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Peak-Performance with a Minimal-Range Differential Pressure Sensors Formed a Thin-Film under Bulk Machining Technology and it Future Research.

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ABSTRACT: In the production field of microelectromechanical systems (MEMS), a small-range (e.g., kPa or sub-kPa) differential pressure sensors problem has remained unsolved for several years. However, these two unsolved problems hindered production volume and wide applications in electronics demands. Firstly, high sensitivity with a very thin and large sensing diaphragm normally fabricated with low yield, and these are quite expensive. The second is high sensitivity with a high deflection of the its diaphragm which causes severe output of non-linearity that reduces the detecting precision or accuracy. This paper presents a so-called thin-film under bulk (TUB) MEMS technique to fabricate high-yield and high performance with low or small-range pressure sensors for "Smart "central air-conditioning systems. With the single-wafer-based TUB structure, pressure-induced stress is highly concentrated in a bulk-silicon beam-island structure for piezoresistive output, where a very thin but uniform poly-silicon diaphragm can be formed under the bulk-silicon structure to sustain the pressure. The beam island reinforced structure brings about decreased deflection and highly linear output of non-linearity that reduced the detecting precision response of the system. Micro-columns are also produced under the bulk-silicon islands as over-range protection stoppers that are important for low-range pressure sensor. The novel high-yield TUB process can be used for low-cost production of "high-performance" pressure sensors for the applications of new-generation smart central air-conditional systems etc., and the bulk/surface combined TUB micromachining technique hopefully to be widely used for the formation of various complex MEMS structures.

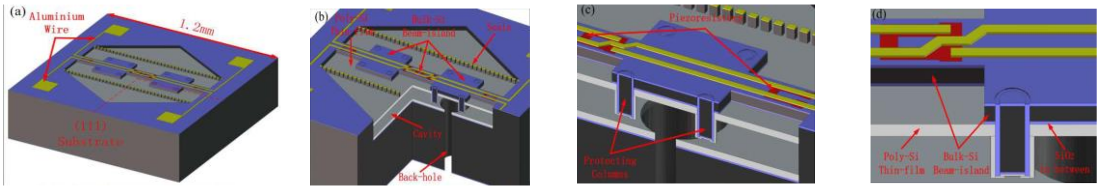
Index Terms - Minimal-range pressure sensor, piezo - resistance, nonlinearity, over-range protection, single- wafer micromachining process, Micromechanical systems (MEM), Thin-film Under Bulk (TUB), Smart, and Techniques.

I. INTRODUCTION

There have been a rampant and abrupt development of silicon-based **MEMS** technologies over the past two decades, a series of high-performance **MEMS** sensor products have been industrialized. There have been being exclusive advantages in high-performance and low-cost batch micro-fabrication, the developed piezoresistive pressure sensors have been one kind of the most needed and successful sensor products of industrial, biomedical and automotive use [1]. Nowadays, **"smart"** consumer-electronics market demand requires huge numbers of low-cost pressure sensors. One kind of such sensors are air absolute pressure sensors that serve as barometers or altimeters that are used for smart-phone and drone applications [2] [3]. Another emerging requirement comes from central air-conditioning systems, where very low cost differential pressure sensors are needed to measure small-range of pressure (about 1 kPa) at individual wind outlets for feedback control. Meanwhile, it is very difficult to get such relatively high-performance with a low or small-range differential pressure sensor product cheaply. This is due to the following reasons: (1) Small-range pressure detection needs high-sensitivity sensors that should employ very thin pressure-sensitive diaphragm, (2) the silicon diaphragm etching yield is normally quite low that directly causes high selling price and low production rate. While considering the traditional pressure sensor fabrication, it normally uses double-wafer process (e.g., aligned bonding between two wafers) which resulted to high cost and large sensor die-size. Some MEMS sensor suppliers like Robert Bosch and ST Microelectronics have developed such single-wafer process to low-cost manufacture barometers for smart cellphones [4], [5].With about 110 kPa measure-range, the barometer can simply consists of a flat silicon diaphragm for pressure sensing. But for the pressure range like 1 kPa low-range sensor however, it required ultra-high sensitivity needs ultra-thin of about (e.g., 1~2 μm) and large (e.g., diameter>1 mm) silicon diaphragm. Regardless this, a very thin and large diaphragm is difficult to be uniformly controlled in fabrication, such a flat thin-diaphragm often causes severe nonlinearity in sensing signal amplitude due to the large deflection which resulted to mechanical nonlinearity [6]. For solving the problem of nonlinearity, the flat diaphragm can be replaced by rigid island and/or beam reinforced diaphragm to avoid excess deflection [7], where more portion of the pressure induced stress can be concentrated in the reinforced structure to secure high piezoresistive sensitivity [8]. This work was reported by [9], a beam-island reinforced diaphragm for both stress concentration (i.e. high sensitivity) and deflection restriction (i.e. low nonlinearity) was investigated. The uncontrollable double-sided process (e.g., diaphragm etching without a stop controller) as reported in the work of [9] is not suitable for high-yield batch fabrication. The MIS micromachining process can also be used to form a cavity under a bulk-silicon diaphragm by opening micro-holes from wafer front-side for the cavity lateral wet etch. The fabrication technique can be compatibly implemented in standard IC foundries for low-cost volume manufacturing [10]. So far, the MIS process has been successfully employed to fabricate a high-yield and low cost pressure sensors, accelerometers, flow sensors, TPMS (tire pressure monitoring system), composite sensors and even resonant bio/chemical sensors, etc. [11]–[16]. As a result of this, both high sensitivity and low nonlinearity can be achieved. In order to enable the highly sensitive low or small-range pressure sensor a highly sensitive and reliable one is needed to sustain against high-pressure impact pulse that is possible in practical applications, over-deflection stopping function is achieved by adding micro columns beneath the beam-island to mechanically stop or regulate the movement when in contact with the bottom plane of the cavity. Conclusively, the TUB technique gives a high-performance and reliable solution to meet the demand of small-range pressure sensors for the application market of smart air-conditioning control and home-automation systems.

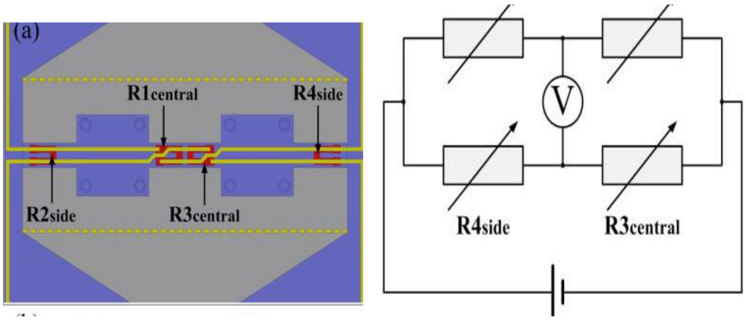
II. THE DESIGN OF THE TUB PRESSURE SENSOR

The three-dimensional structure of the 1.2 mm×1.2 mm sized sensor chip is sketched as shown in Fig. 1(a) was provided with its partly cut structure shown in Fig. 1(b). All the sensing structure is integrated in an n-type (111) silicon substrate. The incorporated cavity under the diaphragm of the differential pressure sensor has two backside holes under the two islands in order to ventilate through the low pressure side or to provide ambient reference pressure into the cavity. Comparing the traditional pressure sensors with flat film, a more complex structure that consists of a poly silicon diaphragm, SCS beam-islands and over-range protecting bottom-columns is needed. In order to adapt to the about 1 kPa small pressure range, the diaphragm thickness is designed as thin as 2 μm [6] and the circum-circle diameter of the hexagonal shaped diaphragm [12] is 950 μm in length. The top SCS beam and twin-islands are optimally designed as 3 times in thickness of the poly-silicon thin-film, i.e., 6 μm, to achieve both high sensitivity and low nonlinearity [9]. This SCS and poly-silicon combined double-layer structure really facilitates independent design of each layer to achieve optimized sensing performance. In order to further clarify the configuration, a close-up schematic is shown in Fig. 1(c) and (d). Two rows of poly-silicon micro-seals for blocking the micro-holes are widely enlarged as shown in Fig. 1, for ease of observation. In fact the micro-seals are quite small in size that can be seen in the SEM image of Fig. 5. The layout of the piezoresistors on the beam-island structure is schematically shown in the top-view of Fig. 2(a). Two piezoresistors are laid at the central beam and other two at the side beams, respectively. When pressure is applied, the two piezoresistors at the side of the beams exhibit opposite resistance change to the other two at the central beam, thereby forming a fully sensitive Wheatstone-bridge that is shown in Fig. 2(b). This is in consent with the theoretic analysis according to the design rule in [6] and [9], finite element simulation is also implemented, with the simulated deflection and stress as illustrated at the left and right sides of Fig. 3, respectively. To accurately get a quantitative relationship between the high-pressure induced large deflection and the diaphragm thickness, nonlinear mechanical simulation program is needed which is shown in .Fig. 3(a).



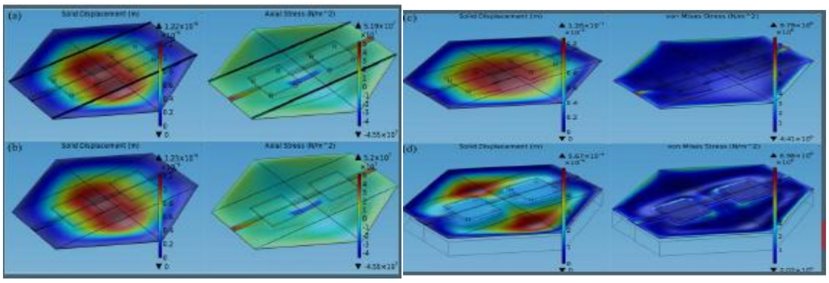
(a) (b) (c) (d)

Figure 1 (a, b, c, and d): Shows the design Procedure of the TUB Pressure Sensor



(a) (b)

Figure 2 : (a) Shows Layout of the piezoresistor at the central beam and side beam. (b) Shows Schematic of the piezoresistor **Wheatstone Bridge** for Pressure sensing**.**



(a) **(b)**

Figure 3: Finite element simulation results of beam-island reinforced TUB diaphragm under applied pressure, with the deflection and stress results shown in (a) and (b) respectively

It is worth mentioning that such a column contact structure for over-load protection is hard to be realized if the conventional (100) silicon wafer is used to form the differential pressure sensors, even though a bottom chip is used to bond with the sensing chip. The reason is that the small gap distance with the downwards column structure is hard to control. It is just the novel TUB process wafer that can do the task.

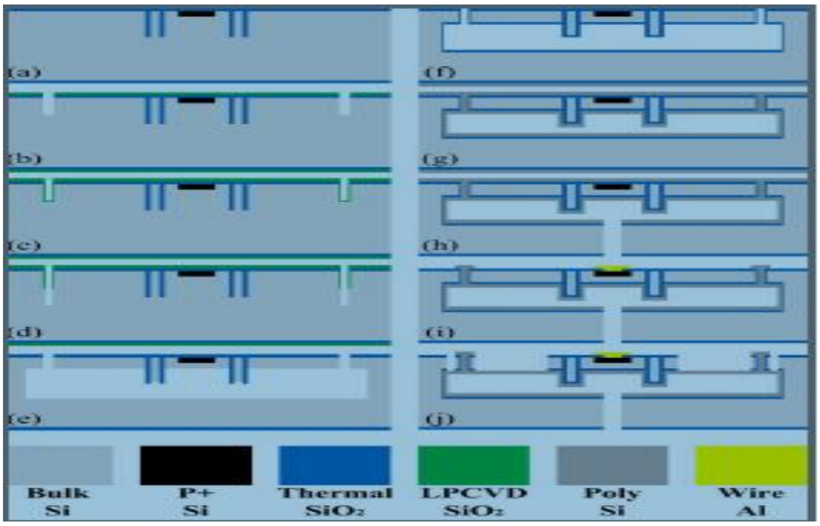


Figure 4. TUB processes for the differential pressure sensors. N-type doped 1-10cm (111) wafers.

The practical composition and analysis for these processes are shown as we have bulk Silicon single-crystalline silicon. P+ Si, heavily doped P-type silicon and thermally oxidized silicon, (LPCVD) Low-pressure chemical vapor deposition and Poly Si: Poly-crystalline, and Aluminum lines for interconnection within the beam.

III. FABRICATION PROCESS

Mostly during the manufacturing process, circular-ring shaped trenches are formed by DRIE (deep reactive ion etching) for the over-range stop columns. SiO2 and poly-silicon are continuously filled into the trenches by thermal oxidization and LPCVD (low pressure chemical vapor deposition), at any point when the trenches are just partly filled. SiO2 is deposited by TEOS (tetraethyl ortho silicate) LPCVD. The Micro-holes are then opened, through which trenches are etched by DRIE. TMAH etch for the formation of the cavity, the trench should be etched a little bit deeper to compensate for better influence and penetration. The surface of the trench is coated with TEOS LPCVD SiO2. The SiO2 at the trench-bottom is removed by RIE to expose SCS at the trench-bottom. TMAH is processed to form the cavity, and a thin thermal SiO2 layer is grown that can cover the whole surface inside the whole cavity and LPCVD poly-silicon is grown inside the cavity via the micro-holes until the trenches are fully refilled, DRIE is performed to form the reference pressure ventilation holes. The dry etch can be automatically stopped by the SiO2 layer pre-formed with the SiO2 layer and the poly-silicon layer sequentially removed by RIE, the two reference pressure holes are opened, then the poly-silicon is annealed in order to remove residual stress, it is hindered at the most area but with the micro seals at the trench top for proper feature. Also the aluminum interconnection for wire bonding is processed by sputtering, patterning and sintering. Then the SiO2 on the diaphragm surface is etched to expose the poly-silicon diaphragm, where the SiO2 layer under the SCS beam-island is retained all this procedures are shown in Fig.5 below.

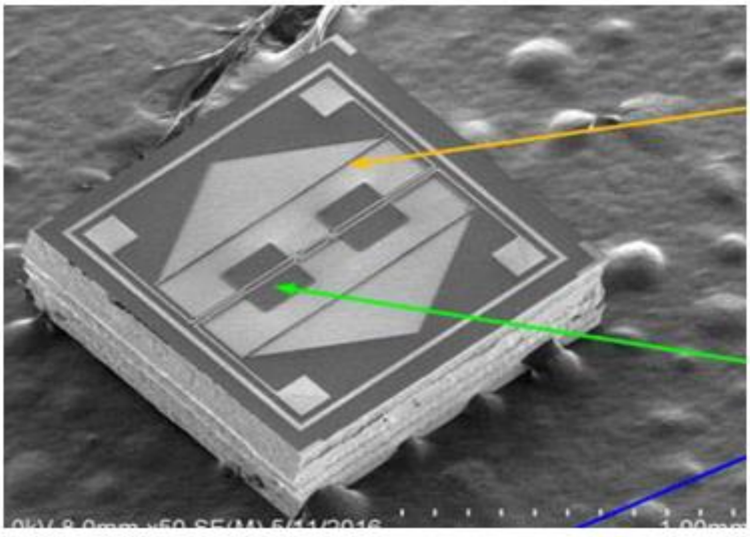


Figure 5 SEM images of the TUB-process fabricated sensor

Future Research

It is my believe that proposed TUB process can be used to fabricate various categories of pressure sensors with varied measure-range by varying the size/thickness of the poly-silicon thin-film or by altering the shape/thickness of the SCS beam-island. Being capable of fabricating complex 3D micromechanical structure, many other kinds of **MEMS** devices have potential to be developed by using the TUB process.

IV. CONCLUSIONS

A high-performance low-range differential pressure sensor with robust overload protection is proposed and can be designed into the TUB structure. The TUB sensor process features have high fabrication yield that facilitates low-cost volume manufacturing in standard semiconductor foundries. By using a very small chip size and the high-yield single-wafer process, the price of the low-range pressure sensor can be quite low and bring about wide applications in the products for central air-conditioning systems, spirometers, smart consumer electronics and even disposable medical tools.

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