Low Temperature Wafer Level Packaging of RF-MEMS Using SU-8 Contact Printing

J. Tian and M. Bartek

Abstract— **A low-temperature wafer-level packaging process based on adhesive wafer bonding utilizing SU-8 spacers and SU-8 contact printing is presented. In this process, thick SU-8 layer (>40 µm) is firstly deposited and patterned on a bare glass wafer forming spacers that are later utilized as a package cavities protecting sensitive RF MEMS devices in the final package. Before this glass capping wafer with pre-formed cavities is adhesively bonded to the target wafer, a roller transfer process is used to print a thin layer of SU-8 selectively on the surface of thick spacers only. The adhesive bonding process occurs after the capping glass wafer and the target silicon wafer are aligned and pressed together (pressure of 200 kPa). During the subsequent UV cure and baking steps, SU-8 become fully cross-linked and provides a strong bond between the wafers. To characterize the bonding strength, tensile tests were carried out and the measurement results show that the bond strength is up to ~20 MPa. This bonding technique is due to its low thermal budget (T<120°C) especially suitable for packaging of temperature sensitive devices.**

Index Terms— **Wafer-level packaging, SU-8 printing, low temperature bonding, bonding strength, tensile test.**

I. INTRODUCTION

MICRO-FABRICATION has been applied widely in the micro-component manufacturing and other optical and communication process elements. As a result, MEMS, sensors and actuators, and VLSI can be extended to high-density, multilayer 3D structures [1]-[3]. The silicon bonding technology plays more and more important role in the modern micro-fabrication. In general, the bonding technology can be divided into two major categories, direct wafer bonding and intermediate layer bonding [1]. The conventional fusion bonding technology, as a representative of the direct bonding, is based on polymerization of silanol (Si-OH) bonds into siloxane (Si-O) bonds.

The bonding relies on both very smooth and flat surfaces (micro-roughness < 4 nm and bow < 5 µm) to adhere, and heat annealing (> 800 ^{o}C) to increase bond strength. These make this bonding technique not feasible for VLSI or MEMS devices packaging.

Typical anodic bonding technology reduces the temperature effect to the bonded structure (300-400 ^{o}C), but the high electrical field involved (700-1200 volt) in the bonding process may seriously affect electrical circuits in the bonded devices. Moreover, this technique utilizes sodium rich glass, such as Corning #7740, in which the mobile Na+ ion is a well-known contamination source for the modern IC manufacturing.

In contrast to these two technologies, intermediate layer bonding may produce low temperature and VLSI device compatible solutions. SU-8, which is a negative tone photoresist from MicroChem Corp., is one of the most attractive materials for wafer level packaging, since it is a photo definable polymer and its bonding process does not involve either high temperature steps (< 120 ^{o}C) or any electric fields. Furthermore, the SU-8 film thicknesses from 1 µm to hundreds of microns can be realized in one spin coat step. Also it is much less sensitive to the surface condition of the bonding substrates.

SU-8, however, has its limitation especially when applied to MEMS devices. The coefficient of thermal expansion (CTE) of SU-8 (~50 ppm/K) is much larger than almost all the materials used in MEMS (e.g. the CTE of silicon is ~2.54 ppm/K), which will result in a high level tensile stress. During the SU-8 process, the MEMS device may potentially be damaged. Furthermore, the SU-8 trapped under free-standing structures can hardly be removed, which will degrade the MEMS device as well.

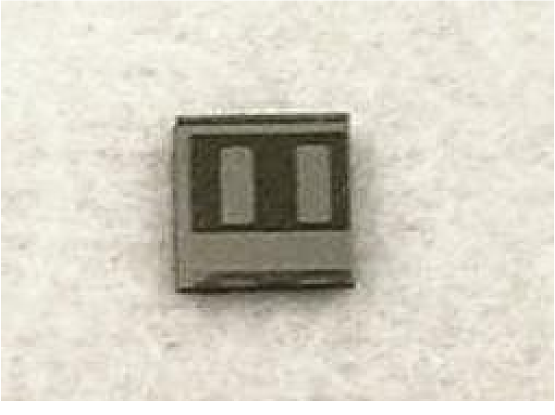

Fig. 1. Sample of a wafer-level package based on SU-8 contact printing technique.

In this study, we developed a wafer level packaging process

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employing SU-8 contact printing; see Fig. 1 for a sample of a bonded device. The bonding temperature of this technique can be as low as 105 °C. This method does not involve too many process steps on the silicon device wafer, thus reduces the negative impact of SU-8. Tensile bonding strength test results for different bonding temperatures and different SU-8 thicknesses are also discussed.

II. EXPERIMENTAL PROCEDURE

Fig. 2 shows the entire process flow for the wafer level packaging with SU-8 contact printing technique.

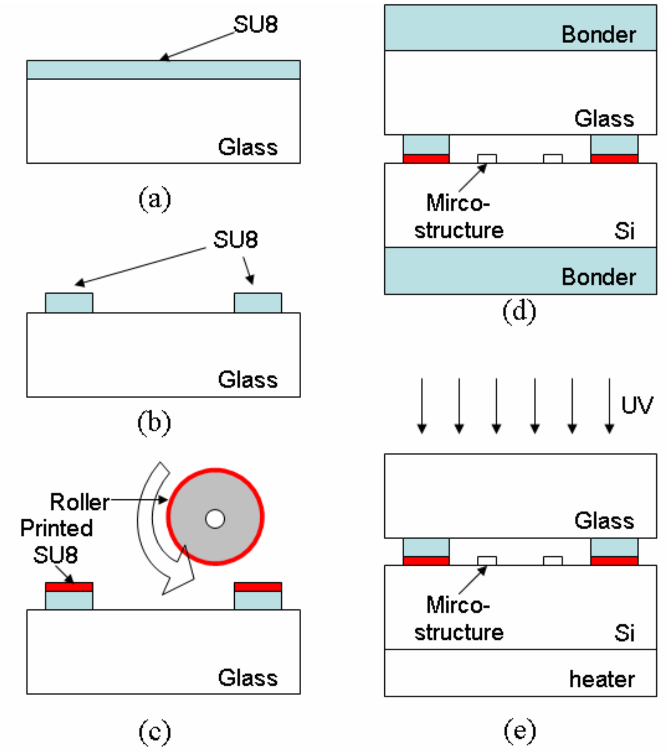

Fig. 2. Process flow for SU-8 contact printing wafer bonding (drawing not in scale), (a) SU-8 coating on the glass substrate, (b) SU-8 exposure with UV light, development and baking, (c) SU-8 contact printing with a roller on the defined SU-8 structure, (d) align with the silicon substrate that has microstructure and press on a wafer bonder under 200 kPa pressure, (e) UV cure and final baking with different evaluation temperatures.

In this study, 4-inch diameter AF-45, sodium-free glass wafers with thickness of ~300 µm were used as the capping substrates for the bonding. In order to promote the adhesion, the glass wafers were first cleaned in HNO_3 bath in order to remove particles on the wafers, and at last fully dehydrated at 200 °C for 10 min in an oven just before coating. SU-8 was then spin-coated on the glass wafers, as shown in Fig. 2(a). In this study, 3 different SU-8 thicknesses (~40, ~60 and ~80 µm) were tested with the spin speed varying from 1200 to 1800 rpm. After soft bake at 95 °C for 10 min, the SU-8 was exposed on a contact aligner and developed to define the testing structures, as shown in Fig. 2(b). Right after the exposure, post exposure bake (PEB) was performed. A slow temperature ramping up and cooling down is essential for the PEB step in order to relax the stress in the SU-8. The stress generated by the SU-8 itself can easily crack the bonding structures, especially in concave corners

After patterning of the SU-8 spacers, the same SU-8 type was used as the 'ink' for the contact printing. Using a roller, these spacers were covered with a thin layer of SU-8 (see Fig. 2(c)). Such 'fresh' adhesive layer is mechanically less resistant to the shear stress created by the two bonding chucks being not leveled absolutely parallel to each other, which may result in a lateral movement [4]. In order to reduce wafer lateral movement in the following bonding step, the inked wafer was aged first at room temperature for 10 min. The printed glass wafer was then aligned and pressed onto the silicon wafer (4 inch) with microstructures. As it is shown in Fig. 2(d), these two wafers were then bonded in a wafer bonder with 200 kPa pressure applied for 5 min. An UV exposure step (350 mJ/cm^2, 10 min) was then employed on the glass side of the bonded wafers to cross-link the printed SU-8. The following baking step (60 min) further cross-links the printed SU-8 in order to improve the bond strength, as shown in the Fig. 2(e). Different final baking temperatures, or the bonding temperature, were evaluated. The detailed evaluation conditions are listed in Table I.

Table I. Evaluation conditions (SU-8 thickness and bonding temperature).

SU8 thickness (µm)	40	60	60	60	60	80
Bonding temperature (°C)	120	95	105	120	135	120

III. RESULTS AND DISCUSSION

A. *SU-8 pattern transfer resolution*

The spatial resolution is defined by the size of the finest structure that can be clearly defined with SU-8 patterning. In this study, since SU-8 was used to define packaging cavities, only trench spatial resolution was evaluated just after SU-8 development.

Since SU-8 is a negative tone photo resist, after its development, the exposed area remains and the non-exposed is removed. The major problem for the SU-8 spatial resolution in trenches actually lies in the development ability. Because of the surface tension of the SU-8, it is hard for the developer to enter narrow trenches, thus resulting in partially developed or even undeveloped trenches. Especially, when dealing with thick SU-8 layers, the trench width plays an important role. The trench spatial resolution defines the size of the smallest cavity that can be achieved in the SU-8 patterning.

Fig. 3 shows fabricated sample with a 60 µm thick SU-8 layer after its development with trenches having following width (from left to right): 5, 10, 15, 20, 25, 30, 50 and 75 µm. It can be observed that the trenches a, b and c, which are 5, 10 and 15 µm wide respectively, are still fully blocked. Trenches d, e and f, which are 20, 25 and 30 µm wide respectively, are partly opened. Only trenches g and h, which are 50 and 75 µm wide, are clearly defined. This might indicate that the dimension of the packaging cavity formed by SU-8 should not be smaller than 50 µm.

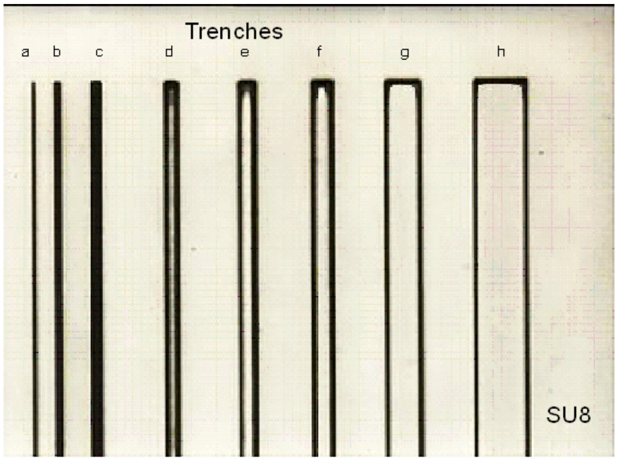

Fig. 3. SU-8 sample used for pattern transfer resolution evaluation. Trench width: a) 5 µm, b) 10 µm, c) 15 µm, d) 20 µm, e) 25 µm, f) 30 µm, g) 50 µm and f) 75 µm; SU-8 thickness: 60 µm.

B. *Inspection of the printed SU-8*

After wafer bonding, the samples were first inspected. One example of the inspection pictures is shown in Fig. 4. It can be seen, that occasionally there are bubbles trapped in the printed SU-8 layer. This may seriously affect the bond strength and cause large fluctuation in the tensile tests, which will be discussed later.

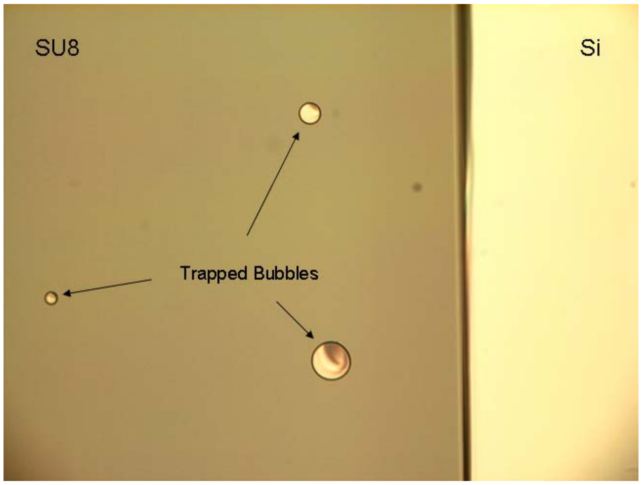

Fig. 4. Inspection shows that there are bubbles trapped in the printed SU-8 layer.

In Fig. 4, it is also observed that there is a ‘skirt’ around the bonding structure. This was further inspected using SEM and the obtained SEM micrograph is shown in Fig. 5. Since the printed SU-8 was still viscous, even though most of the solvents in SU-8 are expected to evaporate quickly, during wafer bonding process this printed layer of SU-8 was pressed out of the bonding area and formed a skirt around the bonding structures. This can be clearly seen in Fig. 5. This skirt is sometimes very large (~30 µm), especially at concave corners. This has to be taken into consideration in the future packaging designs.

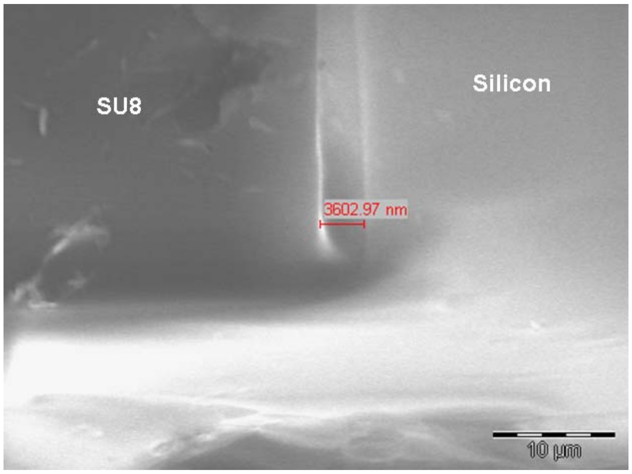

Fig. 5. SEM picture of a corner of the bonded sample.

On the other hand, Fig. 4 and Fig. 5 also show that the printed SU-8 does not flow inside the cavity leaving the silicon surface clean. This is essential for this application. In the case that there was some SU-8 left inside the cavities, it may stick to the vulnerable MEMS devices. With the tensile stress created in SU-8 during the bonding process, the MEMS devices can easily be damaged.

C. *Tensile strength measurements*

The bond quality of the presented technique was investigated by carrying out tensile strength measurements. The tensile strength was measured with a tensile testing machine with a range of up to 10 kN, where samples were glued to pairs of sample holders by epoxy having bond strength higher than the bond strength of SU-8.

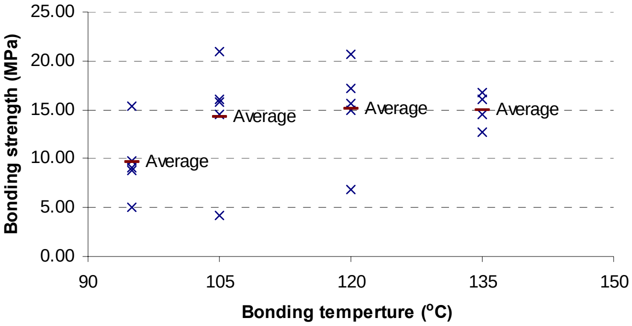

Fig. 6. Tensile strength measurements taken from the bonding temperature variation (SU8 thickness, ~ 60 µm).

The tensile strength measurements taken from the bonding temperature variation (with constant SU-8 thickness of ~60 µm) are plotted in Fig. 6 and in Table II. It can be seen that after 105 °C the average bond strength does not really change. It may suggest that after the final UV exposure step, the printed SU-8 is fully cross-linked and reaches its maximum bond strength, which is 20.9 MPa, at ~105 ^{o}C. Similar results were also obtained in [1]. This temperature is acceptable for all the applications of VLSI, sensors or MEMS devices.

Table II. Results of tensile strength measurements vs. bonding temperature (SU-8 thickness of 60 μm).

Bonding temp. (^{o}C)	95	105	120	135
Avg. bond strength (MPa)	9.62	14.30	15.05	15.01
Max. bond strength (MPa)	15.39	20.93	20.61	16.70
No. of samples	5	5	5	5

The tensile strength measurements taken for the SU-8 thickness variation (with fixed bonding temperature, 120 ^{o}C) are plotted in Fig. 7 and summarized in Table III. In this plot, there is no clear dependence of the bond strength on the SU-8 thickness. This may indicate that the SU-8 thickness does not affect the bond strength in this process.

In both Fig. 6 and Fig. 7, a large data fluctuation is observed. As discussed in the previous section, this may strongly related to the bubbles trapped in the printed SU-8.

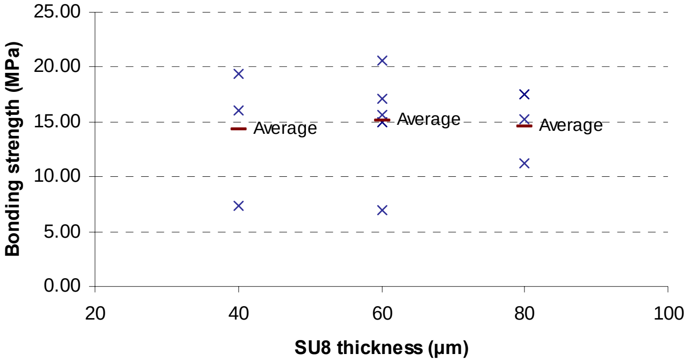

Fig. 7. Tensile strength measurements taken from the SU-8 thickness variation (bonding temperature 120 ^{o}C).

Table III. Results of tensile strength measurements vs. SU-8 layer thickness (bonding temperature of 120°C).

SU-8 thickness (μm)	40	60	80
Avg. bond strength (MPa)	14.29	15.05	14.63
Max. bond strength (MPa)	19.40	20.61	17.5
No. of samples	3	5	3

D. *Failure mode analysis*

After the tensile strength tests, some samples were further inspected to investigate the failure mode. The inspections show that most of the samples were broken at the interface between SU-8 to the glass substrate; some were broken at the interface between the SU-8 and the silicon substrate. And there was no failure in the SU-8, or cohesive failure, found in this experiment. This may suggest that the bonding strength between the printed SU-8 and the pre-patterned SU-8 bonding structure be stronger than the SU-8 adhesion to the substrates. This indicates that the failure mode of this packaging technique is mainly adhesive. This also explains why the bond strength does not change in the SU-8 thickness variation evaluation, which is shown in Fig. 7. Some of the inspection pictures are shown in Fig. 8.

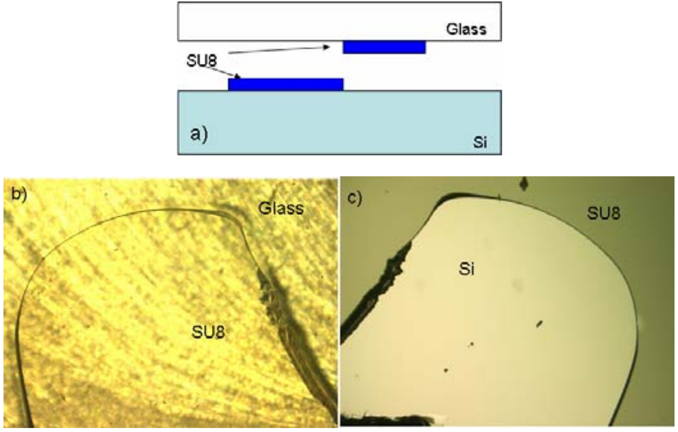

Fig. 8. Failure mode analysis: a) illustration of how some of the samples were broken; b) glass side of a broken sample (the background texture is the surface of the sample holder); c) silicon side of the same sample.

IV. CONCLUSION

This paper shows SU-8 contact printing process for wafer level packaging. In this process thin SU-8 layer is roller printed on SU-8 bonding spacers on a glass wafer which are then bonded to the device wafer. With this process, the SU-8 stress impact to the MEMS structures can be greatly reduced. The maximum bond strength (20.9 MPa), which is larger than the SU-8 adhesion to the substrates, can be reached at 105 ^{o}C. This process allows low temperature and non-electric field wafer level packaging and is particular suitable for sensors and MEMS packaging.

V. ACKNOWLEDGEMENT

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