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Wafer-Level Bonding of MEMS Structures with SU-8 Epoxy Photoresist

Santeri Tuomikoski[1] and Sami Franssila

Microelectronics Centre, Helsinki University of Technology, PO BOX 3500, 02015 TKK, Finland

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Abstract

An adhesive bonding method for fabrication of structures for microelectromechanical systems (MEMS) has been investigated. Negative photoresist SU-8 is used both as the structural material and as the adhesive material. Ultraviolet initiated cross-linking of SU-8 was investigated for bonding of small pillars as well as large uniform areas. Fabrication of thermally- and electrically insulated structures was also done and is reported here. Insulated structures are fabricated with SU-8 as roof, floor and sidewalls of the structure to ensure uniform wetting and surface electrochemistry for microfluidic applications.

1. Introduction

Adhesive bonding has become a major wafer bonding technique in microelectromechanical systems (MEMS). In this method polymeric material is used as an adhesive layer between wafers to be bonded. The method has various advantages over more traditional bonding techniques such as anodic bonding or thermocompression. Temperatures can be lower than 100 °C during adhesive bonding process, enabling wider selection of materials applied on the bonded wafers. Particles are not disturbing bonding if they are smaller than polymer thickness. Adhesive bonding can be applied also for gap filling that is not possible with direct bonding methods. However, unintentional gap filling due to polymer flow can be considered a drawback of adhesive bonding. Low cost and large selection of wafers to be bonded and large number of polymers to be used for bonding are other advantages of adhesive bonding [1].

Unlike anodic or fusion bonding, adhesive bonding does not lead to hermetic sealing. This is acceptable in many microfluidic and packaging applications. These are the major fields of adhesive bonding. Another disadvantage is the poor thermal- and long-term stability of the bonding interface compared with anodic or fusion bonding [1]. However, these properties are dependent on the material and properties can be tailored according to requirements. Material selection for adhesive bonding is large: epoxies, polyimides, fluoropolymers, negative and positive photoresists and especially designed bonding adhesives have been applied [1–3]. In some cases adhesive bonding provides additional thermal or electrical insulation to the component.

SU-8 is epoxy-based negative resist developed by IBM [4]. Today it is widely applied in the field of MEMS because of its unique properties. Compared with traditional MEMS fabrication methods, SU-8 offers a cheap and easy fabrication process to produce high aspect ratio structures. Good transparency enables exposure of layers over 2 mm with UV mask aligner [5]. Aspect ratios up to 66 : 1 have been achieved with UV exposure [6].

SU-8 is highly cross-linked after curing and this enables accurate patterning. SU-8 does not exhibit swelling that is changing the shape of the structures in many negative resist systems [7]. Due to high cross-linking density, SU-8 is mechanically strong and therefore it can be used as a structural material. Application of SU-8 as a temporary structure suffers from high cross-linking density induced difficult removal. However, SU-8 has been widely applied in UV-LIGA because of its high aspect ratio properties [4]. SU-8 has been used in fabrication of closed channels and cavities. SU-8 closure has been done with different adhesives like PVC or other epoxies [8, 9]. SU-8 itself has also been used in adhesive bonding [10–12].

Advantage of using SU-8 for bonding is that it creates strong bonds with itself by cross-linking. In some applications like in electrophoretic separation devices it is preferable to have the whole structure made out of one material only, and therefore structures made fully of SU-8 are emphasized in this study. Applications of SU-8 as bonding adhesive have been mainly in microfluidic devices [10, 11].

In this study simultaneous bonding of large uniform areas and small pillars was investigated. Effects of structural and adhesive layer thicknesses were studied. Bonding quality was evaluated from the amount of non-bonded areas, structure shape stability and from gap-filling properties. Bonding process parameters, temperature, baking times and exposure of SU-8, have been characterized. High yielding process for bonding of small pillars and large uniform areas on the same wafer is reported.

2. Methods

Bonding process was tested in fabrication of enclosed microstrucures between silicon- and Pyrex wafers. Pyrex wafers 7740 from Corning and single side polished silicon wafers from Okmetic were used. SU-8 50 and SU-8 100 supplied from Microchem Corporation were applied in the experiments. SU-8 served both as a material for the channels and also as a bonding adhesive. Bonding was done in class 10 cleanroom to avoid particle contamination.

Basic processing steps are shown in figure 1. Process for fabrication of SU-8 microstrucures begins with application of SU-8 on a clean silicon or glass wafer. Wafers were cleaned before application by immersing them for a short time in hydrofluoric acid (HF) solution (Sioetch 17/02 from Merck). After rinsing in DI-water and drying with nitrogen, wafers were dehydrated in a convection oven at the temperature of 120 °C for at least one hour.

SU-8 was applied on the wafer statically. Viscosity of SU-8 and final spinning speed were adjusted to define layer thickness. Structural layer thicknesses in these experiments were between

[1] e-mail: santeri.tuomikoski@hut.fi

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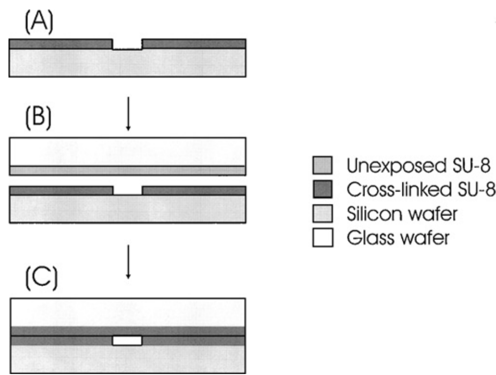

Fig. 1. Process flow for fabrication of closed microchannels. (A) First layer of SU-8 is patterned on silicon or on glass wafer. (B) Bonding layer was spinned on top of glass wafer. After partial soft bake wafers were pressed together. (C) Bonding layer was exposed through the glass wafer and cross-linking during post exposure bake finalized the bonding process.

50 μm and 500 μm. After application of SU-8, wafer was softbaked on a hot plate by ramping the temperature first to 65 °C and after that to 95 °C. Wafer was kept long time at the glass transition temperature of SU-8 to minimize the effect of edge bead and other thickness irregularities. Glass transition temperature of non-cross-linked SU-8 has been measured to be 64 °C [13]. At the glass transition temperature or above, SU-8 exhibits self-planarization. Perfect leveling of the hot plate is required to achieve uniform SU-8 layer thicknesses. Constant rotation of the wafer on the non-leveled hot plate gives satisfying result for most purposes, because it disables flow of SU-8 to one side of the wafer.

Exposure was done in LOMO EM-5006 mask aligner. Standard Hg-lamp was used and optics of the aligner cut wavelengths below 350 nm from the spectra. This is required for SU-8 exposure. Exposure doses were between 900 mJ/cm^2 and 1500 mJ/cm^2 measured at wavelength of 365 nm. After exposure, post exposure bake (PEB) was done by ramping temperature up to 95 °C. Slow cooling back to room temperature reduced thermal expansion coefficient mismatch effects and reduced deformation of the structures. We therefore set cooling rate to 1 °C/minute after PEB. Structures were developed in immersion tank. Developer was propylene glycol methyl ether acetate (PGMEA).

Adhesive bonding layer of SU-8 was applied on a glass wafer after wafer preparation steps as shown in figure 1(b). Adhesive SU-8 layers from 50 μm to 100 μm thickness were applied. Baking times, bonding temperature and exposure of this layer were optimized for the bonding process. Similar to structural layer, also the bonding layer was soft baked on a hot plate followed by contact with structural wafer during cooling. Pressure was applied to initiate contact between wafers. Bonding layer was exposed through the glass wafer and post exposure bake was done to finish bonding by cross-linking of the bonding layer. Unlike reference [11], no additional pressure was applied after initial contact was made. Expensive vacuum bonding system that is often used in adhesive bonding [1] was not required.

Bonding process was also investigated for fabrication of fully insulated structures. In this method a blanket SU-8 layer was spinned on a silicon wafer. Blanket exposure of SU-8 was followed by post exposure bake. On top of the first SU-8, second SU-8 layer was spinned and patterned as described above. Structures made fully of SU-8 are beneficial not only because of good thermal and electrical isolation but also because of symmetry and mechanical stresses. This is an advantage for example in fabrication of microchannels.

3. Results and discussions

Relatively thick bonding layer (50–100 μm) was applied to compensate thickness irregularities of the structural layer. Bonding close to glass transition temperature of SU-8 allowed slight flow of the bonding layer, enabling sealing of large areas. Bonding at this temperature caused unintentional gap filling and possibly some other deformation of the structures. These parameters have been investigated and discussed in this section. Unless otherwise stated, the discussion below is for 65 μm thick bonding layer.

In optimized bonding procedure for 65 μm bonding layer samples were soft baked on a hot plate keeping temperature at the beginning 15 minutes in 65 °C to planarize the layer. After that temperature was ramped up to 95 °C and kept there for 10 minutes. Glass wafer with adhesive SU-8 was cooled down to 68 °C (ramp rate 3 °/min) and the wafer with SU-8 structures was heated up to 68°, and the wafers were pressed together. This thermal equalization reduced structure deformation during bonding. At this temperature void formation was minimized and unintentional gap filling was controlled. Bonding temperature of 68 °C is between earlier published results 75 °C [10] and 48 °C [11].

Pressure to the bonded wafers was applied from one edge and continued over whole wafer. This reduced the amount of air bubbles between bonded layers. Apart from initiation, pressure was not applied during bonding procedure. After contact is achieved over the whole wafer, second layer of SU-8 is exposed through the glass wafer with a dose of 1000 mJ/cm^2. In post exposure bake temperature was first ramped to 95 °C in 5 minutes followed by holding there for 5 more minutes. Again slow cooling was required to reduce stresses in the bonded stack.

By optimization of processing parameters, reasonably good bonding results were achieved. Temperature during bonding should be adjusted to be close to glass transition of SU-8 to avoid complete filling of the structures. By lowering the bonding temperature, filling of the structures can be reduced, but bonding quality suffers. At lower temperatures non-bonding area increases. Below 60 °C high pressure was required to achieve contact. Removal of pressure lead to debonding when contact was made below glass transition temperature of SU-8. Bonding also failed if wafer was held at 95 °C for too long time during soft bake. However, bake should be reasonably long because the amount of solvent should be minimized during softbake, as the remaining solvent reduces cross-linking density and therefore bonding strength.

Bonding of small pillars (25 μm) and large areas simultaneously was successful. Bonding interface of pillars is shown in figure 2. Applied pressure should be adjusted depending on the bonded area. Isolated pillars easily intrude 20 μm into the bonding layer in the case of small pillars. Surrounding structures prevented intrusion. Auxiliary structures next to pillars could be used to minimize intrusion.

Thickness irregularities cause problems in bonding, edge bead being the most important one. Edge bead is caused by surface tension during spinning. Small temperature non-uniformities of the hot plate during soft bake will lead to observable thickness variation. Thickness irregularities cause filling of the gaps because SU-8 flows easily in the temperatures above glass transition of SU-8.

Another problem in the bonding procedure is caused by the stresses in the wafers. SU-8 has coefficient of thermal expansion

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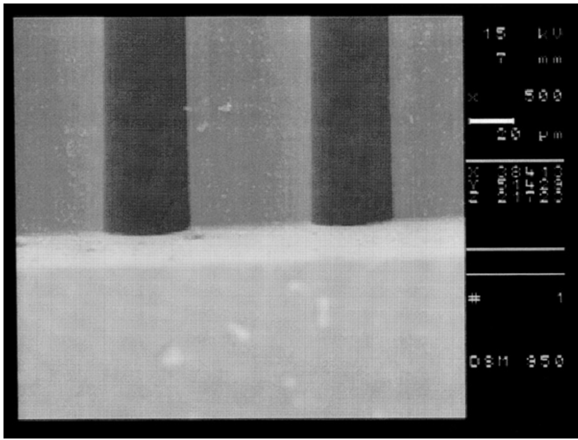
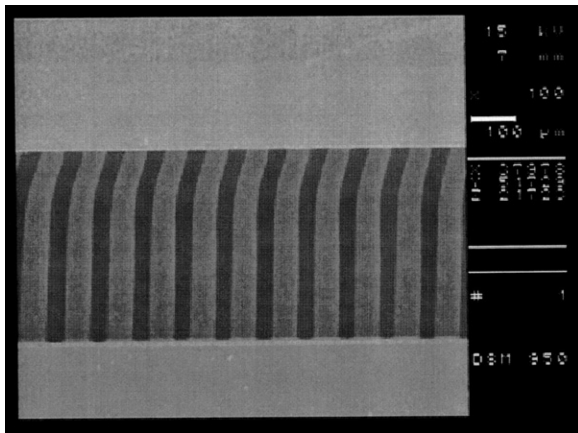


Fig. 2. Bonded SU-8–SU-8 interface of pillars. Pillars are fully connected to SU-8, but not intruded to the bonding layer in the optimized process.



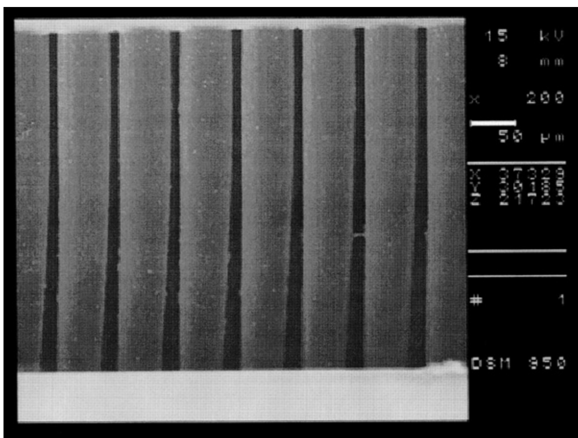


Fig. 3. Stress caused deformations to the pillars. (A) If structural wafer was not heated to the same temperature as bonding wafer, structures were deformed. (B) If both wafers had the same temperature during bonding, no deformations were observable.

(CTE) 52 ppm/°C [14] and silicon and glass wafers have the CTE's less than 3 ppm/°C. Because of the CTE difference wafers were bowed and this made bonding difficult. Thermal stress caused deformation of high aspect ratio pillars as shown in figure 3a. Because of this it is crucial to heat both wafers to the same temperature before bonding. With this treatment bonding can be done without deformation as shown in figure 3b.

Problems occurred mainly in fabrication of fully insulated structures. Both multilayer structures and thick structures had high stresses. Bonding of SU-8 structures up to 500 µm succeeded without problems. Because of the problems caused by gap filling, bonding of the structural layers below 100 µm thickness was difficult. Below 50 µm structural layer thickness gap filling led to very low yields. In multilayer SU-8 structures the problem is more pronounced because thickness irregularities are larger and stresses are complicating the bonding. However, as shown in figure 4, insulated channel with three SU-8 layers have been fabricated successfully.

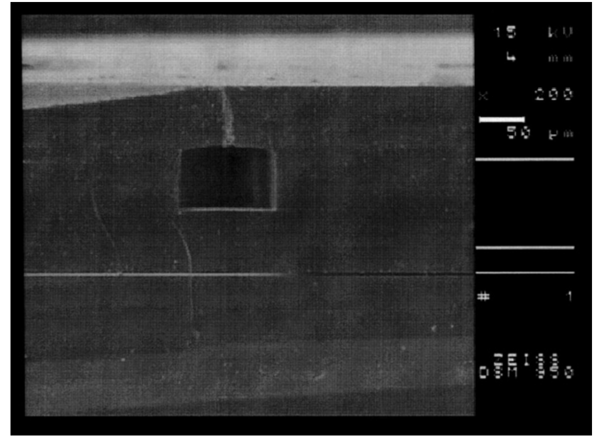


Fig. 4. Insulated SU-8 channel. Structure has Silicon wafer on the bottom followed by three layers of SU-8: insulating layer, structural layer and bonding layer. The sample preparation for the SEM removed the cover glass from the top of SU-8, but bonding interface did not suffer. This proves good mechanical strength of the bonding.

Largest non-bonded areas on 100 mm wafers were about 0.1% of the wafer area. Normally there were less than ten voids larger than 1 mm. In every case non-bonded area was less than 5% of total wafer area. This is an excellent value compared to other reported results [1, 11]. Mechanical strength of the bonds was good: breakage occurred at the SU-8 - silicon or at the SU-8 – glass interface, but not at the bond interface. This can be seen from figure 4. Bonding strength was tested by putting razor blade between the wafers.

Expensive vacuum bonding devices were not required for large area SU-8 adhesive bonding. Air escape channels were not required for the wafer, but those would probably improve the bonding quality. However, in non-patterned wafer micrometer scale voids appeared after bonding. Probably those were caused by outgassing. In patterned wafers where air was able to escape between the glass and silicon wafers small voids were not detected. A non-patterned bonded wafer stack is shown in figure 5.

4. Conclusions

In this study wafer-level bonding with epoxy photoresist SU-8 was investigated for MEMS applications. Bonding with SU-8 was found to have numerous excellent qualities. Bonding at temperature less than 100 °C enables application of various materials like metals or other polymers, enabling low cost MEMS structures with closed channels and cavities to be fabricated. Bonding process is easy and no special equipment is required. Mechanical strength of the bonds was good: breakage occurred at the SU-8 - silicon or at the SU-8 – glass interface, but not at the bond interface. Gap filling during bonding limits the current process leading to lower yields with structural layer thicknesses below 100 µm.

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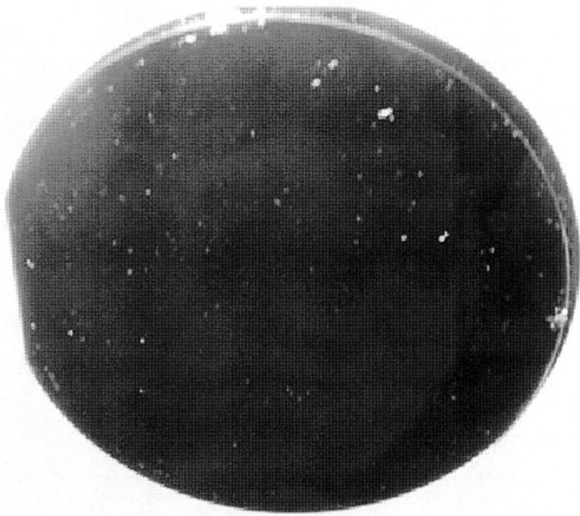

Fig. 5. Non-patterned bonded wafer stack. Bonding without massive air bubbles was done. Amount of non-bonded area was every time less than 5%. Non-bonded areas are seen as white dots.

Bonding with non-bonded area less than 5% was reproducibly demonstrated. Bonding of large, centimeter-scale, and small, micrometer-scale, structures was successful on the same wafer. Pillars of 25 μm diameter were successfully bonded with SU-8. Stability of structure shape was found to be good if both bonded wafers were heated to the same temperature during bonding.

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