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Fabrication of capacitive absolute pressure sensor using Si-Au eutectic bonding in SOI wafer

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Abstract. A capacitive absolute pressure sensor was fabricated using a large deflected diaphragm with a sealed vacuum cavity formed by removing handling silicon wafer and oxide layers from a SOI wafer after eutectic bonding of a silicon wafer to the SOI wafer. The deflected displacements of the diaphragm formed by the vacuum cavity in the fabricated sensor were similar to simulation results. Initial capacitance values were about 2.18pF and 3.65pF under normal atmosphere, where the thicknesses of the diaphragm used to fabricate the vacuum cavity were 20 \( \mu \text{m} \) and 30 \( \mu \text{m} \), respectively. Also, it was confirmed that the differences of capacitance value from 1000hPa to 5hPa were about 2.57pF and 5.35pF, respectively.

1. Introduction

Absolute pressure sensors fabricated using Si MEMS (Micro Electro Mechanical System) technology are usually either piezoresistance type or capacitance type. Capacitive pressure sensors are attractive for many applications such as control systems, industrial processing systems, automotive systems and biomedical systems because of their relatively high sensitivity, excellent hysteresis and repeatability characteristics, low temperature dependence, very good long-term stability, and low power consumption compared to piezoresistance pressure sensors [1-2]. The structure of a capacitive pressure sensor comprises a cavity Si Layer which forms the vacuum cavity, a Si diaphragm used with the upper electrode which also provides the capacitance change, and a glass substrate used to form the lower electrode and provide the air gap.

Conventionally, capacitive absolute pressure sensors are formed from the diaphragm substrate of the upper electrode and fabricated using a CMP (Chemical Mechanical Polishing) process after direct or fusion bonding under vacuum of Si-Si wafers or a highly B-doped Si wafer for each stage, and the glass layer that forms the air gap and the lower electrode is prepared using an etching process.

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However, to fabricate capacitive absolute pressure sensors with sealed vacuum cavities, with leads carrying current from inside the upper electrode diaphragm, requires relatively complex fabrication technology [3]. This is because the process requires heat treatment at more than 1000°C using a vacuum furnace, after initial bonding at a temperature of 500°C to bond the two Si wafers [4]. Also, in the CMP process for fabrication of the deflected diaphragm with vacuum chamber, it is difficult to fabricate a diaphragm of uniform thickness and vacuum cavity, as the thickness of the gap forming the vacuum may become irregular or break down entirely, because deflection of the Si diaphragm occurs as Si thickness decreases.

Therefore, in this research, sensor chips were fabricated with deflected diaphragm wafers using eutectic bonding and a CMP process, to produce highly efficient capacitive absolute pressure sensors requiring a simplified fabrication process. Their characteristics were then analyzed.

2. Fabrication

A Si DSP (double side polished) wafer (t=1mm, ρ = 10-20Ωcm), SOI (20µm/3µm/500µm and 30µm/3µm/500µm, ρ<0.004 Ωcm) wafer and a borosilicate glass substrate (Corning 7740, t = 500µm) were used in starting substrates to fabricate a diaphragm sealed in vacuum and a sensor chip. Figure 1 shows the wafer-level fabrication process for the capacitive absolute pressure sensor.

A low stress silicone nitride film of about 2000Å thickness was formed on the Si wafer through a LPCVD (low pressure chemical vapor deposition) process. Patterns were formed using a Si cavity etch mask after PR was coated on one side of the wafer. The pattern for KOH anisotropic etching was formed by etching silicone nitride film through an ICP-RIE (inductively coupled plasma - reactive ion etching) process. Also, on the other side of the wafer, a dicing line was patterned using a dicing line mask with the same process. A double-sided Si wafer was patterned by passivation of silicon nitride and etched at 80° in 26wt% KOH solution at the same time. Etching of the Si wafer was carried to a depth of 240um degree. After removal of the silicone nitride film, NiCr (100) and Au (5000) thin films were deposited on the cavity-formed wafer using an E-beam vacuum evaporation system for Si-Au eutectic bonding. The cavity-formed Si wafer was bonded onto the SOI wafer at 450°C for 30min under 9×10⁻⁵ mbar pressure using an EV 501 bonder. To obtain a uniformly thick diaphragm deflected by differences of internal and external pressure in the cavity after bonding, handled Si of the SOI wafer was removed in HNA solution after the CMP process, and the wafer was then etched with SiO₂ in BOE (buffered oxide etchant) so that a diaphragm-deflected Si wafer could be obtained.

Next, poly-Si thin film of about 3000Å thickness was deposited on the glass substrate at 550°C through LPCVD. The glass substrate was patterned for silicon dry etching and glass wet etching. The pattern for glass etching was formed by removing poly-Si on the glass substrate using ICP-RIE. The glass substrate was etched to 5µm depth in the diluted HF solution, a mixture of HF, HCl and DI wafer (1:1:2). The poly-Si used as the passivation mask for glass etching was removed in HNA (HF : HNO₃ : CH₃COOH = 1 : 3 : 8) solution. The lower electrode was formed through patterning after 300 thick NiCr and 5000 thick Au were deposited on the etched glass substrate using an E-beam evaporation system. At the same time, the electrode for connection to the diaphragm used as the upper electrode was formed on the etched glass substrate.

Wafer-level sensors were obtained through a Si-glass anodic bonding process with the diaphragm-deflected Si wafer and an etched glass substrate using an EV 501 bonder. Wafer-level sensors were manually separated into sensor chips after half dicing. Finally, a capacitive absolute pressure sensor could be successfully completed by mounting and Au wire bonding on the metal package. The characteristics of the complete sensors were measured using a vacuum system and an LCR meter. Sensor structure and microstructure were observed with an optical microscope and a SEM.
3. Results and Discussion

The vacuum sealed diaphragm was fabricated by removing handled Si of the SOI wafer after Si-Au eutectic bonding using a Si cavity wafer and a SOI wafer. The capacitive absolute pressure sensor was successfully completed by Si-glass anodic bonding between the Si diaphragm wafer sealed in vacuum and an etched glass substrate.

The Si cavity wafer and the SOI wafer were bonded eutectically under a vacuum of about $9 \times 10^{-5}$ mbar. When the bonded wafer is placed in the air outside the bonder, the difference in pressure between the cavity and the exterior occurs. Handled Si of 500 $\mu$m in the SOI wafer is removed through CMP and etching in the HNA solution to fabricate the main diaphragm for the sensing role. When 3 $\mu$m thick SiO$_2$ in diluted HF solution is removed, 20 $\mu$m and 30 $\mu$m thick Si diaphragms are deflected in the form of a circular arc by the difference in pressure between the inner and outer diaphragms, respectively.

Figure 2a) shows optical images of wafer-level deflection and expansion in the diaphragm-deflected wafer. It can be confirmed that the diaphragm is deflected in the form of a circular arc from the cavity. The displacement of the deflected diaphragm was measured using $\alpha$-step, and the result was 16.8 $\mu$m. This result is similar to the displacement deflection of about 17 $\mu$m obtained in the simulation result carried out under vacuum conditions such as in the experiment shown in Fig. 2b). Therefore, it is thought that Si-Au eutectic bonding process, not Si-Si direct bonding process, is sufficient to form a sealed vacuum cavity.
It could be confirmed that an interface of Si-Au alloy between Si and Au is produced, from the SEM photograph as shown in Fig. 3.

In real terms, the thickness of the deposited Au is 5000Å, but that of the Si-Au alloy is 1250Å as shown in Fig. 3b), which is thought to occur because Si-Au alloy increases in density through removal of defects such as voids or pinholes produced during deposition of Au under bonding conditions. Therefore, it is thought that the deflected diaphragm, similar to the simulation result, is obtained by forming a vacuum cavity seal using this process. The diaphragm-deflected by vacuum cavity Si wafer was anodically bonded to the glass substrate forming the lower electrode, and connected to the upper electrode after glass etching for air gap. Figure 4a) shows the fabricated 4” wafer-level packaging of the capacitive absolute pressure sensor array.

Generally, in the dicing process for the wafer-level sensor array, when full dicing is used, sensor chips cannot avoid contamination of the air gap by particles and cooling water. It is very difficult to remove contaminants that remain in the air gap between electrodes because the sensor chip is contaminated by passing through the dicing unit. Therefore, in this paper, the sensor chips were separated from wafer-level packaged device manually, by using partial cutting of the top and bottom sides of the bonded wafer, to protect chips during the dicing process as shown in Fig. 5. The capacitive absolute pressure sensor could be successfully completed by mounting and Au wire bonding onto the metal package as shown in Fig. 4b).
Fig. 4. Optical Images a) 4" wafer-level packaged capacitive absolute pressure sensors by anodic bonding process and b) a sensor chip mounted on the metal can after dicing.

Fig. 5. Concept diagram for separation into sensor chips

As shown in Fig. 6, initial capacitance values were about 2.18pF and 3.65pF under normal atmosphere, where the thicknesses of diaphragm to fabricate vacuum cavity was 20 µm and 30 µm, respectively. Also, it was confirmed that the differences in capacitance value from 1000hPa to 5hPa were about 2.57pF and 5.35pF, respectively.

Fig. 6. The variation of capacitance with decrease in external pressure of the capacitive absolute pressure sensor when thickness of diaphragm is a) 30 µm and b) 20 µm.

4. Conclusions

The capacitive absolute pressure sensor with a large deflected diaphragm was fabricated with a sealed vacuum cavity formed by removing handled silicon wafer and oxide layers from a SOI wafer after eutectically bonding a silicon wafer to the SOI wafer.
The deflected displacements of the diaphragm formed by vacuum cavity in the fabricated sensor were nearly similar to the simulation result, which is thought that results from the dense interface produced between the cavity-formed Si and top layer Si of the SOI wafer by the Si-Au eutectic bonding process. Initial capacitance values were about 2.18pF and 3.65pF under normal atmosphere, where thicknesses of diaphragm to fabricate vacuum cavity were 20 μm and 30 μm, respectively. Also, it was confirmed that the differences of capacitance value from 1000hPa to 5hPa were about 2.57pF and 5.35pF, respectively.

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