PERGAMON

MECHATRONICS

Mechatronics 8 (1998) 585–593

A pressure transducer with a single-sided multilevel structure by maskless etching technology

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Received 24 November 1997; accepted 4 February 1998

Abstract

A novel single-sided multilevel beam-diaphragm-mass structure has been designed and fabricated for high sensitivity silicon pressure transducers by using a novel anisotropic etching technology. The structure consists of three thin beams on a deep-etched thin diaphragm and two masses. Each mass consists of a mesa for stress concentration and a small island (post) on the mesa for overrange protection. As all the structures are on the back side of the wafer, the front side remains flat. The piezoresistors are diffused resistors on the front side in the locations with beams on the back. The multilevel structure features (1) flat front side facilitating metal interconnection; (2) small islands for overrange protection so that the electrostatic force caused by electrostatic bonding between the masses and the glass substrate is minimal; and (3) high burst pressure of the diaphragm. A prototype pressure transducer of 400 Pa operation range and 0.6% nonlinearity has been tested.

1. Introduction

Anisotropic etching technology has long been used for piezoresistive silicon pressure transducers. To improve the performances of the devices, the mechanical structures of the pressure transducers have been evolving continuously.

The simplest structure for a pressure transducer is a flat diaphragm structure which

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0957–4158/98 $—see front matter
PII: S0957–4158(98)00010–5

has been widely used since the 1970s. For better performances (high sensitivity and low nonlinearity), the structure with masses on the back was introduced by Whitter [1] in the late 1970s. For higher sensitivity, the scheme of anisotropic etching on front surface to form an additional structure level was first proposed by one of the authors in the late 1980s [2]. Pressure transducer structures with a dumbbell-shaped front beam were developed for high sensitivity pressure transducers. Back masses can also be cooperated to form a beam-diaphragm-mass-structure. Some more structures with front beams (ribs) or masses were also proposed for the same purposes by some authors in the early 1990s [3, 4].

The mechanical structures (beams, ribs or masses) on the front surface facilitate the alignment between the piezoresistors and the mechanical structures for stress concentration on the front side and the shallow etching is much easier to control than the deep etching from the back. However, the structures on the front side often pose restraints on metal interconnection and reduce the compatibility with IC process. Therefore, it would be ideal if both the shallow beams and masses can be formed on the back solely by an etching from the back side.

As the conventional anisotropic etching can only produce one new level by a series of steps of 'mask deposition-mask patterning-masked etching', multilevel structures have to be formed by repeating the step series many times. However, the etching depths for the etchings can only be shallow ones (not exceeding a few tens of micrometers) except for the last one. Therefore, it is impossible to form structure levels far from the original surface by a conventional anisotropic etching technology.

Described in this paper is a novel single-sided multilevel structure for silicon pressure transducer formed by a technology called 'masked-maskless anisotropic etching' [5, 6]. The structure has four levels, three of them are far from the original surface. The structure is formed only by etching from the back side so that the front surface remains flat.

2. Masked-maskless etching for multilevel structures

'Masked-maskless etching technology' [6] is a special etching technology which can create many new levels by a single 'masked-maskless' etching process. The structure levels created can be deep in the etching cavity. The principle of the creation of new levels by maskless etching is reviewed briefly in this section.

Suppose that a (100) silicon wafer has an etching mask as shown in Fig. 1(a). The mask has a narrow window in $\langle 110 \rangle$ direction with a large opening on the left as a control. The wafer is first etched with the mask in aqueous KOH solution for a depth, h. The cross-section of the etched wafer at this moment is shown by the thick broken line a_1–b_1 in Fig. 1(b). As is well known, the side-walls of the etching cavity comprise $\{111\}$ planes. Then the mask is stripped and the wafer is maskless-etched in KOH. During the maskless etching, both top and bottom levels are etched downward. In the meantime, the fast etching $\{311\}$ planes emerge at the convex edges of the $\{111\}$ sidewalls and cut the $\{111\}$ sidewalls from the top while the $\{111\}$ sidewalls extended downwards with the etching down at the bottom level. If h is large enough, the two

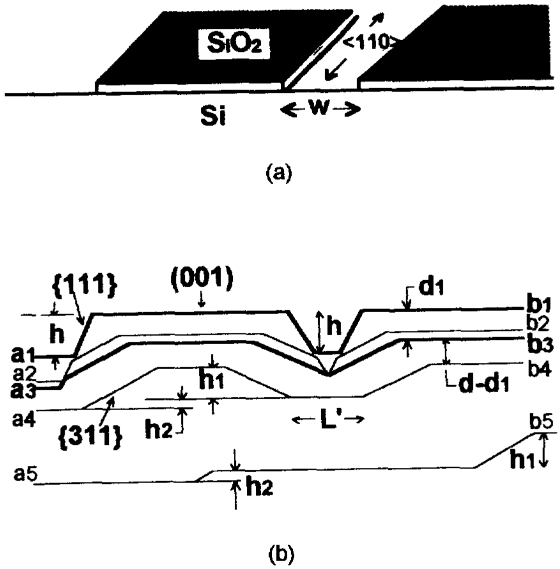


Fig. 1. The creation of a new level by maskless etching technology.

{111} sidewalls in the opposite sides of the narrow window will meet at the low end and etching stops for the bottom of the narrow window until the {111} sidewalls are replaced completely by the {311} sidewalls. The thin broken line a_2–b_2 in Fig. 1(b) shows the cross-section of the wafer after the {111} sidewalls meet at the low end. After some more etching period, two {111} sidewalls in the narrow window are replaced completely by the {311} sidewalls (refer to thick broken line a_3–b_3) and, then, a flat bottom reappears in the narrow window due to the lateral moving of the {311} sidewalls [1], as shown by the thin broken line a_4–b_4. Apparently, the reappearing bottom of the narrow window is not so deep as the bottom in the large opening because etching has never stopped there. The height difference between the new level and the bottom in the large opening is decided by the width of the narrow window and the etching depth h.

According to geometric calculations, the condition for creating a new level is that the etching depth, h, of the masked etching shall be larger than a critical depth h_0

$$h_0 = \frac{w}{\mathrm{tg}\alpha}\left[1 - \frac{\sin(\alpha-\theta)}{r_3 \sin\alpha}\right] = \left(0.707 - \frac{0.426}{r_3}\right)w \tag{1}$$

where r_3 is the ratio of etching rates for {311} and {100} planes,i.e. R(311) and R(100) respectively. r_3 is a function of KOH concentration and is usually larger than one, e.g. $r_3 = 1.71$ for 40% KOH by weight for temperature between 40–60°C. Therefore, for 40% KOH, h_0 is $0.456w$.

The etching depth, d_1, of the maskless etching is needed for the {311} sidewalls to replace completely the {111} sidewalls in the condition of $h > h_0$ is

$$d_1 = \frac{w}{r_3}\left(\frac{\cos\theta}{\mathrm{tg}\alpha} - \frac{\sin\theta}{2}\right) = \frac{0.426w}{r_3} \quad (2)$$

The new structure level appears when the etching depth of the maskless etching d, exceeds d_1 and the width of the level is

$$L = 2(d-d_1)(2.35\,r_3-2.12) \quad (3)$$

The height difference between the new level and the top (100) plane is

$$h_1 = h_0 \quad (4)$$

and the height difference between the new level and the etched bottom in the large opening is

$$h_2 = h-h_0 \quad (5)$$

It means that the original single step, h, formed by masked etching is now split into two steps, h_1 and h_2 by the maskless etching.

The ridge in-between the two etching windows can be cut flat by the lateral moving of the two {311} planes on both sides of the ridge in the following etching, as shown by the thin broken line a_5–b_5. Once the ridge in-between the two bottoms is cut off due to prolonged etching, the two bottoms will be close neighbours as shown by a_5–b_5 in Fig. 1; both are moving laterally in the same direction and the same rate as the {311} sidewall.

The etching depth of the maskless etching required to cut off the ridge between the windows:

$$d_\mathrm{r} = \frac{w}{2.345r_3} + \frac{B+w}{2(2.345r_3-2.12)} \quad (6)$$

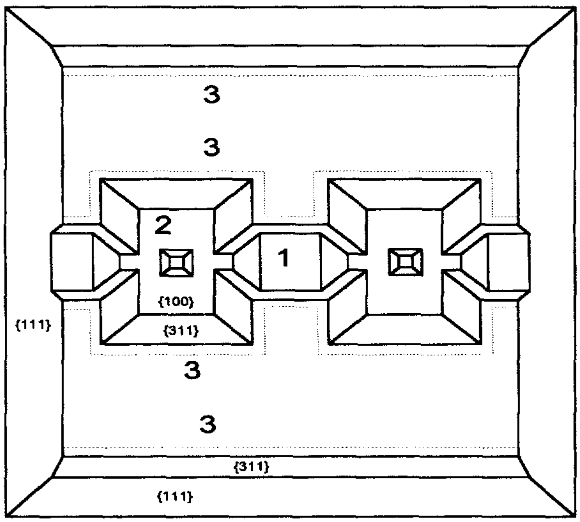
where B is the width of the mask between two windows. Once the ridge is cut off, the width of the new level reaches its stable value of $B+w$.

It has been observed in experiments that the convex edges on top of the {311} sidewalls are ideally prismatic, but the concave edges formed by the etch bottom and the {311} sidewalls are rounded-up a little depending on the distance of lateral movement of the {311} sidewalls. The roundups might be caused by the emergence of planes neighbouring (001) bottom after the {111} sidewalls are replaced by {311} planes and the investigation will be reported elsewhere.

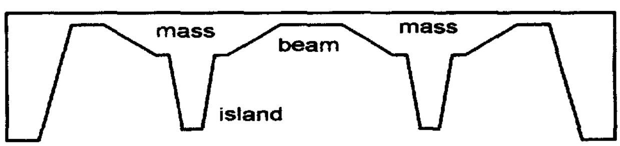
3. Single-sided multilevel structure

As an improvement to front-side beam-diaphragm structure [1] or doublesided beam-diaphragm-mass structures for high sensitivity pressure transducers, a single-sided beam-diaphragm-mass structure has been designed and fabricated by using the masked-maskless etching technology mentioned in the above section. The structures on the back side of the structure is schematically shown in Fig. 2.

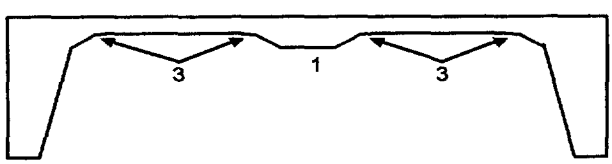
There are four structure levels inside the etched cavity. The bottom level is the back side of the diaphragm which is about two hundred and twenty micrometer deep from the unetched frame. Going up from the bottom, the second level is for three beams



(a) The schematic view of the multilevel structure



(b) The schematic cross-sectional view along the beam



(c) The schematic cross-sectional view across the central beam

Fig. 2. The schematic view of a single-sided island-beam-diaphragm structure (not to scale). (a) The schematic view of the multilevel structure; (b) The schematic cross-sectional view along the beam; (c) The schematic cross-sectional view across the central beam.

and the third level is the top of two masses. There is one small island (post) on each mass. For a typical design in our lab, the second level is about ten micrometer high from the bottom and the third level is about ninety micron high from the bottom. The top of the post is about 210 micron high from the bottom or about ten micrometer lower than the frame.

This structure is essentially a beam-diaphragm-mass structure, but differs from the previous beam-diaphragm-mass structure in some respects.

The first feature is that the beams are now on the back side deep in the etched bottom instead of on the front side formed by shallow etching. As the single-sided beam-diaphragm-mass structure has a flat front surface so that, the metal interconnection is more flexible and the IC process will not be hampered by the uneven surface.

The second feature of the structure is that the total height of the mass is now divided into two parts: a mesa with {311} sidewalls and a small post on the mesa. As the mesa is still much thicker than the diaphragm the mesa can maintain its role in stress concentration. As the total height of the mesa and the post is as high as the original mass (the top of the post is about ten microns lower than the frame) the tip of the post can still stop the movement of the mass in an over range condition. The volume cut of the mass has two advantages. First, the frequency response of the device will be improved by cutting short of the mass. Second, the electrostatic force between the masses and the glass substrate will be significantly reduced when the frame of the silicon chip is electrostatically bonded to the glass substrate by a electrostatic bonding process for packaging.

The third feature of the structure is that the corners between the diaphragm and the frame, and between the diaphragm and mesas along the beam directions, have slow curvatures consisting of {311} plane and the roundups. Therefore, the burst pressure after the tops of the islands are stopped moving by touching the glass substrate under large overrange pressure increases due to the curved corner profile [7].

The process for the pressure transducer starts with a (100), double polished, n-silicon wafer. The process steps for the front side are normal IC process steps to form the piezoresistors and connect them into a Wheatstone Bridge. The process steps for the back etching are described here.

Large etching window covering the whole cavity areas on the back side of the wafer are formed by a photolithographic step and BHF etching on silicon dioxide. Then the silicon in the windows is etched to a depth of about ten microns, depending on the requirement of overtravelling stop. Following this, the silicon wafer is deposited with 200 nm silicon dioxide on silicon and 150 nm silicon nitride on top of the silicon dioxide film. The wafer goes for photolithographic steps again to form a composed nitride/oxide mask. The silicon nitride mask is formed first followed by the silicon dioxide mask inside the window of nitride mask, the nitride mask for the frame and the posts for overrange stop. The area with silicon dioxide mask is for masked etch and maskless etch followed to form the rest structures.

For masked-maskless etching, the wafer is first etched in 40% KOH etchant to a depth of about 90 micron. The wafer is rinsed and the silicon dioxide mask is striped

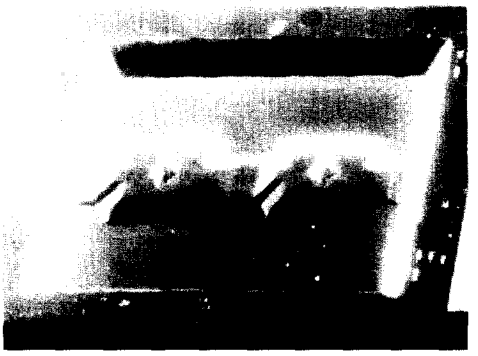


Fig. 3. The SEM picture of a multilevel structure for high sensitivity pressure transducer.

by BHF etch. Then the wafer is put back in the KOH solution again for maskless etching. The maskless etching is restricted by the nitride mask. The etching is continued until the thickness of the diaphragm is thin enough.

4. Experimental results

The SEM picture of the single-sided multilevel structure is shown in Fig. 3. To read the fairly complicated picture, readers are advised to consult the schematic drawing shown in Fig. 2. Four structure levels inside the cavity can be clearly recognised.

The sensor chips are then encapsulated by the most popular packaging scheme for pressure transducers. The sensor chip is first electrostatically bonded to a polished glass plate with a vent hole at the centre, as shown in Fig. 4. The silicon-glass structure is then mounted on a TO metal can type package, also with a vent hole on the bottom. The pressure is applied through a hole on the cap.

Some of the pressure transducers with the sophisticated multilevel structure are first calibrated in a low pressure range (0.5–1.0 kPa) for its sensitivity and nonlinearity

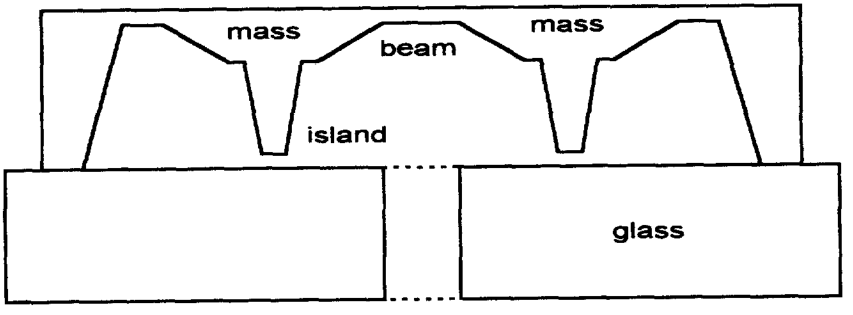


Fig. 4. Schematic view of the sensor-glass structure.

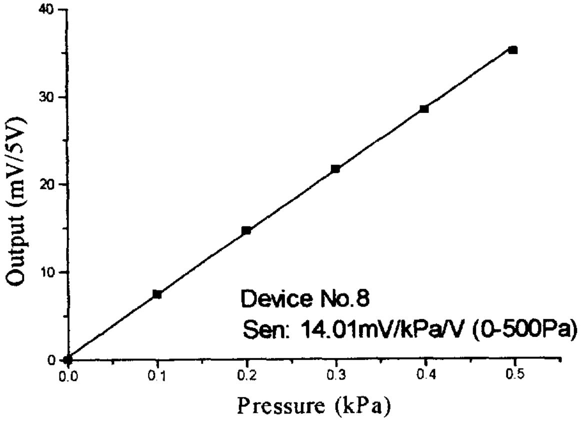


Fig. 5. Pressure response of the devices.

and then tested in pressure up to 50 kPa to evaluate the overrange protection capability provided by the over travelling stop mechanism.

Test results for one of the devices is shown in Figs 5, 6 and 7. The sensitivity is 34 mV/400 pa at 5 V power supply and the nonlinearity is found to be about 0.6% by the best fit straight line method.

5. Conclusions

A sophisticated single-sided multilevel beam-diaphragm-mass structure has been fabricated for a piezoresistive silicon pressure transducers by masked-maskless anisotropic etching technology. The structure consists of three thin beams on a deep-etched thin diaphragm and the two dual-step masses. The pressure transducers feature high

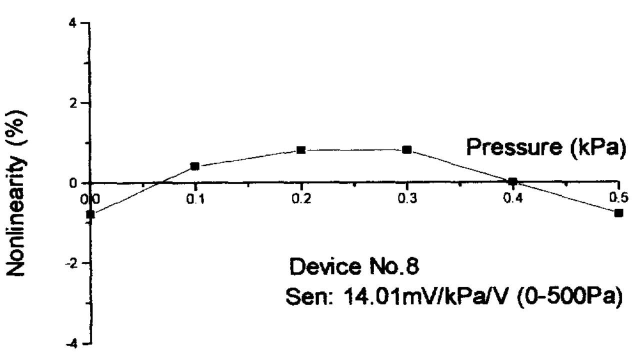


Fig. 6. The nonlinearity of the high sensitivity pressure transducer.

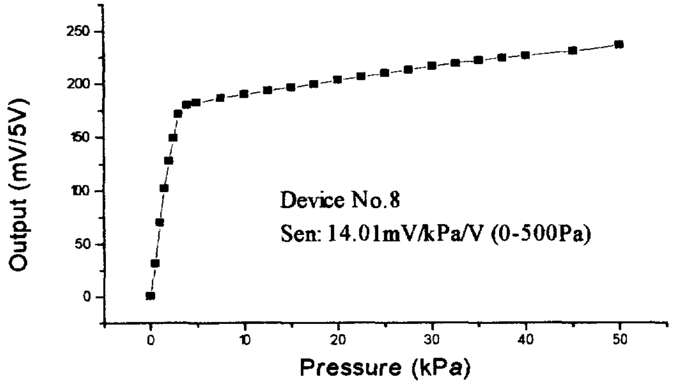


Fig. 7. Overrange performance of the pressure transducer.

sensitivity with operation range as low as 0.5 kPa and high burst pressure more than one hundred times higher than its operation range.

Acknowledgement

The work is supported by the State Key Labs of Transducer Technology, the 9th Five-Year-Plan of China and the NSF of China.

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