the sensing structure area on the back side by double-sided aligning and then open the window by RIE (reactive ion etch).

(g) Setup the pn junction self-stop system. The wafer was mounted in a Teflon holder to protect the front side of the wafer from etching, and then immersed in 40wt% KOH, before etching began. The etching temperature is set to 80℃ and the responding etching rate is 1μm/min.

(h) Form sealed cavity using epoxy by adhesive bonding in the common pressure. The residual pressure in the cavity is about 1010hPa.

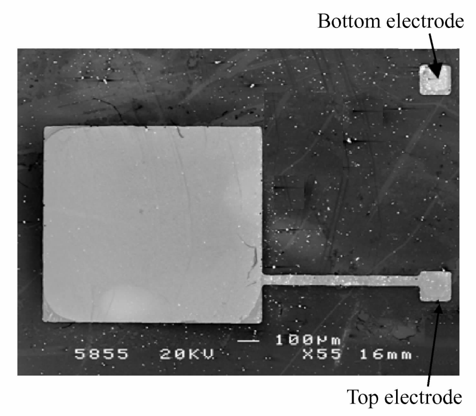

Fig. 3 Top view of the capacitive pressure sensor

Only three masks were used during the fabrication process (used to etch the contact and electrodes, and to open the windows on the backside during steps (d), (e) and (f)). Figure 3 gives the SEM photos of the sensor.

3 Test results

3.1 Membrane after the self-stop

The sensitivity of the sensor is dependent on the membrane's thickness of the sensor, and the characteristic uniformity of the batch sensors is also related to the thickness. As an important parameter, the thickness is measured. Five different samples are randomly chosen, whose thickness are about 3 ± 0.1μm, showing good uniformity. Figure 4 shows the cross section of a membrane after self-stop, in which the membrane is 3μm thick, close to the thickness of n-type silicon (about 2.9μm thick by the pn junction coloration method). The test result indicates etching is effectively self-stopped at the interface of the pn junction.

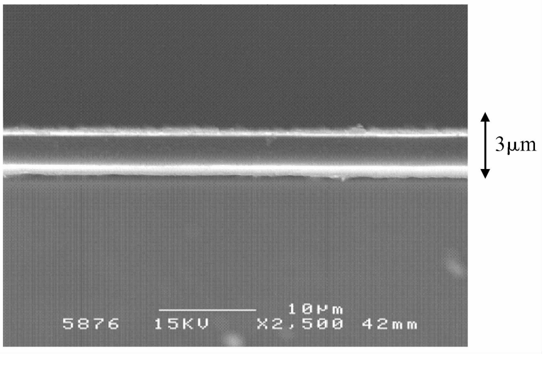

Fig. 4 Cross section of a membrane after pn junction self-stop etching

Table 1 Results of the sensor with different side lengths

Side length of the sensor/μm	1000	1200	1400	1500
Initial capacitance /pF	208	297	393	454
Sensitivity /(fF/hPa)	1.8	2.3	3.6	4.6

3.2 Pressure response

Test results of the sensors with different side lengths are presented. As pressure applied is from 1010 to 410hPa (1hPa = 100Pa) at room temperature, the initial capacitance and sensitivity corresponding to different side lengths are recorded in Table 1. A sensor with a large side length improves the sensitivity; On the other hand, it also increases the layout area and initial capacitance, and hence increases the power dissipation. It is necessary to optimize the parameters according to demand.

A typical pressure response of the sensor with the side length of 1500μm is shown in Fig. 5 (where the horizontal axis is differential pressure, defined as the difference of the pressure applied and the residual pressure in the cavity). The figure shows the sensitivity is 4.6fF/hPa and the nonlinearity is about 6.4% over the full range from 1010 to 410hPa. Correspondingly, the horizontal axis is from 0 to 600hPa when the residual pressure in the cavity is 1010hPa. Figure 5 also shows the hysteresis characteristic of the sensor. The max hysteresis is about 3.6% and appears in the range from 200 to 400hPa. The sensor presents good linearity and hysteresis.

4 Analyses

The sensing capacitor is similar to a plate capacitor, and it is given by

$$C = \varepsilon A/d \qquad (1)$$

where C is the capacitance, ε is the permittivity, and A and d are the area and displacement of the electrodes, respectively.

From Eq. (1), the relative variation of the capacitance is given by

$$\Delta C/C = -\Delta d/d + \Delta A/A + \Delta\varepsilon/\varepsilon \qquad (2)$$

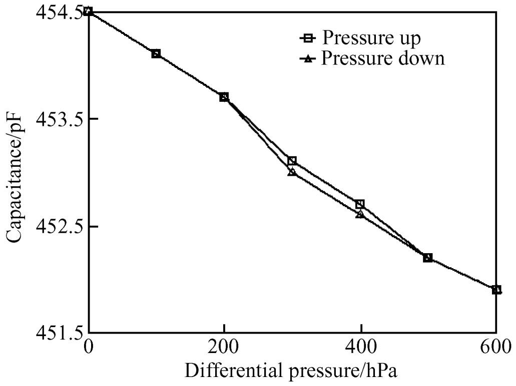

Fig.5 Curves of the capacitance as a function of pressure $L = 1500\mu$m

where the terms $-\Delta d/d$ and $\Delta A/A$ represent the influence of the geometric defromation, and the term $\Delta\varepsilon/\varepsilon$ represents the influence of the permittivity variation. $\Delta d/d$ and $\Delta A/A$ can be written as

$$\Delta A/A = \int_{-L/2}^{L/2}\int_{-L/2}^{L/2}(\varepsilon_x + \varepsilon_y)\mathrm{d}x\mathrm{d}y/L^2 \qquad (3)$$

$$\Delta d/d = \frac{v}{(v-1)}\Delta A/A \qquad (4)$$

where L is the side length of the square membrane, ε_x and ε_y represnt the strain in the x and y directions, and v is the Poisson rate of the dielectric, which is 0.17 for SiO_2.

The complex membranes of the sensor deform and extend under applied pressure, and hence increase the area and decrease the displacement of the capacitor, both of which lead to increase in the capacitance. Table 2 gives the capacitance variation ΔC due to geometric deformation under different pressures. The general calculation is as follows: the entity model of the sensor is built in ANSYS, and mesh the model using Shell 181 element (50 × 50); Then, carry the boundary condition and pressure load. In the next step, calculate the strain at each node under different pressures. Finally, the calculation results were carried into Eqs. (3) and (4), and solved for ΔC due to geometric variation.

The capacitance variation only due to permittivity change can be calculated by Eq. (2) combined with the value of Fig. 5 and Table 2. Figure 6 shows that as the differential pressure varies from 0 to 600hPa, the permittivity change decreases the capacitance, and

Table 2 Capacitance changes due to geometry deformation under different pressures $L = 1500\mu$m

Differential pressure /hPa	0	100	200	300	400	500	600
ΔC only due to area variation/pF	0	0.1081	0.1813	0.2439	0.3004	0.3519	0.4009
ΔC due to geometric variation/pF	0	0.1302	0.2184	0.2939	0.3619	0.4239	0.4830

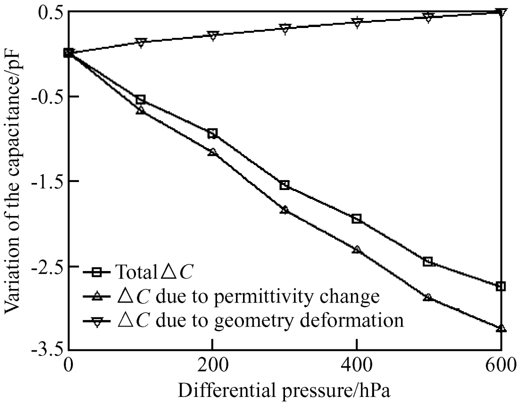

Fig.6　Influence of the permittivity change and geometry deformation to ΔC

the total capacitance change due to the permittivity change is 3.23pF. Meanwhile the geometric deformation makes the capacitance increase, and the capacitance change due to the geometric deformation is 0.483pF. This result shows that the permittivity change has a reverse influence on the capacitance variation compared to the geometric change, and the permittivity change plays a major part in the capacitance variation.

5　Conclusion

A novel capacitive pressure sensor is presented; the sensing capacitor consists of complex membranes including metal/oxide/n-type silicon. The results show that permittivity variation plays an important role in the capacitance variation. The sensor introduced in Refs.[4,5] is incompatible with the CMOS process and difficult to integrate with its interface circuit since heavily doped self-stop etching technology was used during the fabrication. The improved structure presented in this paper overcomes these disadvantages. A conceptual cross section of the sensor integrated with its interface circuit based on CMOS process is shown in Fig. 7, where the sensing capacitor consists of n well silicon/gate oxide/poly gate. The sensor can be fabricated in a standard CMOS process combined with some post processing, such as pn junction self-stop etching that is used to release the cavity and control the thickness accurately and anodic bonding that is used to seal the cavity.

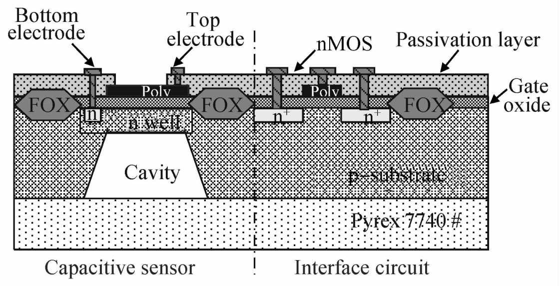

Fig.7　Conceptual schematic of the monolithic capacitive pressure sensor

Table 3 gives the test results of the sensor with a side length of 1000μm compared to other kinds of capacitive pressure sensors. The results show that the proposed sensor has higher sensitivity and is easier to fabricate because it only needs three masks during fabrication. Further work should pay attention to the mechanism of the permittivity variation under applied pressure.

Table 3　Comparison between the proposed sensor and other kinds of capacitive pressure sensors

Type	Displacement variation[9]	Displacement variation[10]	Displacement variation[3]	Sensor proposed ($L = 1000\mu$m)
Sensitivity/(fF/hPa)	0.56	1	1.96	1.8
Step number of the lithography	4 steps	4 steps	5 steps	3 steps

References

[1] Suzuki K, Ishihara T, Hirata M, et al. Nonlinear analysis of a CMOS integrated silicon pressure sensor. IEEE Trans Electron Devices, 1987, 34(6): 1360

[2] Chavan A V, Wise K D. Batch-processed vacuum-sealed capacitive pressure sensors. J Microelectromech Syst, 2001, 10: 580

[3] Ko W H, Wang Q. Touch mode capacitive pressures. Sensors and Actuators A, 1999, 75: 242

[4] Zhou M X, Huang Q A, Qin M, et al. A novel capacitive pressure sensor based on sandwich structures. Journal of Microelectromechanical Systems, 2005, 14(6): 1272

[5] Zhou M X, Huang Q A, Qin M. A capacitive pressure sensor with a novel multi-layered composite membrane structure fabricated by a three-mask process. Proceedings of Transducers, 2005: 200

[6] Shkel Y M, Ferrier N J. Electrostriction enhancement of solid-state capacitance sensing. IEEE/ASME Trans Mechatronics, 2003, 8(3): 318

[7] Shkel Y M, Klingenberg D J. Electrostriction of polarizable materials: comparison of models with experimental data. J Appl Phys, 1998, 83(12): 7834

[8] Kloeck B, Collins S D, de Rooij N F, et al. Study of electrochemical etch-stop for high-precision thickness control of silicon membranes. IEEE Trans Electron Devices, 1989, 36(4): 663

[9] Kim H, Jeong Y G, Chun K. Improvement of the linearity of a capacitive pressure sensor using an interdigitated electrode structure. Sensors and Actuators A, 1997, 62: 586

[10] Renard S, Pisella C, Collet J, et al. Capacitive pressure and inertial sensors by epi-SOI surface micromachining. Proceedings of IEEE Sensors, 2002, 2: 1385

一种新型电容式压力传感器*

黄晓东　黄见秋　秦　明[†]　黄庆安

（东南大学 MEMS 教育部重点实验室，南京　210096）

摘要： 提出了一种新的电容式压力传感器，传感器结构为由 Al/SiO_2/n-type Si 等三层方形膜构成的固态电容. 传感器采用 pn 结自停止腐蚀和粘结剂键合的方式制造，制造过程仅需三块掩模板. 对不同边长传感器进行测试，在 410～1010hPa 的动态范围，边长为 1000，1200 和 1400μm 的压力传感器，相应灵敏度分别为 1.8，2.3 和 3.6fF/hPa. 边长为 1500μm 的传感器，其灵敏度为 4.6fF/hPa，全程非线性度为 6.4%，最大滞回误差为 3.6%. 分析结果表明介电常数变化是引起电容变化的主要原因.

关键词： 电容式压力传感器；电致伸缩；pn 结自停止腐蚀；粘结剂键合；线性度

EEACC： 2575；8460

中图分类号： TP212.12　　**文献标识码：** A　　**文章编号：** 0253-4177(2008)03-0428-05

---

* 国家自然科学基金重点项目资助（批准号：90607002）

† 通信作者. Email：mqin@seu.edu.cn

2007-09-01 收到，2007-11-09 定稿

©2008 中国电子学会