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Low-cost PDMS seal ring for single-side wet etching of MEMS structures

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Abstract

We describe a new O-ring setup for wet-etching processes of microelectromechanical systems (MEMS). Our new low-cost approach using siloxane-based seal rings entails the single-side etching of silicon and silicon dioxide using potassium hydroxide and buffered hydrofluoric acid, respectively. With this approach, the wafer is not immersed into the etching solution, but only the side to be etched is in contact with the solution, hence the previously fabricated device elements on the other side of the wafer are not damaged. In one process for etching silicon the etch solution is heated by an infrared lamp. We describe the fabrication of various cantilever-based sensors, such as arrays of 0.8-μm-thick levers for a chemical/electronic nose, and 5-μm-thick silicon cantilevers having piezoresistive sensors. Our technique has good uniformity and process control and, in addition, eliminates mechanical stress on the fragile wafers incurred by wafer chucks, which are required for the conventional immersion approach. It has improved process yield and reduces the waste of chemicals.

Keywords: Poly(dimethylsiloxane) (PDMS); Seal ring; Wet etching

1. Introduction

Many structures in microelectromechanical systems (MEMS) such as membranes and freestanding cantilevers require a wet-etching process on only one side of the wafer. In such a fabrication process, it is essential that the other side of the wafer and its edges are protected. In the past, individual chucks have provided this functionality by means of rubber O-ring seals on each side of the wafer, which is then immersed into the etching solution. Pressure on the chuck squeezes the two O-rings against the wafer surfaces, hence guaranteeing a good seal against the etching solution. However, the pressure applied generates substantial stress on the wafer, which is enhanced if etching takes place at temperatures different from the mounting temperature because of the difference in the thermal expansion between wafer and chuck material. Therefore, if the chucks are not properly constructed, the pressure applied to them can cause a decrease in the yield of thin membranes, which crack or break quite easily. Our low-cost approach eliminates this problem and achieves a process yield as high as that attained with more sophisticated and complex immersion types of etch chucks.

Another disadvantage of current immersion wet-etching techniques is the size of the etch apparatus needed (usually a thermostatically controlled bath) and the volume of the etchant required to cover the entire wafer chuck (typically several liters). For handling and safety reasons it would be preferable to have a smaller setup and to reduce the liquid volume to the minimum needed for etching. In addition this would be an economically appealing and environmentally friendly procedure. Of course, in mass production aimed at high-throughput parallel wafer etching, this issue is less important, but for small-scale prototype fabrication it can provide a low-cost solution to reduce the complexity of the etch apparatus as well as the waste of chemicals.

In this paper we demonstrate the use of a novel single-side wet-etch setup using a seal ring made of poly(dimethylsiloxane) (PDMS) (Dow Corning, Midland, MI) [1]. This elastomeric material has recently attracted immense interest as stamps for microcontact printing and/or micromolding in capillaries [2,3]. For our purpose, the elasticity and adhesion properties of PDMS are exploited by using it as a seal to confine an etching solution to a desired area. Here, the surface adhesion properties of PDMS allow a perfect sealing against the etchant solution without applying great pressure to the ring. After being rinsed in DI water, the PDMS rubber ring can be reused many times. With the setup described we

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have been able to perform two important process steps in a MEMS fabrication sequence: (a) wet etching from one side through a silicon wafer using heated potassium hydroxide (KOH), and (b) single-side etching of a silicon-dioxide layer by buffered hydrofluoric acid (BHF).

2. PDMS seal-ring fabrication

The fabrication of a seal ring requires a replication process from a master mold machined in Teflon or another suitable material. The PDMS is mixed in a 10:1 ratio with the prepolymer components of Sylgard 184, following the recommendations of the manufacturer. Homogeneous and bubble-free mixing of the polymer is accomplished by using an automatic dispenser (Dopag, Cham, Switzerland). Our homemade rings are formed by pouring the liquid PDMS into the master as shown in Fig. 1. The low-energy siloxane fluid fills the crevices of the master, forming a negative replica of the master mold. Cross linking of the siloxane is done by a curing process in an oven at 60°C for ~24 h. The result is an elastomeric solid that accurately retains the shape of the mold even after removal from it. Any imaginable shape of the PDMS replica is possible. For our purpose we have fabricated rings suitable for sealing the border of a 10 mm silicon wafer. The outer and inner diameters as well as the thickness of the ring are 100, 84 and 12 mm, respectively. The high chemical stability of the PDMS material allows the seal ring to be used for many kinds of wet-etching applications. No metal parts are used in the PDMS ring setup or come in contact with the etching solution. This is important for preserving good etch-rate control when using KOH because, as Hein et al. [4] have shown, metallic impurities dissolved in a KOH solution have a strong effect on the anisotropy of silicon etching.

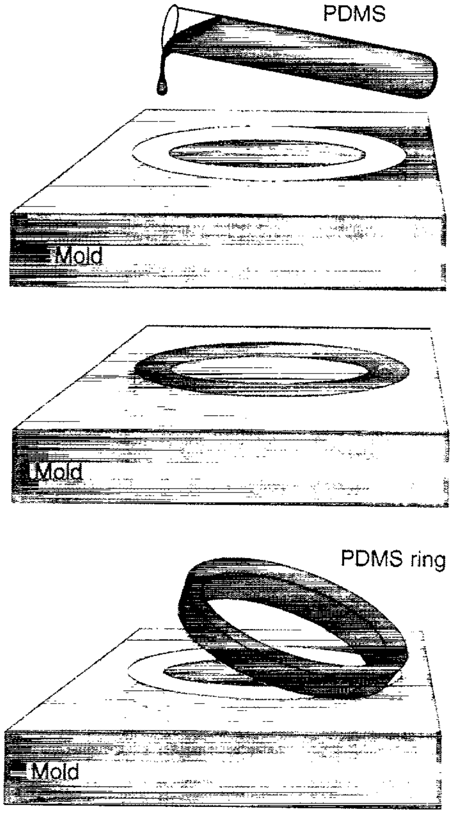

Fig. 1. Schematic illustration of PDMS seal ring fabrication. Liquid siloxane is poured into the mold (top), cured at 60°C for 24 h (center), and the ring is removed from the mold (bottom).

3. Using the PDMS ring for single-side wet etching

For our purpose of single-side wet etching, the wafer is placed horizontally on a ring holder that does not touch the wafer's active part. The PDMS ring is placed on the wafer border, establishing intimate contact with the etch mask layer over the entire ring width (about 8 mm). The excellent adhesion properties of the PDMS by its own weight are normally sufficient to provide a good seal. However, in order to ensure sealing for long etch times (> 1 h), we apply light pressure between ring and wafer. This can be done by using an additional weighted ring, for instance.

The etching solution is then poured onto the surface to be etched as shown in the schematic view in Fig. 2. The ring

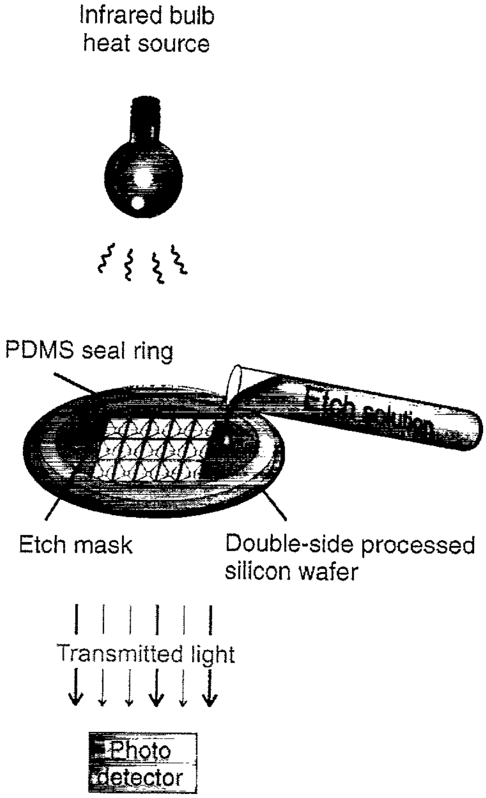

Fig. 2. Schematic illustration of the etch set-up. The seal ring is placed on top of the wafer to be single-side etched. The adhesion between the PDMS ring and the wafer mask is sufficient to provide excellent confining of the etch solution within the ring diameter. In our case we heated the etch solution (KOH) to 60°C with an infrared heat source. The transmitted light can be used for monitoring the etch progress.

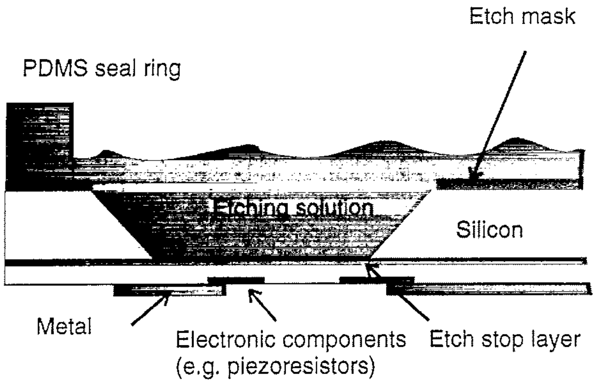

Fig. 3. Enlargement of the etch interface showing a cross through the wafer with part of the PDMS seal ring (left side). This nicely shows that the prefabricated elements on the other side of the wafer (implant, metals, dielectrics, etc.) are not touched by the etch solution nor by any other chuck part.

confines the solution as in a beaker, the side walls of which are the inner side walls of the PDMS ring, with the wafer surface to be etched forming its bottom. Details of the interface between etch solution, seal ring, and etch mask are shown in Fig. 3.

The KOH is heated to 60°C by an infrared lamp (Fig. 2). The light transmitted through the thin membrane near the end of the etch process simultaneously provides the means to monitor the etch stop either visually or with a photodetector. In one of our fabrication processes for the piezoresistive cantilevers, the buried silicon-dioxide layer of a silicon-on-insulator (SOI) wafer is used as an etch stop. In the other case where no etch-stop layer is present, visual control of the transmitted light is a sufficiently safe way to stop the etching in time.

Compared to conventional wet-etch baths, a great advantage of our method is the smaller amount of chemicals required. For instance, to etch through a silicon wafer 100 mm in diameter and 500 μm thick with a mask coverage of approximately 40%, only 250 ml of KOH is required, instead of the several liters for an immersion etch bath. The control of the etch rate with such a small amount of etchant is critical owing to the fast saturation of the KOH and enrichment of dissolved silicon compound that occur. In our experiment this enrichment does not affect the silicon etch rate significantly. However, it starts to change the etch rate ratio between (100) and (110) crystal planes when the silicon content exceeds ~60 mg/cm^3 as shown by Dorsch et al. [5]. This in turn affects the undercutting of convex-corner compensation structures. For this reason, we refresh the KOH solution after 4 h.

The same procedure as for the KOH etching is applicable for single-side etching of silicon dioxide using BHF, where no heating is required and where the etching is isotropic. We have etched the 1-μm-thick buried silicon-dioxide layer of a SOI wafer without altering the metal and dioxide structures on the reverse side of the wafer. The BHF solution does attack the siloxane ring, but so slowly that it causes no overt problems in our experiments.

4. Microfabricating silicon structures by using the single-side wet-etch seal ring

Our new single-side, wet-etch setup has been used to fabricate a series of cantilever-based micromachined silicon sensors [6,7]. In both cases a backside etching is required locally to etch the silicon wafer to a thin membrane. In the fabrication process for piezoresistive cantilevers [7], the buried silicon-dioxide layer of the SOI wafer provides the etch stop layer. At this point of the process, the wafer's topside is already patterned with metal, which has to be protected. Fig. 3 shows an enlargement of the etch interface. In this case, the topside must not come in contact at all with the etch solution or with any mechanical part that could damage the fragile structures. The KOH solution was renewed every 4 h to keep the etch rate at ~16 μm/h for the entire duration of the etching. The local etch rate varies within 1–2% over the wafer surface, which is mainly due to the local intensity variation of the infrared radiation. Owing to the etch-stop layer this drawback has little impact on our devices. In contrast to most conventional KOH etch techniques, the wafer is placed horizontally in the solution rather than vertically. However, we detected no significant effect on the (100) silicon etch rate. Fig. 4 demonstrates the capabilities of the new approach. It shows a through-light optical photograph of a 100 mm wafer processed using a PDMS seal ring. The silicon membrane (5 μm thick) after reaching the etch-stop layer appears light, whereas the individual chips carrying the micromechanical sensors are 400 μm thick and appear dark.

The second fabrication process for a cantilever array for electronic nose applications [6] uses an n-type silicon wafer for the sensor base and a p-doped surface layer for the cantilever beams. The backside etching of n-type silicon using 60°C, 40% KOH is controlled visually and stopped when the

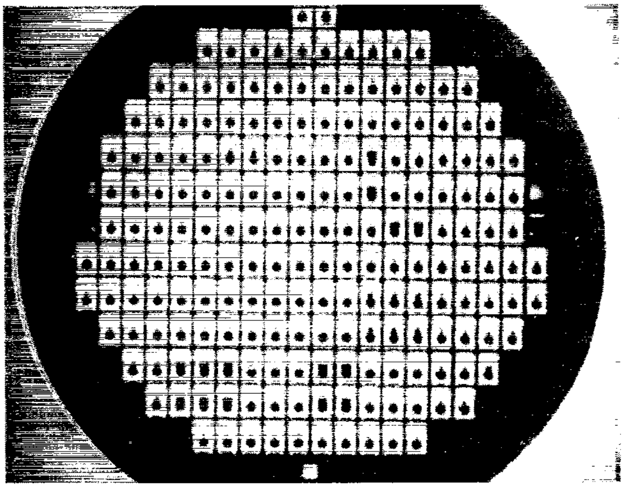

Fig. 4. Optical micrograph using a bottom-side illumination of a 100 mm silicon wafer with piezoresistive sensors processed with our etch setup. The dark and light parts show the individual chips (500 μm thick) and the thin membrane (5 μm), respectively. The silicon-dioxide interface provides good etch stop, which yields uniform membrane thickness over the entire wafer surface.

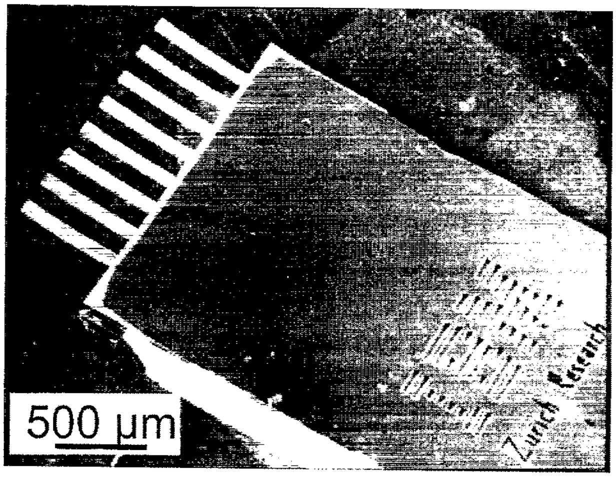

Fig. 5. Scanning electron micrograph of an array of parallel cantilevers for electronic nose applications. The p-doped levers are 0.8 µm thick and are fabricated by a combined dry/wet-etching process using the single-side wet-etch chuck.

infrared light begins to be transmitted through the membrane (at about 5–10 µm membrane thickness). The remaining n-silicon is then removed in an ethylenediamin-pyrocatechol (EDP) etch, which does not etch the previously structured p-doped silicon cantilevers. Fig. 5 shows the resulting array of 0.8-µm-thick cantilevers.

5. Conclusions

The PDMS seal ring has proved to be a reliable, low-cost setup for single-side wet-etching process steps. The main advantage of using the PDMS ring is that no mechanical pressure needs to be applied to seal the wafer against the etchant, which reduces the stress on the wafer and considerably improves yield. As a result of the molding process for making the PDMS ring, many geometrical shapes of the seal are feasible. Moreover, easy operation of etching and rinsing cycles make it simple to monitor the etching progress. As the wafer is not totally immersed in an etch bath, the single-side etch setup with a reduced consumption of chemicals is an economically appealing and environmentally friendly procedure for small-scale or prototype fabrication. The infrared lamp used to heat the etchant can be used to monitor the etch process via the transmission of the light through the thin membranes. For high-throughput, high-quality membrane fabrication, further improvements are necessary regarding the etch control due to fluctuation of temperature and enrichment of the etch chemicals. This could be implemented, for instance, by a circulation of fresh and temperature-controlled etching solution in order to automate this step.

Another improvement would be to implement in situ measurements of the etch rate of silicon by using a laser reflectance interferometer as demonstrated by Steinsland et al. [8].

We have found the PDMS seal ring to be very useful and versatile for various wet-etching applications where only one wafer side is allowed to come into contact with an etching solution.

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