Design and Realisation of a Quasi Monolithic Silicon Load Cell

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SUMMARY

In this paper, the first silicon load cell is presented designed for measuring a load up to 1000 kg. A prototype has been realised. An improved cryogenic RIE process with high aspect ratio was developed for the fabrication of thin springs. Low temperature silicon direct bonding was used for the final assembly. The mechanical structure was tested using poly silicon strain gauges. Encapsulated resonant strain gauges [1] will be used in the final design in order to obtain the desired accuracy of 0.03%.
Keywords: Force sensor, RIE etching, Silicon Direct Bonding

INTRODUCTION

Load cells are force sensors used in weighing equipment. Most conventional load cells are made from steel or aluminium. When a load is applied, the metal part of the load cell deforms, which is measured by resistive strain gauges. To minimise hysteresis and creep, expensive materials and fabrication techniques have to be used. Silicon does not suffer from hysteresis and creep, and therefore it is an ideal material for use in load cells. Using silicon as the base material allows the fabrication of very accurate load cells. Furthermore, the load cell can be fabricated by using standard micromachining techniques.

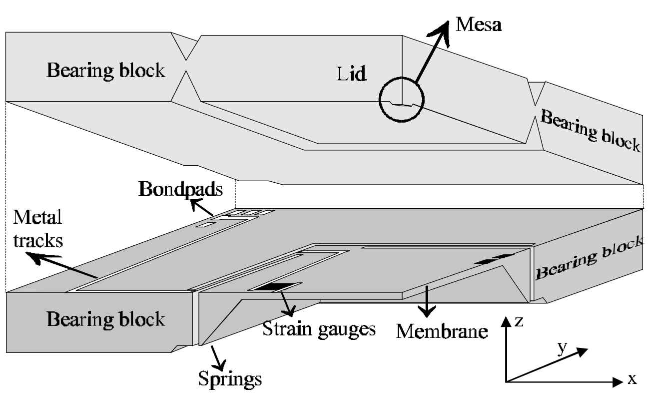

Figure 1. Three dimensional cross section of a quarter of a load cell .

DESIGN AND OPERATION

The load cell consists of two silicon wafers, bonded on top of each other. Figure 1 shows one quarter of a load cell.
The strain gauges are placed on a membrane (30μm) in the middle of the load cell. The frame of the loadcell is a bearing block, which carries the complete load. In the middle of the top wafer is a lid. In the centre at the bottom of the lid there is a small mesa which connects the lid to the membrane. The dimensions of the load cell are approximately 0.8 x 0.8 cm. with a height of 0.7 cm.
When a load is applied, the bearing block is compressed and it acts like a stiff spring. A downward displacement of the lid is observed (Figure 2).

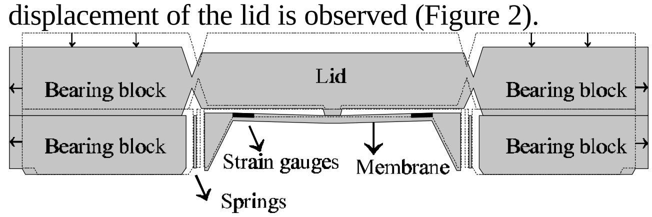

Figure 2. A cross section of a loaded load cell.

The membrane itself is also displaced downwards due to the connection via the springs with the bearing block of the bottom wafer, but this is not as much as the displacement of the lid (because its connection lies lower). The mesa will push the membrane down and make it bend, the strain sensors measure the induced strain.
For a proper measurement, the membrane is suspended to the bearing block by springs (Figure 3), in order to isolate it from horizontal displacements of the block. This is necessary because when a load is applied, the bearing block will not only be compressed in the z-direction but it also expands in the x and y direction. This effect was simulated using the finite element program ANSYS [2]. It showed that without springs, the expansion causes additional bending of the membrane, thus disturbing the strain measurement. Furthermore, when using stainless steel as the material on top of the load cell to conduct the force into the load cell (the housing), the steel will suffer from creep and hysteresis in the x-y direction. Without springs, this would also be sensed by the membrane.

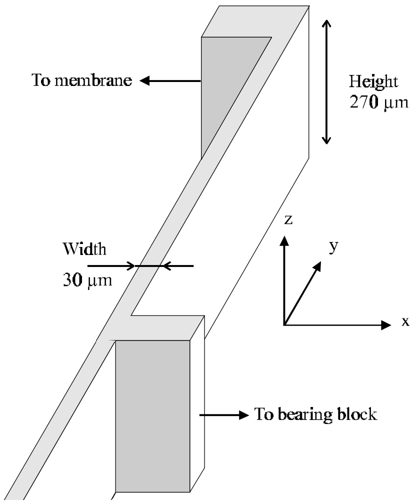

Figure 3. Thin springs; weak in the x-y direction, stiff in the z direction.

Gauge positions

A load will induce a strain on the membrane. When the maximum load is applied, the strain measured by the encapsulated built-in resonant strain gauge has to be $1\cdot10^{-5}$ for optimal sensitivity of this gauge. The maximum strain in any place in the silicon of the load cell has to be less than 0.01 to avoid fracture. The operation of the load cell is verified by a finite element analysis (ANSYS 5.3). A plot of the strain induced on the membrane at maximum load is given in Figure 4. The triangle is one eighth of the full membrane.

The strain gauges are placed at the position where the maximum strain is $|10^{-5}|$ (see Figure 4).

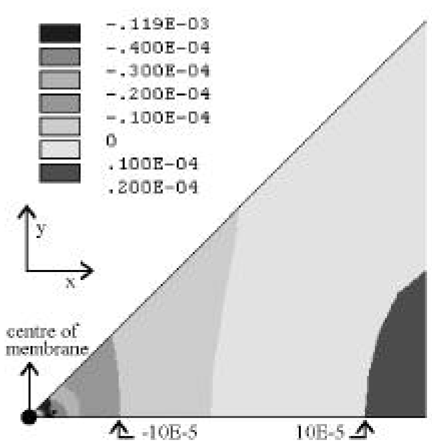

Figure 4. Strain in x direction on membrane (showing one eighth of the membrane).

REALISATION

The top wafer was made using KOH etching. Simple compensation structures [3] were used to protect convex corners from underetching.

Figure 5 shows the processing scheme used for the bottom wafer. First, 1µm low stress LPCVD nitride is deposited on a silicon substrate (1). After patterning, the membrane is etched using KOH (2). Next, poly silicon is deposited (3). It functions as a mask material for nitride removal in 50% HF to clear the bond surface (4), and is patterned into the strain gauges (5). Aluminium is deposited by lift off techniques (6). Finally the springs can be made (7). After this, no lithography can be performed on the wafer anymore. Now, the wafer is ready to be bonded to the top wafer. The last two steps will be explained into further details below.

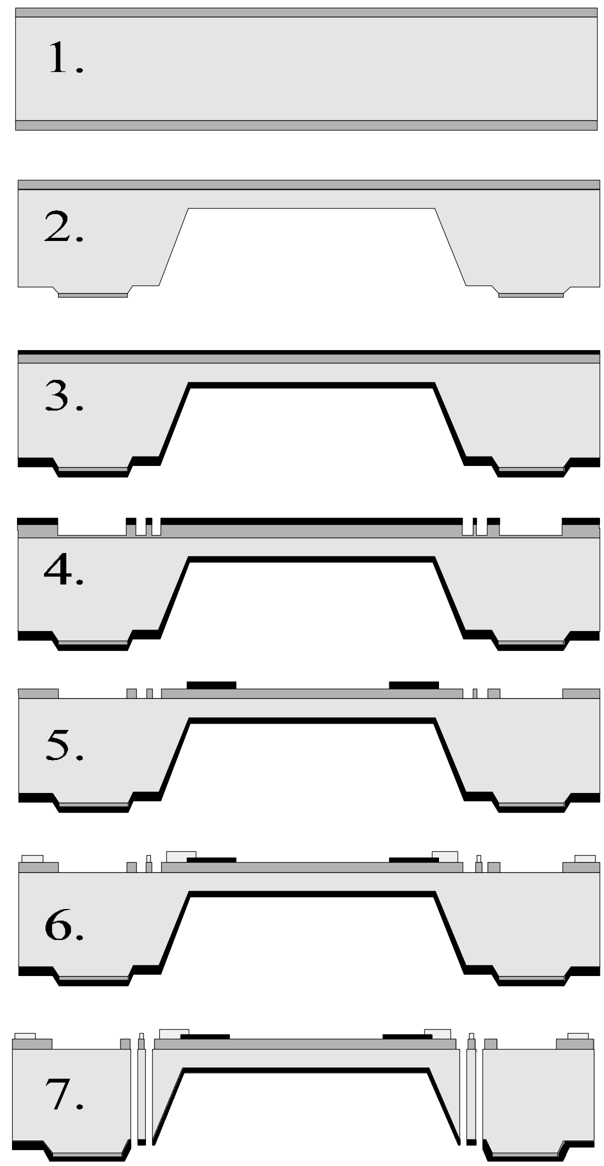

Figure 5. The processing scheme of the bottom wafer.

Fabrication Of Thin Springs

The mechanical structure of the load cell requires thin springs; beams of 30 (width) by 1150 (length) by 270 µm (height). The springs are made by dry cryogenic high density reactive ion etching (RIE) using SF_6/O_2 based chemistry with low ion energies. The deep trench etching with an aspect ration of 8 is performed in an Oxford Plasmalab System 100 [4].

The RIE process was improved to increase the selectivity of resist up to 1000 and the aspect ratio up to 8. Temperature is one of the parameters that can be used to tune the profile of the trench. In Figure 6 the temperature was varied between -110°C and -90°C.

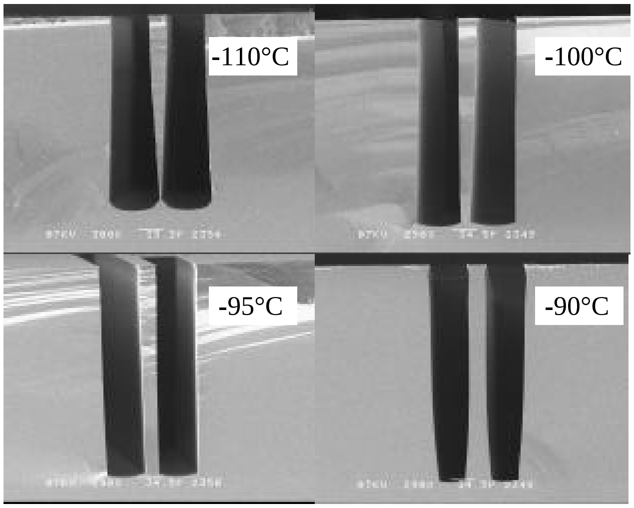

Figure 6. Influence of temperature on profile.

Wafer through etching

The substrate holder is cooled with liquid nitrogen to a temperature of about -110°C. Helium gas is used to keep the wafer in heat contact with the holder. When a hole is etched through the wafer, the RIE process is disturbed because the helium gas can escape. To prevent this, a polymer layer is applied to the backside. The resulting hole is shown in Figure 7. This figure shows on the left the bearing block, and on the right the thin spring. The membrane was removed for this picture. Although the top of the spring has a bottle neck shape, this result is satisfactory for the load cell.

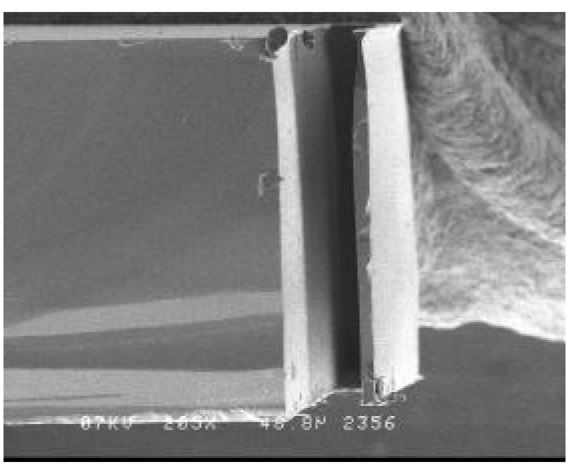

Figure 7. Wafer through etching.

Low Temperature Silicon Direct Bonding

To complete the load cell, two wafers are bonded to each other. A common way to bond the wafers is by silicon fusion bonding; wafers are contacted at room temperature and annealed at a temperature of 1100°C. It results in very strong bonds, but temperatures higher than 450°C will destroy the aluminium connections of the load cell. An interesting alternative is Low Temperature Silicon Direct Bonding (LTSDB).

To achieve a suitable low temperature bond, the surface of the wafers must be treated in a special way before contacting at room temperature and annealing at 450°C. Several procedures were tested, all were preceded by a standard wafer clean (2x 5 min. fuming HNO_3 (100%), rinse, 15 min. boiling (95 °C) HNO_3 (70%), rinse). The bond energy was calculated from the gap length, introduced by inserting a thin blade between the bonded wafers. The three special treatments are:

1. PE oxygen plasma; 1 min. 120 Watts, 55 sccm O_2, 150 °C, 2 mbar [5, 6].
2. RIE oxygen plasma: 1 min. 30 Watt, 20 sccm O_2, 20 °C, 150 mTorr [7, 8].
3. 1% HF dip, 60 sec., followed by a 100% HNO_3 dip, 10 min. [9, 10].

The results are listed in Table 1.

Table 1: Low temperature bond quality

Treatment:	**Bond energy: [J/m^2]**
PE O_2 plasma	**1.07**
RIE O_2 plasma	**0.73**
100% HNO_3 dip	**0.34**
no extra treatment	**0.69**

It appears that the Plasma Enhanced O_2 plasma gives the strongest bond. The much better result of a RIE plasma as mentioned in literature [7, 8] could not be observed. A bond strength of only 0.34 J/m^2 is sufficient to survive the sawing, the most critical step for the load cell after bonding. But bonds of more than 1 J/m^2 have been made.

MEASUREMENT RESULTS

So far, several load cell devices have successfully been fabricated. The mechanical structure was tested using poly silicon strain gauges, in a Wheatstone bridge configuration. Figure 8 shows some first measurement results, where a small load is applied to the centre of the membrane manually. A lever was used to decrease the force acting on the membrane. Figure 8 also shows the corresponding displacement of the centre of the membrane due to the applied force. As expected for these small forces there is a linear relationship between the force and the output signal of the Wheatstone bridge.

Some first measurements have also been performed on complete load cells. However, so far no reproducible results have been obtained due to the absence of a suitable package. Research now focuses on techniques to apply a load homogeneously to the edge of the load cell.

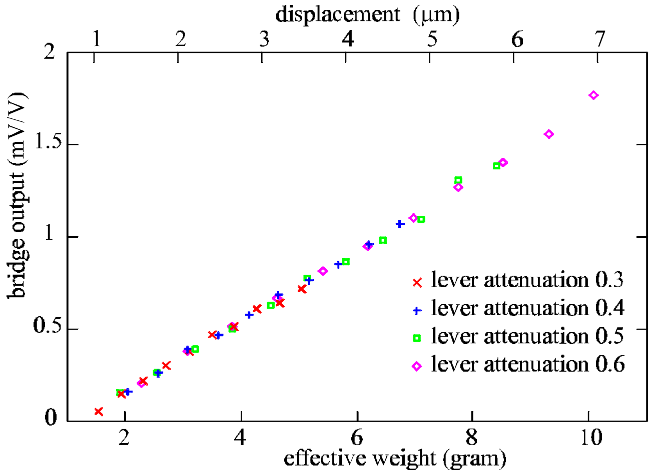

Figure 8. Output signal of the Wheatstone bridge as a function of an applied weight at the centre of the membrane.

CONCLUSIONS

A silicon quasi monolithic load cell was realised. KOH etching was used to define the major structure of the load cell. An essential element in the design of the load cell are the thin springs. They make sure that any movement in the xy direction, due to expansion of the bearing block or creep and hysteresis in the steel, is not passed on to the membrane. For this prototype, the springs are made with anisotropic cryogenic RIE etching. Photo resist was used as a masking material, because of its compatibility with the other process steps. To make the high springs possible, a new recipe was developed which increased the selectivity of resist. A polymer layer was applied as a backside protection, preventing the process to be disturbed once a hole was etched through the wafer.
Several Low Temperature Silicon Direct Bonding procedures were tested for bonding the top and bottom wafer. The low temperature (450°C) prevents the aluminium connections to be damaged. Good bonds of more than 1 J/m^2 have been made at this temperature. Measurements are performed using poly silicon strain gauges.

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