A SINGLE-WAFER-BASED SINGLE-SIDED BULK-MICROMACHINING TECHNIQUE FOR HIGH-YIELD AND LOW-COST VOLUME PRODUCTION OF PRESSURE SENSORS

Jiachou Wang and Xinxin Li
State Key Lab of Transducer Technology, and, Science and Technology on Microsystem Lab,
Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, CHINA

ABSTRACT

This paper presents a novel single-wafer-based single-sided bulk-micromachining piezoresistive pressure sensor that features highly uniform diaphragm thickness and ultra-small size. Without double-side alignment and wafer bonding needed, the single-crystalline silicon piezoresistive pressure sensors can be volume manufactured in standard IC-foundries with ultra-low fabrication cost for applications of consumer electronics. The pressure sensor sensitivity range 750KPa is about 0.033mV/V/KPa and the non-linearity is less than ±0.1%·FS. Even though the two rows of opening holes are embedded in the silicon diaphragm, the tested zero-point temperature coefficient as low as -0.022%/ ºC ·FS (-40ºC to +120ºC) indicates no obvious influence to the sensor stability.

KEYWORDS

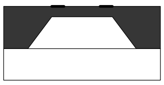
Pressure sensor, single-sided micromachining, hexagonal diaphragm, piezoresistance

INTRODUCTION

Schematically in the 1st row of Table.1, conventional piezoresistive absolute-pressure sensors use backside etching to form the pressure-sensitive diaphragm and wafer-bonding to seal the pressure-reference cavity [1]. Since the bonded structure and the anisotropic-etching-induced inclined sidewalls cause a large device-size, the foundry fabrication cost cannot be very low. Even worse, the backside-etching formed diaphragm thickness is not uniform due to the non-uniformity in deep etching depth, thereby, lowering fabrication yield and sensitivity uniformity. Even if the etching rate is uniform, the diaphragm thickness is still not uniform due to the wafer thickness non-uniformity (spec. ±10μm or ±20μm, comparable with the desired diaphragm thickness). A modified sensor structure (2nd row of Table.1) that uses pre-bonded and post-thinning technique (or use expensive SOI wafer with BOX-layer as sacrificial-layer) still suffers the diaphragm non-uniformity that comes from the grinding-polishing thinning process. As a result, the diaphragm has to be thicker but this in turn causes a larger device-size (as the measure-range is fixed).

To solve the problems and realize compatible volume-fabrication in IC-foundry (avoid double-side micromachining and wafer-bonding), we develop a single-wafer-based and front-side fabrication technique to form the sensor that is schematically shown and compared with the conventional counterparts in Table.1.

Table 1: Comparison of our present sensor structure (at the 3rd row) compared with conventional ones

Sensor structures by cross section	Performance comparison		
	Structure/fabrication style	Device size/fabrication cost	Diaphragm uniformity control/yield
	Silicon-glass bonded/double-sided process	Big size/high cost	Poor control/low yield
	Silicon-silicon bonded (or use SOI wafer)/double-sided alignment needed	Medium size/high cost	Medium control/medium yield
 Our present sensor	Single-polished single-wafer/single-sided process	Small size/low cost	Good control/high yield

DESIGN OF THE PRESSURE SENSOR

Fig.1 shows the schematic of our proposed pressure sensor structure. Compared with the traditional bulk-micromachined pressure sensor structure reported in [2]-[5], herein the reference-pressure cavity beneath the diaphragm is embedded into the silicon substrate by using lateral under-etch.

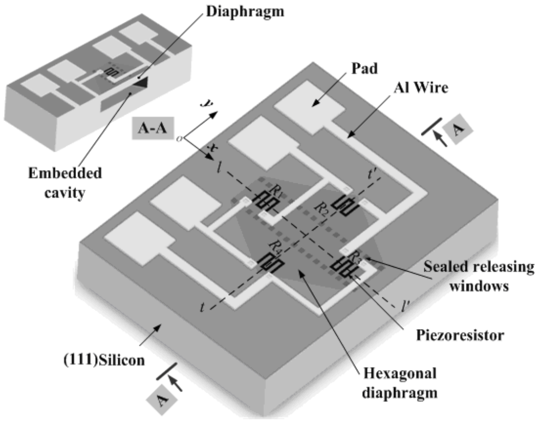


Figure 1: 3-D schematic of our proposed sensor structure with front-side fabricated hexagonal diaphragm above an embedded-cavity.

Shown in Fig.2 is the top-view design schematic for the pressure diaphragm formation from wafer front-side. Two rows of release opening hole are aligned <111> orientation for the diaphragm formed by lateral under-etch along <110> and <211> orientation with all the boundary walls as {111} planes. Based on (111)-silicon anisotropic etching theory [6], [7] and software simulation results, hexagonal-shaped diaphragm can be finally formed by (111) etching stop.

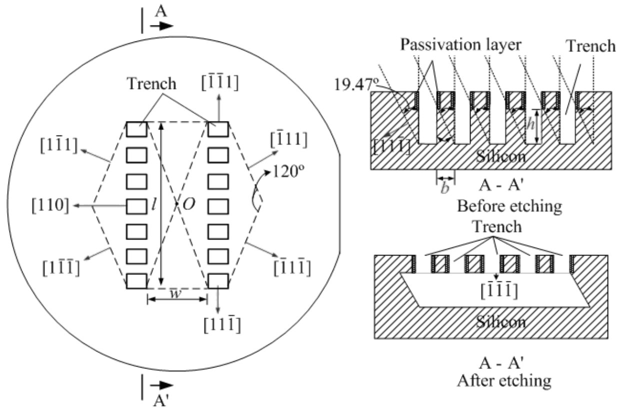


Figure 2: Front-side release holes and hexagonal-diaphragm formation scheme in (111) wafer is top-view shown at the left-side. The diaphragm formation by lateral under-etch is sketched with a cross-sectional view at the right-side.

With ANSYS stress simulation, four piezoresistors are optimally designed at the maximum stress locations of the diaphragm to form a full-sensitive Wheatstone-bridge shown in Fig.1. We design a 750KPa-range absolute pressure sensor, with l=350μm, w=56μm (see Fig.2) and the diaphragm thickness of 10μm. The designed sensitivity is 0.035mV/V/KPa.

FABRICATION

Fig.3 shows the single-wafer-based single-sided fabrication steps. 450μm-thick n-type (111) wafer is used and the entire process requires only 4 mask-layers. The fabrication details in follows:

(a) A 0.2μm-thick SiO_2 layer is thermally grown on both sides of the wafer by dry oxidation.

(b) After thermal oxidization, photolithographic steps are conducted from the front side of the wafer for patterning piezoresistors on a photoresist layer. Then buffered HF is used to etch SiO_2, with the photoresist as etching mask. Piezoresistors are formed by boron ion implantation followed by drive-in process. The doping concentration is controlled at the level of about $1\times10^{19}/cm^{-3}$.

(c) LPCVD low stress nitride and dioxide is deposited sequentially as a hard mask for following silicon DRIE and the final KOH or TMAH lateral under-etch to form a reference-pressure cavity and release the diaphragm. Two rows of opening hole are patterned with the second-mask photolithography, and then with the patterned photoresist layers as mask, DRIE trench is etched to a designed depth to define the thickness of the diaphragm.

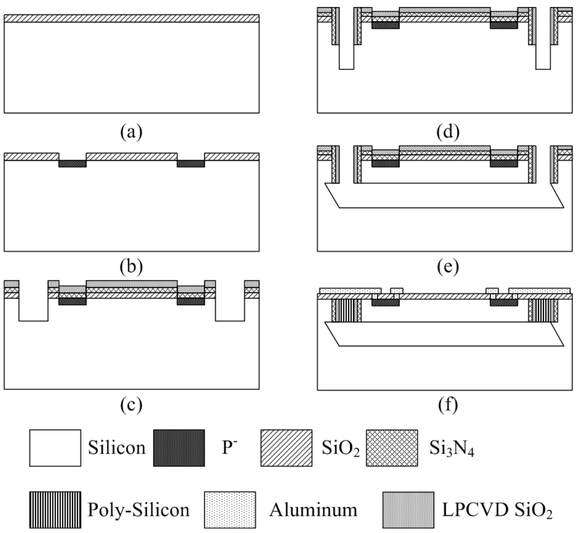
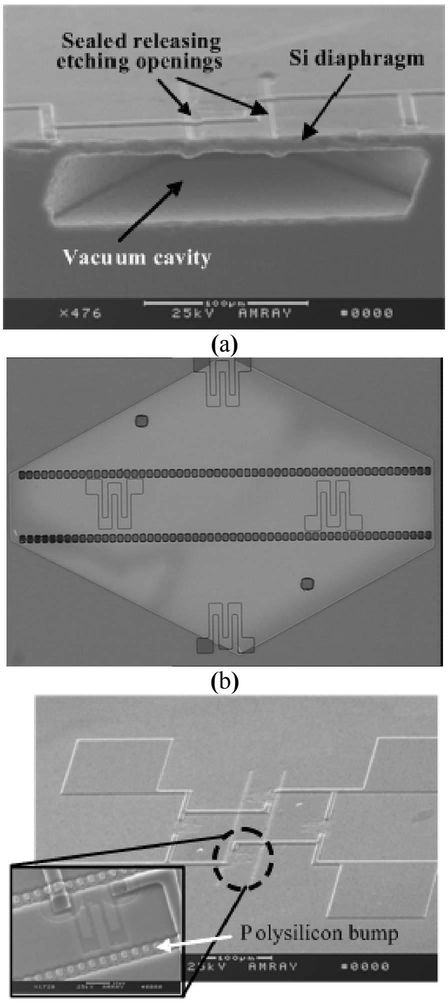


Figure 3: Fabrication process flow for the pressure sensor



(a)

(b)

(c)

Figure 4: Images of the fabrication sensor. (a) Cross-section of the diaphragm and cavity; (b) Hexagonal-shaped diaphragm; (c) Sensor chip top-view with an inset showing the sealed release holes.

(d) Low-stress nitride and TEOS layers are sequentially deposited to protect the trenches sidewalls from the following anisotropic etch. The passivation layers at the trench bottom are then dry etched with RIE. DRIE is processed again for an extra depth of the trench where silicon is exposed for further lateral wet etch (the depth is equal to that of the reference cavity.

(e) Aqueous KOH or TMAH is used to laterally under-etch along <110> and <211> orientation that is finally stopped at (111) plane to form the hexagonal diaphragm.

(f) Conformal poly-Si is LPCVD deposited to seal the openings hole and the reference-pressure cavity is hermetically in low vacuum. After the poly-Si at other regions is removed, piezoresistive contact holes are opened and aluminum interconnection is formed.

It is deserved to point out that the fabrication precision of the 10μm-thick diaphragm is determined by the 10μm-deep front-side DRIE trench etching depth. If conventional backside etching method used, the 10μm diaphragm thickness should be determined by the wafer thickness (450μm) subtracted by the backside etching depth of 440μm. Obviously, our front-sided fabrication method features much higher uniformity and yield.

The fabricated pressure sensor is with the diaphragm and the vacuum cavity shown in the cross-sectional SEM of Fig.4 (a). The hexagonal shape of the diaphragm can be clearly seen in Fig.4 (b) and the front-side sealed release holes are shown in Fig.4(c).

RESULTS AND DISCUSSION

Druck DPI-104 pressure gauge and PV211 hand-held pump system is used to measure the performance of the pressure sensor. The measured output voltage as a function of applied pressure at room temperature of 20ºC is shown in Fig.5, resulting in a sensitivity of 0.033mV/V/KPa under 3.3V power supply for the Wheatstone-bridge without any amplification. The full measure range of absolute pressure is 750KPa. The measured sensitivity is slightly lower than the designed 0.035mV/V/KPa. The discrepancy in sensitivity is probably due to the fabrication tolerance. For example, during the cavity vacuum-sealing process, the trench refilling polysilicon is quite conformal and may also deposit on the bottom surface of the diaphragm, which may lead to a little bit thicker pressure-sensor diaphragm than the designed thickness of 10μm. Still based on the result in Fig.5, a lower than ±0.1% ·FS non-linearity error of the pressure sensor is generally obtained that is defined by the best straight-line fitting method.

Fig. 6 shows the zero-point offset voltage of the fabricated pressure sensor as a function of temperatures. Based on the results shown in Fig.6, it is clear that even though the two rows of opening holes are embedded in the single crystalline silicon diaphragm, the tested temperature coefficient of offset (*TCO*) as low as -0.022%/ ºC·FS from -40ºC to +120ºC indicates no obvious influence to the sensor stability and the temperature coefficient of sensitivity (*TCS*) is about -0.18%/ ºC without any compensation.

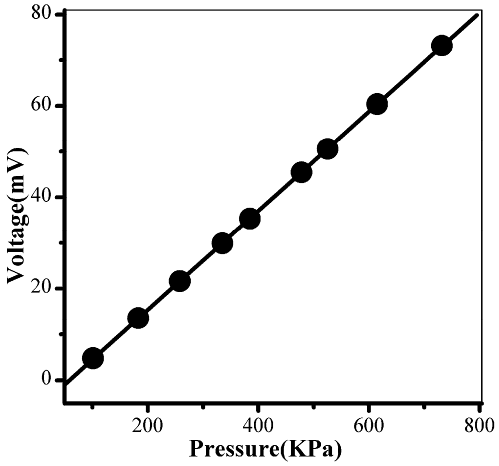


Figure 5: Tested sensor output voltage vs pressure.

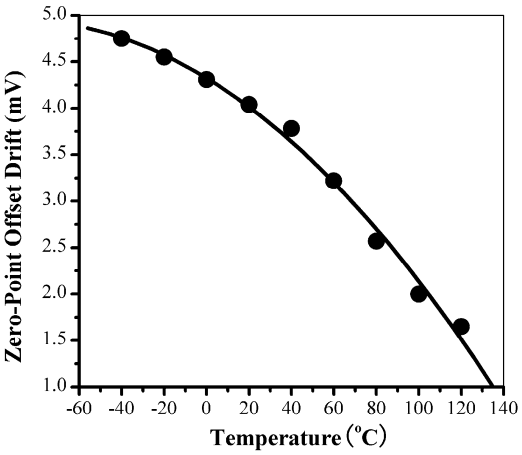


Figure 6: Tested zero-point offset voltage of the pressure sensor in terms of temperature change.

CONCLUSION

In summary, the pressure sensors have been proposed and fabricated with a novel single-wafer-based single-sided bulk-micromachining technology. The diced sensor chip dimensions are as small as 0.6×0.6×0.45mm^3. If high-yield volume-fabricated in a 6- or 8-inch IC foundry, ultra-low fabrication cost of one US-cent per sensor can be reasonably realized.

ACKNOWLEDGEMENTS

This research is supported by NSFC Project (60725414, 91023046), Chinese 973 Program (2011CB309503) and the National S&T Major Project (2009ZX02038). Xinxin Li also thanks Korean WCU project (R32-2009-000-20087-0).

REFERENCES

[1] W. P. Eaton, J. H. Smith, “Micromachinined pressure sensor: review and recent developments,” Smart Mater Struct, vol. 6, pp. 530–539, May 1997.

[2] Y. Zhang, B. Liu, L. Liu, Z. Zhang, Z. Tan, H. Lin, T. Ren, “Design, fabrication and characterization of novel piezoresistive pressure microsensor for TPMS,” *IEEE2006*, pp. 443-446.

[3] H. Jin, D. Lu, S. Shen, M. Bao, “High linearity piezoresistance micromachining accelerometer with low range,” Journal of Functional Materials and Devices. Vol, 9, no.2, pp. 135-151, 2001.

[4] Y. Zhang, B. Liu, L. Liu, Z. Zhang, Z. Tan, H. Lin, “Design and fabrication characterization of novel piezoreisitive pressure microsensor for TPMS,” *in Proc. IEEE Solid-State Circuits, 2006*, pp. 443-446.

[5] T. Chou, C. Chu, C. Lin, K. Chiang, “Sensitivity analysis of packaging effect of silicon-based piezoresistive pressure sensor,” Sens. Actuators A. Phys., vol.152, no.1, pp. 19-38, May. 2009.

[6] H. Seidel, L. Csepregi, A. Heuberger, H. Baumgärtel, “Anisotropic etching of crystalline silicon in alkaline solutions,” J. Electrochem. Soc., vol.137, no. 11, pp. 3612-3626, Nov. 1990.

[7] S. W. Lee, S. J. Park, J. P. Kim, S. C. Lee and D. D. Cho, “Surface/bulk micromachined single-crystalline-silicon micro-gyroscope,” IEEE/ASME J. Microelectromech. Syst., vol.9, pp. 557-567, Dec. 2000.

CONTACT

* Xinxin Li, tel: +86-21-62131794; xxli@mail.sim.ac.cn