Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Engineering 47 (2012) 1513 – 1517
Procedia Engineering
www.elsevier.com/locate/procedia

Proc. Eurosensors XXVI, September 9-12, 2012, Kraków, Poland

Spontaneous Diaphragm Buckling Control Process on Piezoelectric Ultrasonic Microsensors for High Sensitivity

Kaoru Yamashita*, Hikaru Tanaka, Yi Yang, Minoru Noda

Graduate School of Science and Technology, Kyoto Institute of Technology, Masugasaki, Kyoto 606-8585, Japan

Abstract

A new fabrication process has been proposed for high sensitivity piezoelectric ultrasonic microsensors based on spontaneous diaphragm buckling. The buckling deflection and direction of the diaphragms strongly affect the sensitivity of the sensors; upward-deflected diaphragms cause higher sensitivity. The sensor has a tensile piezoelectric layer and a compressive thermally oxidized silicon layer in the diaphragm and the buckling behavior is determined by the combination of the stresses. The fabrication process of the piezoelectric layer has been optimized for yield of spontaneously upward buckling and height of the buckling deflection. Totally the diaphragms over 90% of fabricated 196 ones buckle spontaneously upward with deflection over 5 μm through the new process, giving the sensors on them higher sensitivity by 6.7 times on average than that on flat ones.

Keywords: ultrasonic sensor, sensitivity, diaphragm, buckling, residual stress, sol-gel PZT

1. Introduction

Diaphragm-type ultrasonic microsensors have been developed based on capacitive, piezoresistive or piezoelectric detection principle. The piezoresistive and piezoelectric diaphragm sensors detect ultrasound signal as in-plain strain vibration, and it is reported on the piezoelectric sensors that a static deflection of the diaphragm strongly affects the sensitivity, moreover that an upward-deflected diaphragm show higher sensitivity [1]. Figure 1 shows a schematic illustration of the structure of a piezoelectric diaphragm-type ultrasonic microsensor. A piezoelectric capacitor of 1 μm-thick lead-zirconate-titanate (PZT) film with gold and platinum/titanium electrodes is formed on a 1 μm-thick thermally oxidized silicon (SiO_2)

---

* Corresponding author. Tel.: +81-75-724-7446; fax: +81-75-724-7400.
E-main address: yamashita.kaoru@kit.ac.jp.

doi:10.1016/j.proeng.2012.09.324

diaphragm. The sensor piezoelectrically detects in-plain strain converted from flexural vibration of the diaphragm. The conversion efficiency is in proportion to the derivative of the in-plain strain to the flexural deflection. Figure 2 shows calculation results of in-plain strain which has a linear component S_b from bending moment and a nonlinear component S_e from structural expansion [2]. S_e is negligible on a diaphragm having a small deflection but it rapidly increases with increasing the deflection. The two components of the strain are summed up on the statically upward-deflected diaphragms and cancel each other on the downward ones. Thus the upward-deflected diaphragm causes higher sensitivity.

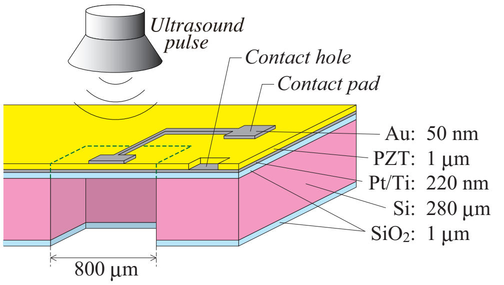


Fig. 1. Schematic illustration of the structure of the piezoelectric diaphragm-type ultrasonic microsensor.

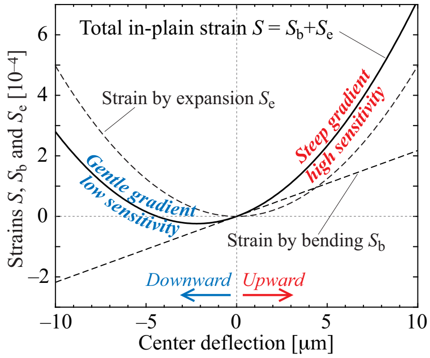


Fig. 2. Calculation results of in-plain strains S_b, S_e and total strain $S = S_b + S_e$ versus diaphragm deflection.

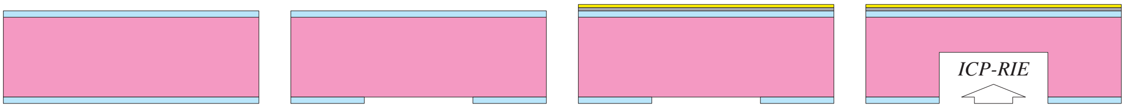
Thermally oxidized SiO_2 has a strong compressive stress, and an SiO_2 diaphragm fixed at all edges buckles due to the stress and shows a static deflection. Since the diaphragm spontaneously buckled downward in the conventional fabrication process, a re-buckling process by applying external pressure on the diaphragm was developed [1], even on a fragile SiO_2 diaphragm structure [2]. The re-buckling process, however, is troublesome because it is out of a normal silicon MEMS (Microelectromechanical systems) process sequence and it might break the diaphragms. In this work, the authors have developed a new fabrication process that enables the diaphragms to spontaneously buckle upward.

2. Buckling Control Process

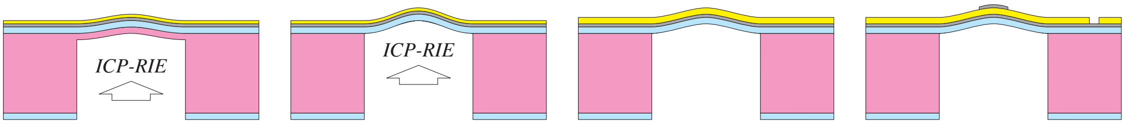
Simple SiO_2 diaphragms formed by conventional backside silicon-deep etching spontaneously buckle downward. The authors have assumed that the key issue of the downward buckling is the combination of the stresses in the bilayer structure of SiO_2 and remained silicon in the diaphragm at the moment of the buckling. The front side material, SiO_2, expands and the backside part, residual silicon, prevents the expansion, and this combination results in downward buckling. This suggests that a no- or tensile-stressed layer on the front side of the diaphragm might cause spontaneously upward buckling. A sol-gel derived PZT film causes a tensile stress induced by volume shrinkage during crystallization annealing, and the PZT film is suitable for the front-side-tensile-stress material. However, a 1 μm-thick sol-gel PZT film causes too strong tensile stress to allow the whole diaphragm structure to buckle [3]. To find an adequate intermediate way, we divided the PZT fabrication process in two steps before and after the diaphragm buckling.

The newly developed fabrication process is illustrated in Fig. 3. First PZT for the front-side-tensile-stress is formed at step (c) and full thickness of PZT is completed at step (g) up to 1 μm. If the thickness of the first PZT is adequate, the whole diaphragm buckles upward at step (e). The adequate thickness has been investigated with respect for yield of the upward-buckled diaphragms and buckling deflection.

Figure 4 shows the deflection of the diaphragms and the number of spontaneously upward-buckled diaphragms at the process step of Fig. 3 (f) versus the first PZT thickness. The deflection decreases with increasing the first PZT thickness because the tensile stress increases. The number of upward-buckled diaphragms increases with increasing the first PZT thickness except the case of 1 μm-thick. Finally we decided the first PZT thickness as 0.67 μm (two thirds of the full-thickness) which yields upward-buckling diaphragms over 90%.



(a) Both side oxidized Si wafer (b) Windows for Si bulk etching (c) Bottom electrode & ***1st PZT*** (d) Silicon backside etching



(e) Whole diaphragm buckling (f) Diaphragm released (g) ***Full-thickness PZT*** completed (h) Sensor structure completed

Fig. 3. Proposed new fabrication process of spontaneously upward-buckled diaphragm sensors. An adequate tensile stress on the front side at step (e) allows the diaphragm to spontaneously buckle upward.

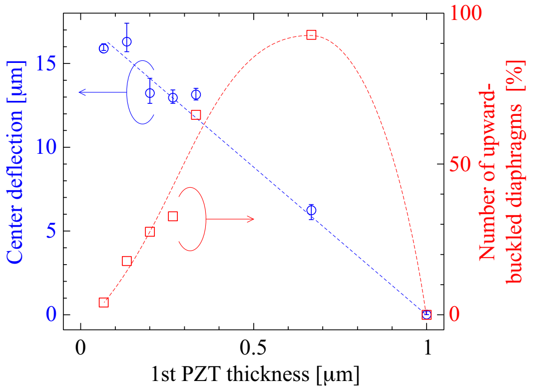


Fig. 4. The number of spontaneously upward-buckled diaphragms and the center deflection versus the first PZT thickness. The number of diaphragms is indicated by percentage to the 196 fabricated ones.

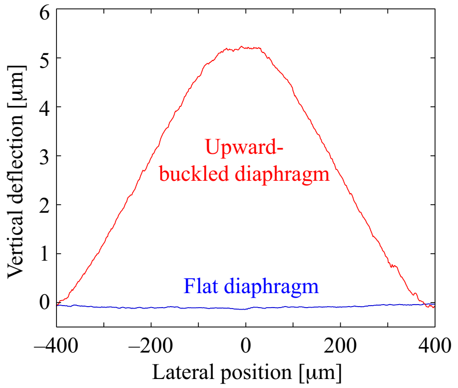


Fig. 5. Typical deflection profiles of the upward-buckled diaphragm and the flat diaphragm.

3. Evaluation of Fabricated Sensors

We have fabricated completely structured sensors throughout the process shown in Fig. 3 with the first PZT thickness 0.67 μm. Figure 5 shows examples of the diaphragm deflection profiles of the upward-buckled diaphragm and of the flat diaphragm. A smooth buckling profile up to 5.2 μm is achieved by the spontaneous upward-buckling. Figure 6 shows response waveforms against an ultrasonic pulse received by the upward-buckled sensor and the flat sensor. The sensitivity has been improved by 6.4 times through the upward-deflection technique. The relationship between the sensitivity and the buckling deflection of the fabricated sensors is shown in Fig. 7. Although there are some scattering in the sensitivity due to the scattering of the buckling deflection, totally a higher sensitivity by 6.7 times is obtained on the upward-buckled diaphragm sensors than flat ones on average.

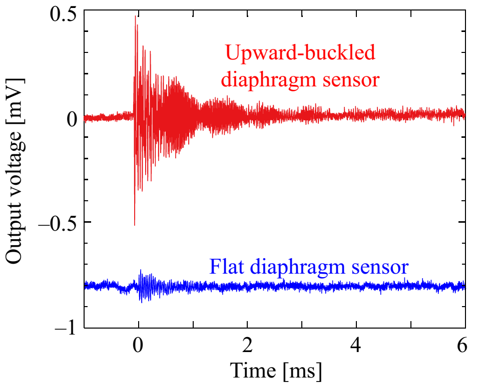


Fig. 6. Typical response waveforms to an ultrasound pulse received by the sensors on the upward-buckled and flat diaphragms.

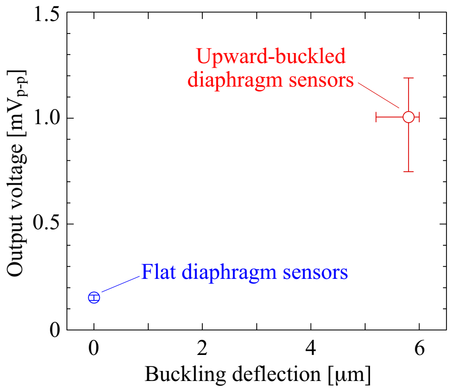


Fig. 7. The output peak-to-peak voltages of the fabricated sensors to an ultrasonic pulse versus buckling deflection of their diaphragms.

4. Conclusions

A new fabrication process of diaphragm-type piezoelectric ultrasonic microsensors has been proposed to make the diaphragms spontaneously buckle upward for high sensitivity. Buckling is caused by a compressive stress essentially, and the stress combination of compressive and tensile ones in the diaphragm has been considered at the buckling moment during the backside silicon etching. An assumption has made that a diaphragm having tensile stress on its front side buckles spontaneously upward, and a sol-gel PZT film has been selected as the front-side-tensile-stress layer. To find an adequate thickness of the stress layer, the PZT fabrication process has been divided into two steps before and after the buckling of the diaphragm. The thickness of the PZT has optimized for the yield of the spontaneously upward-buckled diaphragms and the buckling deflection and the best thickness has been found to be 0.67 μm which is two thirds of the full thickness of 1 μm. The sensors have been fabricated through the new process with the optimum parameter and 92% of the sensors have shown spontaneously upward buckling over 5 μm. The upward buckled-diaphragm sensors have shown higher sensitivity by 6.7 times than flat ones on average.

Acknowledgements

This work was partially supported by Grant-in-Aide for Scientific Research (B) 23360136 form Japan Society of the Promotion of Science.

References

[1] Kaoru Yamashita, Hiroki Nishimoto, Masanori Okuyama. Diaphragm deflection control of piezoelectric ultrasonic microsensors for sensitivity improvement. *Sens. Act. A* 2007; **139**:118–123.

[2] Kaoru Yamashita, Tomoya Yoshizaki, Minoru Noda, Masanori Okuyama. Buckling control of silicon dioxide diaphrgms for sensitivity enhancement of piezoelectric ultrasonic microsensors. *IEE Jpn. Trans. Sens. Micromach.* 2011; **131**:235–239.

[3] Kaoru Yamashita, Tomohiro Watanabe, Tomoya Yoshizaki, Minoru Noda, Masanori Okuyama. Buckling control of silicon dioxide diaphragms by lateral stress enhancement for sensitivity improvement of piezoelectric ultrasonic microsensors. *Sens. Act. A* 2011; **165**:54–58.