Vacuum packaging for microsensors by glass–silicon anodic bonding

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Abstract

Vacuum packaging by the glass–silicon anodic bonding process is studied. The residual gas generated during the anodic bonding process and that desorbed from the silicon and glass surface increase the pressure in a sealed cavity. In order to fabricate a vacuum sealed cavity, two methods are proposed to eliminate the residual gas; (i) the residual gases are evacuated through a small opening after bonding and then the opening is plugged by depositing a material in vacuum, (ii) the residual gases are absorbed by a getter inside the sealed cavity. A non-evaporable getter (NEG) is used for the second method. A vacuum sealing of tens of Torr is obtained by the first method. The second method and a combination of the two methods enables vacuum sealing at a pressure lower than 10^{-5} Torr. A prototype of a capacitive vacuum sensor is fabricated by using the second method.

Introduction

Packaging is very important for microsensors. Since an air tight seal can be realized by anodic bonding of glass and silicon, many packaged pressure sensors and accelerometers have been developed using bonded glass–silicon structures [1]. In some microsensors, vacuum packaged structures are advantageous. The squeeze film damping effect should be reduced in capacitive accelerometers to improve their dynamic response. In IR sensors, thermal conductance between a sensing element and its package should be minimized for high sensitivity. The high Q factor required in resonant sensors for high resolution and wide dynamic range can be obtained by reducing air dumping [2]. The sensitivity of thin diaphragm pressure sensors is very high if the reference cavity pressure is kept extremely low [3]. For these purposes, vacuum sealed cavities are widely required.

Anodic bonding of glass–silicon in vacuum to obtain a vacuum sealed cavity has already been reported [1]. However, it was not possible to make a high vacuum cavity by this method. Two residual gas sources which pose a problem for vacuum sealing have to be considered. One is gas generation during the anodic bonding process [4]. The other is gas desorption from the inner surface of the sealed cavity. In order to create a high vacuum cavity, these gases must be eliminated. This paper describes studies on vacuum packaging for microsensors. A prototype of a capacitive absolute pressure sensor fabricated for vacuum sensing is also described.

Experimental

General considerations

High vacuum sealing methods are classified into two categories. In one type the residual gas in the cavity is evacuated through an opening after anodic bonding and then the opening is plugged by depositing Al or SiO. In the other a small vacuum pump is placed in the sealed cavity. A non-evaporable getter (NEG: SAES Getters: ST122/CTAM) is used as a small vacuum pump.

In order to maintain the cavity in high vacuum, the sources of residual gas, which are desorption from the inner wall of the cavity and the NEG [5], and gas generation during anodic bonding must be considered. We examined three methods for sealing in vacuum. The first method (method A) is that residual gas in the cavity is evacuated through an opening, and the opening is plugged by evaporating Al or SiO in vacuum (Fig. 1(a)). The second method (method B) is to adsorb the residual gas by a non-evaporable getter (NEG) in the sealed cavity (Fig. 1(b)). The third method (method C) is a combination of method A and method B (Fig. 1(c)).

Non-evaporable getter (NEG)

The NEG (SAES Getters: ST122/CTAM) used is an Ni/Cr ribbon of 0.05 mm thick, 2 mm wide and 6 mm long covered with a mixture of porous Ti and Zr–V–Fe alloy. Before activation, the NEG does not adsorb gases because its surface is covered by oxides and carbides. To absorb gases, the NEG must be activated at around 400 °C. Since the anodic bonding temperature is also

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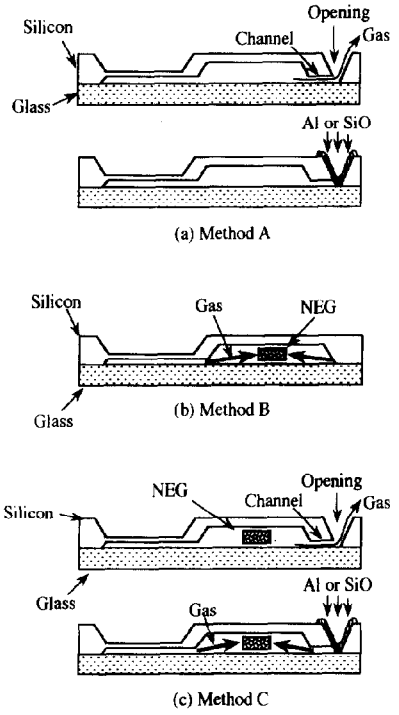

Fig. 1. Methods of vacuum packaging for microsensors.

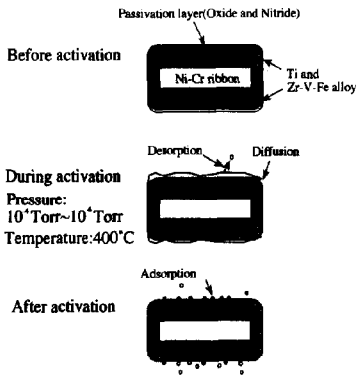

Fig. 2. NEG activation sequence.

400 °C, the NEG is activated during the anodic bonding process. The active metallic surface is formed by the activation because surface oxides and carbides are diffused into the bulk [5]. Then the NEG can adsorb the residual gases. A schematic diagram of the activation sequence is shown in Fig. 2.

Test device structure 1 (TD 1) for methods A and C

In order to evaluate the three methods, we fabricated two kinds of test devices. The structure of test device 1 (TD1) for methods A and C is shown in Fig. 3. It consists of Pyrex glass and silicon having a diaphragm, an NEG room, a reference cavity, a channel and an

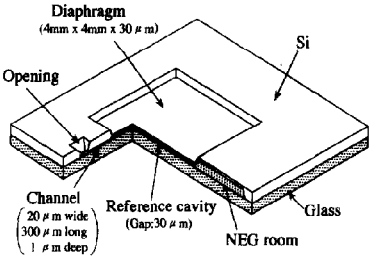

Fig. 3. Test device structure 1 (TD1) for methods A and C.

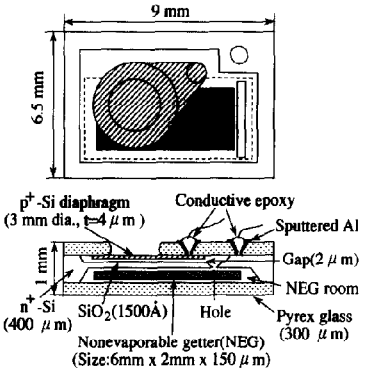

Fig. 4. Test device structure 2 (TD2) for method B.

opening. The diaphragm is 4×4 mm square and 30 μm in thickness. The gap between the diaphragm and glass is 30 μm. The dimensions of the channel are 20 μm wide, 300 μm long and 1 μm deep.

Test device structure 2 (TD 2) for method B

The structure of test device 2 (TD2) which can be used for a capacitive vacuum sensor is shown in Fig. 4. To avoid dust from the NEG coming into the cavity, the NEG room was formed on the backside of the wafer and was connected to the reference cavity through a small hole. The sensor capacitor is formed between an Si substrate and a p^+-Si diaphragm of 3 mm in diameter and 4 μm in thickness on a glass substrate. The gap between these electrodes is designed to be about 2 μm and the calculated capacitance is about 75 pF. This structure enables the deflection of the diaphragm to be detected by the capacitance change.

Deflection measurement

The measurement set-up is shown in Fig. 5. A small vacuum chamber having a window on the lid is connected to a sorption pump or a turbo molecular pump. The test device is placed under the window so the diaphragm deflection can be observed. Diaphragm center deflection is measured by a microscope with an optical displacement sensor (OLYMPUS: ZP101) or one with a calibrated focus adjustment (UNION: Hisomet) to estimate

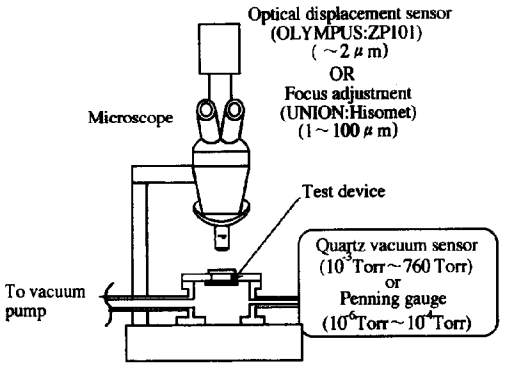

Fig. 5. Optical deflection measurement set-up.

the pressure inside a sealed cavity. As shown in Fig. 6, there is no pressure difference across the diaphragm when the diaphragm is flat, and hence the pressure in the vacuum chamber is assumed to be equal to that in a sealed cavity. Pressure inside the chamber is measured by a quartz vacuum sensor (10^{-3} Torr ~1 atm) and a Penning gauge (10^{-6}–10^{-3} Torr). By changing the pressure in the chamber, the center deflection of the diaphragm is measured in the range from 0.1 to 100 μm.

Results

Method A

In method A, evaporation of Al and SiO on the opening was carried out under a pressure of 10^{-6} Torr after the glass–silicon anodic bonding process. Before evaporation, the gas inside the cavity was evacuated through a channel for 2 h. The opening was plugged with Al thicker than 8 μm. The pressure inside the cavity was approximately 200 Torr. In the case of SiO, evacuation was carried out with substrate heating at 170 °C. The opening was plugged with 2 μm thick SiO. The estimated pressure inside the cavity was about 60 Torr.

Two methods of deposition using a focused ion beam (FIB) were also tested. One is W deposition assisted by a Ga ion beam and the other is sputter redeposition of silicon under 1×10^{-6} Torr. They were used to plug the opening. The pressure inside the cavity obtained by these two methods was about 200 Torr.

Method B

The TD2 shown in Fig. 4 was used for evaluating the quality of the sealing by method B. In method B a non-evaporable getter pump is placed in the sealed cavity.

At first we did not perform any special heat treatment for desorbing gas from the NEG before the anodic bonding process. The anodic bonding process was carried out under a pressure of 10^{-6} Torr. After the anodic bonding process in vacuum, it was heated up to 400 °C. The NEG was reactivated so as to absorb the residual gases in the cavity. Figure 6 shows the diaphragm center deflection versus the applied pressure (P_0) with respect to reactivation time. Before reactivation, the pressure inside the cavity was around 400 Torr so that the diaphragm was inflated in the vacuum chamber. As the reactivation time was increased, the diaphragm became flat. Even after long NEG reactivation, the pressure inside the cavity was not lower than 5 Torr. It is assumed that the gettering function of the NEG was saturated.

In order to desorb gas from the NEG, a heat treatment was carried out at 300 °C for 1 h before the anodic bonding process. The anodic bonding process was successively carried out in vacuum. This heat treatment was also applied for the TD2 without the NEG. Figure 7 shows the diaphragm center deflection versus the applied pressure measured with and without the NEG. The pressure in the cavity of the device with the NEG

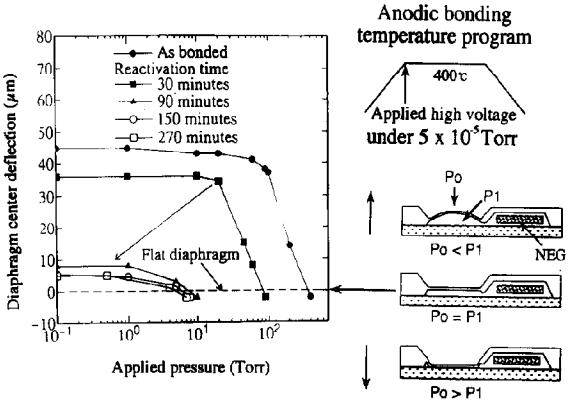

Fig. 6. Diaphragm center deflection for method B without preheating.

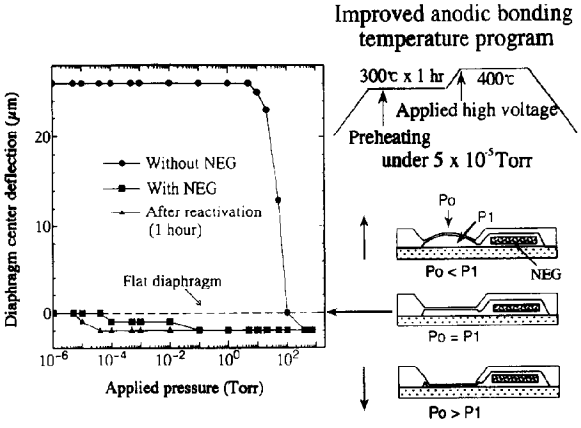

Fig. 7. Diaphragm center deflection for method B with preheating.

was 4×10^{-5} Torr. The cavity pressure was decreased from 400 Torr to 4×10^{-5} Torr by preheating at 300 °C. This shows the preheating is quite effective in desorbing the gases from the NEG. In this case, the NEG was activated during the anodic bonding process and an additional reactivation was not carried out. With additional reactivation of 1 h, the pressure was lower than 1×10^{-5} Torr.

Method C

The procedure of method C is: (i) desorption of gases from the NEG, silicon and glass; (ii) anodic bonding; (iii) evacuation of residual gas in the cavity through a channel; (iv) plugging the opening; (v) reactivation of the NEG. All these processes except (v) have to be done continuously in vacuum. Figure 8 shows the center deflection of the diaphragm of the device. In this device, the NEG was reactivated at 400 °C for 2 h. The pressure inside the cavity was lower than 1×10^{-5} Torr. The center deflection change of the device under atmospheric pressure is shown in Fig. 9.

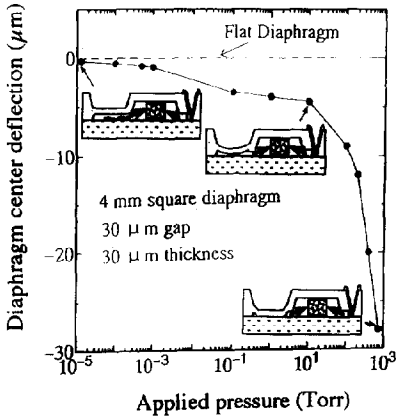

Fig. 8. Diaphragm center deflection for method C.

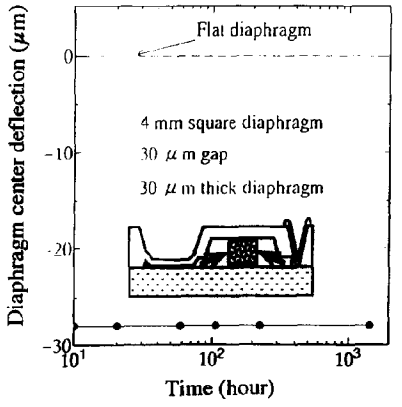

Fig. 9. Diaphragm center deflection change under atmospheric pressure in method C.

No change was observed for 2 months, which indicates that leakage through the plugged opening was very small.

Capacitive vacuum sensor

Fabrication

The fabrication sequence for producing a capacitive vacuum sensor of the TD2 is shown in Fig. 10. The process started with a p-type (100) 300 μm thick silicon wafer. At first, Si was etched 30 μm in depth by TMAH. Boron was diffused to 4 μm in depth with a solid boron source (OWENS, Illinois: BORON PLUS) at 1150 °C for 3.5 h. The p^+ diffused silicon was then anodically bonded to a glass having holes. The undiffused portion of the wafer was subsequently etched away to produce a thin diaphragm of 4 μm thick. The glass with a thin p^+ diaphragm was then anodically bonded to the n^+-Si substrate at 400 °C. The n^+-Si substrate has a space for the NEG. After putting the NEG in the space, another Pyrex glass was anodically bonded under high vacuum. Next, lead wires were connected to the n^+-Si substrate and p^+-Si diaphragm.

Performance

The performance of the capacitive vacuum sensor shown in Fig. 4 was evaluated. Figure 11 shows the relationship between the sensor capacitance (C) and the pressure (P). The capacitance was directly measured by an LCR meter (HP 4248A). Total capacitance change was 151.72 pF from 760 to 10^{-3} Torr. In the range

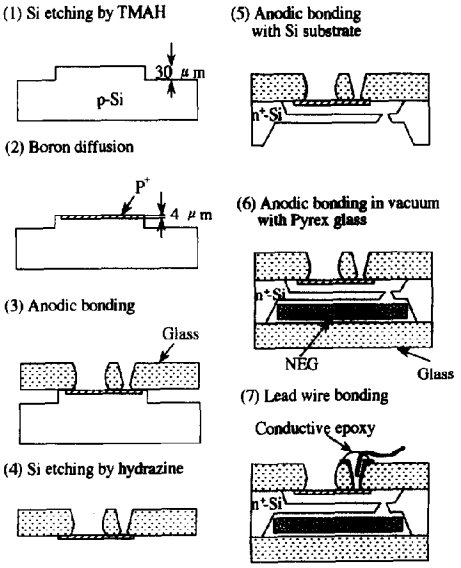

Fig. 10. Fabrication process of vacuum sensor.

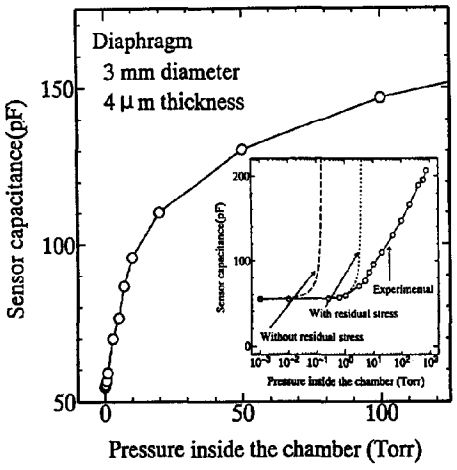

Fig. 11. Dependence of sensor capacitance on the applied pressure. Calculated characteristics for a stress free diaphragm (– – –) [6] and for a diaphragm with built-in stress (---) [7] are also shown.

from 10^{-3} to 1 Torr, the sensitivity, dC/dP was high, of about 4.32 fF/mTorr, in this range. From 1 Torr to atmospheric pressure the sensitivity is lower, of about 0.19 fF/mTorr. The measurable pressure range can be changed by choosing the diameter of the diaphragm.

Discussion

The sources of residual gas are desorption from the inner wall of the cavity, gas generation during anodic bonding process and desorption from the NEG [5]. To maintain a high vacuum in the cavity, plugging after evacuating and gettering by the NEG are examined. The problem of residual gas by desorption from the inner wall was solved by preheating before sealing (method A). The problem of gas generation during the anodic bonding process was partly solved by absorbing it by the NEG (method B) but fully solved by evacuating the gas before plugging the opening and further absorbing it with NEG (method C). The problem of desorption from the NEG is solved by preheating at 300 °C in vacuum (method B). After considering these three solutions for eliminating the residual gas, vacuum sealing lower than 10^{-5} Torr was realized by methods B and C.

Plugging with Al requires a deposited layer of about 8 μm thick while that with SiO requires 2 μm thick. The Al plug can be used as an electrical feedthrough.

According to the structural analysis of a circular plate with clamped edge [6], the diaphragm center contacts with the counter electrode at a pressure of tens of mTorr. Figure 11 shows the relationship between sensor capacitance and pressure. The difference between the analysis and the experiment is thought to be due to the high tensile stress of the boron diffused thin membrane [7].

Chau and Wise deduced the equation of diaphragm center deflection which includes the effect of the internal stress in a boron diffused thin membrane [7]. By using this equation, we calculated the contact pressure, i.e. the pressure at which the diaphragm center will touch the counter electrode. For a 2 μm gap of the sensor capacitance, the calculated contact pressure is of about 2 Torr. This is in good agreement with our experiments.

However, for pressures above the contact pressure, the equation of Chau and Wise does not apply as it does not include the finite curvature of the diaphragm under the applied pressure. In our experiments, the capacitance of the sensor increased with the applied pressure even after the diaphragm center touched the counter electrode, which is covered with a thin silicon dioxide insulating layer. Increasing pressure results in an increased touching area, i.e. increased capacitance.

Conclusions

Vacuum packaging by glass–silicon anodic bonding is presented. The attainable pressure of a sealed cavity was lower than 10^{-5} Torr using an NEG as the internal getter. An absolute pressure sensor was fabricated by this method. This vacuum packaging would be applicable for many kinds of microsensors and vacuum microelectronic devices, etc.

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Biographies

Hiroji Henmi received the B.Eng. degree in metallurgical engineering from the Muroran Institute of

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Masayoshi Esashi received the B.Eng. degree in electronic engineering and Ph.D. degree in engineering from Tohoku University, Japan, in 1971 and 1976, respectively. From 1976 to 1981, he served as a research associate at the Electronic Engineering Department of Tohoku University. During this period, he worked on biomedical transducers fabricated by micromachining. From 1981 to 1990, he was an associate professor. Since 1990, he has been a professor in the Department of Mechatronics and Precision Engineering, Tohoku University. His current research is on intelligent sensors and sensor–actuator systems fabricated by micromachining.