

# BCB Contact Printing for Patterned Adhesive Full-Wafer Bonded 0-Level Packages

Joachim Oberhammer and Göran Stemme, *Member, IEEE*

**Abstract**—Adhesive wafer bonding with a patterned polymer layer is increasingly attracting attention as cheap and simple 0-level packaging technology for microstructures, because the patterned polymer both fulfills the bonding function and determines the volumes between the two wafers housing the devices to be packaged. To be able to pattern a polymer, it has to be cross-linked to a certain degree which makes the material rigid and less adhesive for the bonding afterward. In this paper, a simple method is presented which combines the advantages of a patterned adhesive layer with the advantages of a liquid polymer phase before the bonding. The pattern in the adhesive layer is "inked" with viscous polymer by pressing the substrate toward an auxiliary wafer with a thin liquid polymer layer. Then, the substrate with the inked pattern is finally bonded to the top wafer. Benzocyclobutene (BCB) was used both for the patterned structures and as the "ink". Tensile bond strength tests were carried out on patterned adhesive bonded samples fabricated with and without this contact printing method. The bonding yield is significantly improved with the contact printing method, the fabrication procedure is more robust and the test results show that the bond strength is at least 2 times higher. An investigation of the samples' failure mechanisms revealed that the bond strength even exceeds the adhesion forces of the BCB to the substrate. Furthermore, the BCB contact printing method was successfully applied for 0-level glass-lid packaging done by full-wafer bonding with a patterned adhesive layer. Here, the encapsulating lids are separated after the bonding by dicing the top wafer independently of the bottom wafer. [1232]

## I. INTRODUCTION

### A. Patterned Adhesive Bonding

**A**DHESIVE full-wafer bonding is a technique using a polymer as intermediate layer between the two wafers to be bonded [1]–[3]. The polymer is applied, usually by spin coating, on one of the two wafers, and the bonding is carried out involving pressure and a temperature high enough to fully cross-link the polymer in order to achieve a strong adhesion between the wafers and the polymer, and to get a strong bulk of the polymer itself. Some polymers can also be cross-linked at room temperature by photo-curing or by the hardening of two components epoxy.

The main advantages of adhesive bonding are as follows:

- integrated circuit (IC) compatibility due to low temperature processing and since no voltages are involved as compared to anodic bonding;

- insensitivity to particles and surface nonuniformities up to a few micrometers;
- the thickness of the adhesive intermediate bonding layer can be chosen within a wide range;
- simple and robust processing;
- polymers show relatively good adhesion to most materials used in microsystems and microelectronics production;
- the process is independent of the substrate materials and different substrates can be bonded to each other;
- polymers do not contain ions which might diffuse into silicon and change its electrical characteristics;
- the adhesive can be patterned before the bonding to create defined cavities in the bonding layer;
- due to their elastic properties, polymer bonding layers act as a stress buffer between the bonded structures.

A variety of polymer materials used in electronics production are suitable for adhesive bonding. Materials for a specific bonding application should be selected considering process compatibility, thermal stability, mechanical stability, creep strength, chemical resistance, handling, etc. The main restriction in the polymer choice is that the material is not allowed to evolve volatile substances during the cross-linking, which create delaminations and cracks due to trapped gases in the bonding interface.

Benzocyclobutene (BCB) [4]–[7] from the Dow Chemical Company was found to be suitable for adhesive bonding [8], since its curing process does not involve catalysts and thus no detectable outgassing of the polymer occurs after evaporating the solvents. It is also possible to pattern this material in a soft-cured, i.e., not fully crosslinked state, which makes it suitable for wafer bonding with patterns in the adhesive layer. The patterning can be done either by dry-etching [9], [10] or by using a photosensitive version of the material [11]. Successful bonding with such a patterned BCB layer was already reported, both by using photosensitive BCB [12] and by using dry-etch BCB [13]. Dry-etch BCB is available in different viscosities resulting in a single-layer thickness ranging from 1 to 26  $\mu\text{m}$ , and the photo-sensitive version is available for single-layers up to 40  $\mu\text{m}$ .

The bond strength of a patterned adhesive layer is lower than the bond strength of an unpatterned layer, since the polymer has to be cross-linked to a certain degree before the bonding, in order to be chemically and physically resistant enough for the patterning processes. Also, the soft-cured BCB is much less elastic than an uncured and basically liquid BCB layer, which decreases the bonding yield in case of surface nonuniformities on both of the wafers to be bonded [13].

In this paper, a simple method is presented which combines the advantages of a patterned adhesive layer with the advantages

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The authors are with the Microsystem Technology Group, Department of Signals, Sensors and Systems, at the Royal Institute of Technology, SE-100 44 Stockholm, Sweden (e-mail: joachim.oberhammer@s3.kth.se).

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of a viscous polymer phase before the bonding. The pattern in the adhesive layer is "inked" by pressing the substrate with the pattern toward an auxiliary wafer with a thin and almost-liquid polymer layer. Then, the substrate with the inked pattern is finally bonded to the second wafer.

### B. Wafer-Level Packaging by Adhesive Bonding

In electronics manufacturing, wafer-level packaging (WLP) is a trend in flip-chip mounting of integrated circuits (IC) directly to the printed circuit board (PCB) or multichip-module (MCM), without a separate carrier for redistribution of the pads [14]. Thus, the sawing of the wafer is the last process step. In MEMS, the term wafer-level packaging is used if the cavity containing the mechanical device is sealed and tested on wafer level, then diced and finally integrated into the high-level system or the final electronic package. The key-advantages of this wafer-level approach for both electronics and MEMS are substantially lower cost and higher volume throughput and a higher degree of system miniaturization [15], [16].

Glass-lid encapsulation on wafer-level with flip-chip-like techniques, where each encapsulating lid is individually placed and bonded to the corresponding device on the still complete substrate wafer, was shown with b-stage epoxy [17] and with photosensitive BCB [18]. The disadvantages of this wafer-level capping technique are that the caps have to be separated by a die saw before the bonding and thus introduce a source of particles to the process chain, and that the packaging process of the whole wafer takes a very long time due to the individual chip alignment and bonding. Wafer-level packaging by full wafer bonding significantly parallelizes the packaging process which is reduced to one single bonding step. Anodic bonding follows this approach and became a key packaging technology which enabled high volume fabrication of MEMS microactuators and microsensors like accelerometers [19].

The authors of the present paper recently demonstrated an encapsulation technique by full-wafer bonding using a patterned BCB layer. Here, a full wafer is bonded to the substrate wafer containing the devices to be packaged and BCB patterns in the shape of rings surrounding the devices. The encapsulating lids are diced after the bonding without harming the substrate wafer [20]. In the present paper, the BCB contact printing technique is applied to improve the yield and reliability of this 0-level packaging method.

Packaging by polymer bonding does not provide with hermeticity in terms of gas-tightness [21, Section 14.4.1], even for an epoxy-based polymer such as BCB. The authors of the present paper already published a method to improve the hermeticity of BCB bonded packages by adding an additional silicon nitride diffusion barrier in form of a passivation layer [22].

## II. FABRICATION

Fig. 1 shows the fabrication sequence of the 0-level glass-lid encapsulation technique by using the BCB contact printing method. The 100 mm diameter, 500  $\mu\text{m}$  thick silicon substrate wafer contains the BCB pattern in the shape of a wall surrounding the device to be packaged [see Fig. 1(a)]. The contact printing method can also be applied with any other patternable

organic or nonorganic material to achieve a local adhesive bond by printing and curing a viscous polymer. In this paper, dry-etch BCB CYCLOTENE 3022-56 is used as patternable material with a resulting layer thickness of 18  $\mu\text{m}$ . On some wafers, adhesion promoter AP8000 was applied before spinning the BCB to investigate a possible bond strength improvement. The BCB is spun onto the substrate and soft-cured at 210  $^{\circ}\text{C}$  for 30 min before patterning it in  $\text{CF}_4/\text{O}_2$  plasma with a Shipley SPR 5740 photoresist mask with a thickness of 20  $\mu\text{m}$ . The "ink" for the contact printing, also BCB of the same kind, is spun onto an auxiliary silicon wafer with a resulting thickness of 1  $\mu\text{m}$ . This layer is not cured and the wafer is not even put onto a hotplate, to keep the BCB as viscous as possible. The top surface of the BCB pattern on the substrate is then "inked" by pressing the auxiliary wafer to the substrate wafer [see Fig. 1(c)]. This process is carried out in a commercially available substrate bonder Karl Suss SB6, involving a bonding pressure of 350 to 500 mbar for 10 min. Afterward, the wafers are separated by inserting a razor blade in between the two wafers. Since no bonding and no curing of the BCB film occurred, the auxiliary wafer can be easily removed, leaving a thin liquid BCB layer on top of the BCB pattern of the substrate [see Fig. 1(d)] the top glass wafer, 100 mm diameter and 500  $\mu\text{m}$  thick, is then bonded to the substrate, applying a pressure of 2.5 bar and a temperature of 250  $^{\circ}\text{C}$  for 1 hour, to fully crosslink both of the polymer films [see Fig. 1(f)]. For the glass-lid packaging, the outlines of the final glass-lids might be cut into the front-side of the glass wafer before the bonding [see Fig. 1(e)]. Such grooves allow a lower vertical accuracy of the die saw when finally dicing the top wafer after the bonding to separate the glass-lids [see Fig. 1(g)]. This process step may be omitted if the thickness of the polymer layer is larger than the vertical accuracy of the die saw. After the bonding, only the top wafer is cut along the outlines of the glass-lids without harming structures on the bottom wafer, and unbonded glass parts just fall off. Finally, also the bottom wafer is diced [see Fig. 1(h)].

To fabricate the samples required for the bond interface investigation, it would be sufficient to cut the bonded wafers with one single cut into test samples. As a more general glass-lid encapsulation technique, the presented method cutting the top wafer independently of the bottom wafer has the advantage that structures on the front-side of the bottom wafer, such as electrical contact pads for wire-bonding, can easily be accessed. Fig. 2 shows an array of glass-lid packages still on the substrate wafer after dicing the glass wafer only. Fig. 3 shows a photograph of one of the samples after the whole fabrication procedure.

It should be mentioned that a similar improvement of the bonding technique could also be achieved by simply spinning a thin polymer layer directly on the top wafer. However, the local transfer of the thin polymer layer has the advantage that the top wafer can also contain microsystem structures which might not allow to be covered by a polymer film. Another modification of the fabrication is the spinning and patterning of the BCB pattern on the top wafer instead of the bottom wafer, if the bottom wafer contains free-etched mechanical structures which can not be covered by the spin-on polymer. If both wafers contain sensitive mechanical structures, the BCB could also be printed on the wafer.

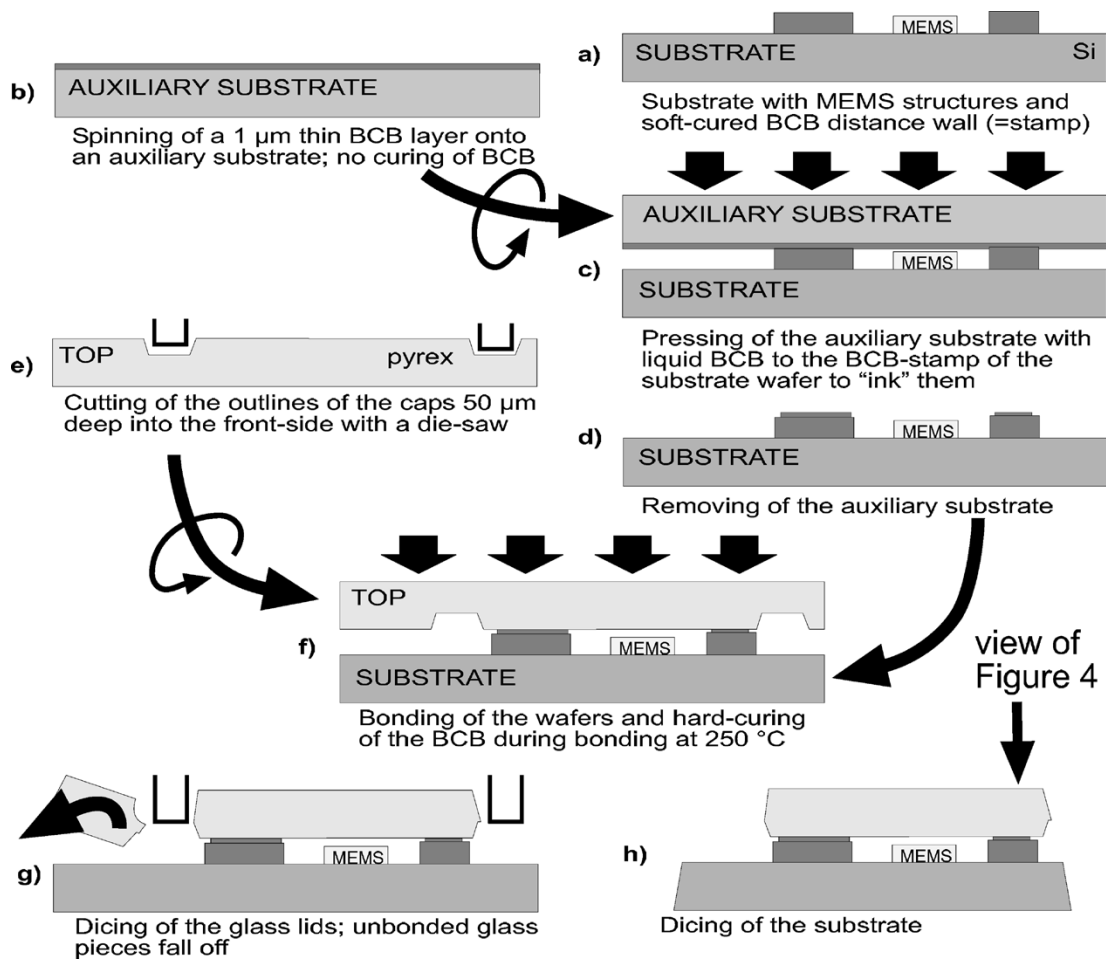


Fig. 1. Process flow of the glass lid encapsulation technique by BCB contact printing.

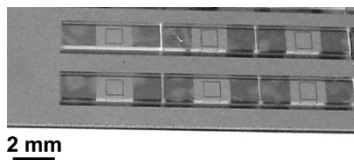


Fig. 2. Array of glass-lid packages on the substrate wafer after dicing the glass wafer.

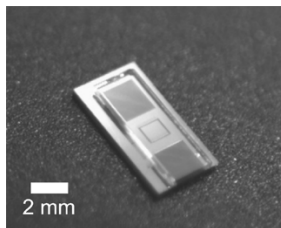


Fig. 3. Single sample after dicing, before carrying out the tensile strength test.

For the samples fabricated with the "conventional" patterned BCB bonding technique, the soft-cured BCB was directly bonded to the top glass wafer after patterning the polymer. This is possible since the material is cross-linked to only about 50% during the soft-curing, making it robust enough for the patterning but still leaving it sufficiently adhesive for the bonding. During the bonding process, the material is fully

cured and creates a bond with the surface of the glass wafer. The degree of soft-curing and thus the soft-curing parameters are very important for a successful patterning and bonding [13], whereas it is very uncritical for the BCB contact printing method which also works using a fully cured BCB pattern.

The fabrication with both methods uses the same photomask for the patterning of the BCB, the same procedure for its soft-curing and its patterning, and the same final bonding procedure. The only difference is the transfer of the "BCB-ink" to the BCB pattern for the contact printing method.

### III. BONDING RESULTS

#### A. BCB-Ink Transfer

The BCB-ink is still viscous even though most of the solvents of the thin film are expected to be evaporated quickly. Therefore, the patterned ink is flowing slightly out of shape during the bonding procedure, as shown in the microscope photograph of Fig. 4, taken through the glass wafer after bonding. Especially in concave corners, the BCB is also flowing into the cavity. However, this effect can be predicted and the volume deformation of the viscous BCB film can be considered in the design by knowing the width of the BCB wall and the ratio of the thickness of the BCB-ink layer to the thickness of the BCB wall. For the fabricated samples with a 18- $\mu\text{m}$ -thick and 100- $\mu\text{m}$ -wide BCB wall and a 1- $\mu\text{m}$ -thick BCB-ink layer, the BCB flow into

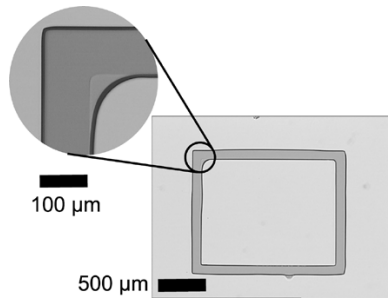


Fig. 4. Microscope picture through the covering glass wafer after bonding with the BCB printing technique, showing the 'BCB-ink' slightly flowing out of the shapes of the BCB stamp, which occurs especially in concave corners.

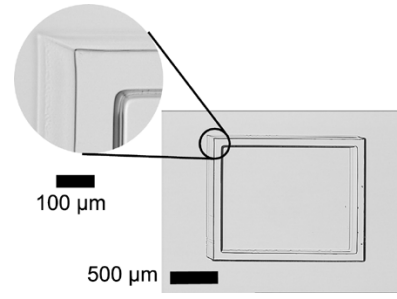


Fig. 6. Microscope picture of the "negative imprint" of the BCB stamp in the liquid BCB layer of the auxiliary wafer.

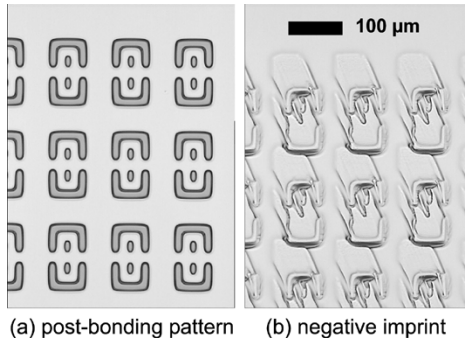


Fig. 5. Also small patterns, here with a line width of  $10\ \mu\text{m}$ , keep their shapes during printing quite well (a), even though the negative imprint is distorted when removing the auxiliary wafer (b).

the encapsulated cavity is calculated to be less than  $3\ \mu\text{m}$ , assuming a uniform displacement of the material and a complete transfer of the ink from the auxiliary wafer. Measurements on the samples confirmed a flow in this order of magnitude and also a very uniform displacement, except in concave corners where the flow length for a pattern width of  $100\ \mu\text{m}$  was measured to be between  $5$  and  $10\ \mu\text{m}$ , in some cases even up to  $30\ \mu\text{m}$ , as shown in Fig. 4. Smaller pattern areas however also cause less volume deformation of the BCB-ink, thus small features with a width of  $10\ \mu\text{m}$  are distorted by less than  $2\ \mu\text{m}$  and even concave corners are very sharp after the bonding process, as shown in Fig. 5(a).

Fig. 6 shows the negative imprint of the BCB-stamp of Fig. 4 in the BCB layer on the auxiliary wafer after separating the auxiliary wafer from the substrate wafer. The BCB is transferred very uniformly to the BCB stamp which leads to a very homogeneous bond. That means that 1) the adhesion of the viscous BCB film to the BCB pattern is higher than the adhesion of the film to the auxiliary silicon wafer substrate, and 2) that the cohesive forces within the viscous BCB film are smaller than both the adhesion to the BCB pattern and the adhesion to the auxiliary wafer. When investigating the auxiliary wafer, a pattern shift in the range of  $100\ \mu\text{m}$  was observed. The authors assume that the displacement between the auxiliary wafer and the substrate wafer occurs during the manual separation of the two wafers, and not during the film transfer in the bonder. This assumption is also supported by the observation that during the final bonding of the glass wafer to the substrate wafer, the wafers move not more than a few micrometers, because a "smeared" BCB pattern would be visible on the glass wafer after the bonding if

the movement between the wafers would have been larger than the volume deformation of the ink. As demonstrated in Fig. 5, even inked patterns with a feature size of  $10\ \mu\text{m}$  do not show any such "smearing effect" at all, and thus the wafer movement during the bonding is assumed to be less than  $2\ \mu\text{m}$ . That is much less than was found during previous research work, done at our institute with the same bonding machine, which revealed that the post bonding alignment accuracy for adhesive bonding using viscous (not pre-cured) epoxy-based resins such as BCB with a thickness of  $2$  to  $3\ \mu\text{m}$  is in the range of up to  $15\ \mu\text{m}$  [23]<sup>1</sup>. For the present investigation however, the not precured transferred BCB film is assumed to be much thinner than the actual layer thickness on the auxiliary wafer due to some displacement of the BCB underneath the pattern caused by the involved pressure during the "inking" process, and thus results in a larger mechanical resistance against lateral movements during the final bonding.

The whole process of transferring the BCB ink and the bonding with the soft-cured/viscous BCB layers was found to be very robust, since already the first process parameter set was very successful and all the pictures of the bonded structures and the auxiliary wafer are taken from the very first bonding experiment (Figs. 4–6).

### B. Bond Interface Investigation

The test samples fabricated with the "conventional" patterned BCB bonding technique are classified in the following text as group A, as group B1 and B2 if fabricated with the BCB contact printing method, whereas group B1 was fabricated without using adhesion promoter between the silicon substrate and the BCB pattern, and group B2 with applying the adhesion promoter AP8000.

The bond quality of the samples was investigated by carrying out tensile strength measurements, by visual inspection through the glass wafer, and by scanning acoustic microscopy (SAM). Since the top wafer was a glass wafer in all bonding experiments, delaminations in the bond interface can easily be found by visual inspection with a microscope. Also, scanning acoustic microscopy has proved to be a very suitable inspection tool since it can be used also for non transparent materials, even though the lateral resolution is not as good as with visual inspection. The

<sup>1</sup>The wafer movement in adhesive bonding with not pre-cured adhesives is larger than typically observed in other wafer bonding techniques such as anodic bonding, because a viscous 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 results in a lateral movement.

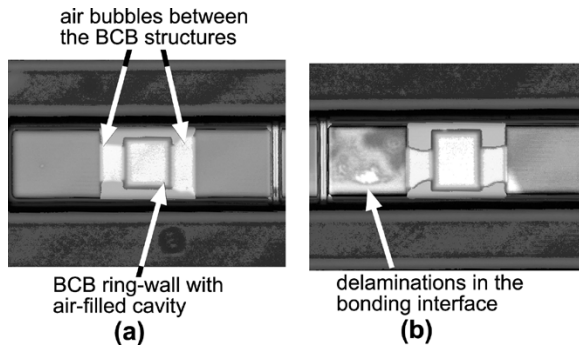


Fig. 7. Scanning acoustic microscope pictures of the bond interface of soft-cured BCB (group A): (a) well bonded sample and (b) voids in the interface.

TABLE I  
RESULTS OF TENSILE STRENGTH MEASUREMENT OF THE  
BCB-BONDED SAMPLES

	Unit	soft-cured BCB (group A)	BCB contact printing without AP (group B1)	with AP (group B2)
avg. bond strength	MPa	3.97	11.34	8.68
max. bond strength	MPa	7.71	21.32	14.64
number of samples	-	11	5	11

tensile strength was measured with a pull-tester with a capability of up to 1 kN, and the samples were glued to the sample holders by epoxy. The strength of the epoxy for the set-up is similar to the bond strength of the BCB, but the glued area is much larger than the bonded area.

Due to the fact that the soft-cured BCB of the samples of group A is not as flexible as the viscous BCB, some of the samples of group A had delaminations in the bond interface. Fig. 7 shows SAM pictures of samples of group A. The sample in Fig. 7(a) is very well bonded, whereas the sample in Fig. 7(b) clearly has delaminations over a large area. SAM is done in a heated water bath and all of the pictures taken have trapped air bubbles inside the encapsulated cavity and between BCB structures. The well bonded area was for 78% of the samples of group A lower than 70% of the BCB pattern, whereas all of the samples of the groups B1 and B2 had an almost 100% successfully bonded area.

Tensile strength measurements were carried out on 11 samples of group A, on 5 samples of group B1 and on 11 samples of group B2. The average bond strength of the samples of group B1 (BCB contact printed without adhesion promoter) was with 11.34 MPa almost 3 times higher than the average bond strength of the samples of group A ("conventional" patterned soft-cured BCB bonding technique) with 3.97 MPa. The average bond strength of the samples of group B2 (BCB contact printed with adhesion promoter) was unexpectedly slightly lower than the average bond strength of the samples of group B1, but still significantly higher than the average bond strength of those of group A. A summary of the measurements is given in Table I, and the measurement results of all tested samples are shown in Fig. 8. Table II gives an overview of the bond strength of different bonding methods to be compared with the technique proposed in the present paper.

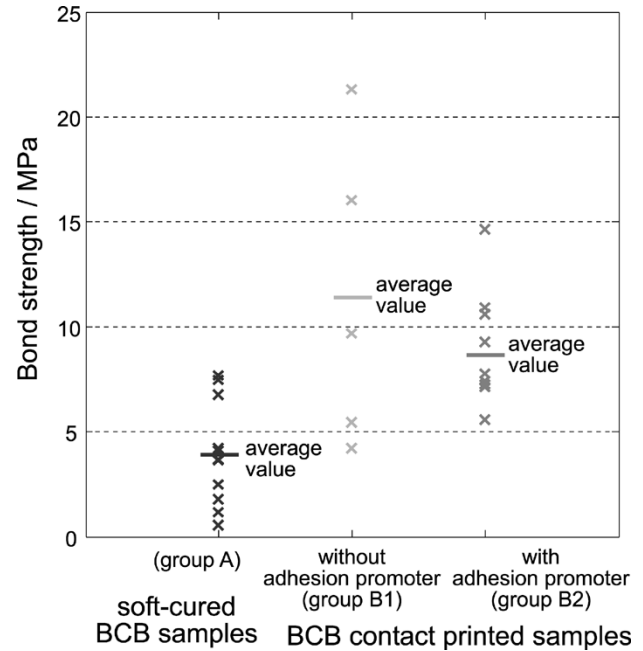


Fig. 8. Tensile strength measurement results of soft-cured BCB bonded samples and BCB contact-printed samples with and without adhesion promoter, corresponding to Table I.

TABLE II  
BOND STRENGTH OF DIFFERENT FULL-WAFER BONDING TECHNIQUES

bonding technique	bond strength with reference
anodic bond. glass-silicon	30–40 MPa [19], >10 MPa [24]
anodic bond. silicon-glass-silicon	>30 MPa [25], 9.2–10.0 MPa [26]
anodic bond. glass-aluminum	>12 MPa [25]
fusion bond. silicon-silicon	23.5 MPa [27]
direct bond. glass-glass	10 MPa [28]
eutectic bond. silicon-gold	18 MPa [29]
patterned adh. bond. SU-8 to SU-8	16 MPa [30], 20.6 MPa [31]
patterned adh. bond. BCB	9–11 MPa [the present paper]

After the tensile strength tests, some samples of group A and all 11 samples of group B2 were further inspected to investigate the failure mode. The samples of group A broke at the interface of the BCB-pattern to the glass wafer which is the actual bonding interface. Thus, the bond strength of the already soft-cured BCB is lower than the adhesion force between spun-on BCB and the silicon substrate. The failure mode of all of the samples of group B2 is of adhesive nature. Seven samples broke at the interface between the BCB-pattern and the silicon wafer [see Fig. 9(b)], and the remaining four samples broke partly at the BCB to the glass wafer interface and partly at the BCB-pattern to the silicon wafer interface [see Fig. 9(c)]. Thus, no cohesive fracture was observed between the two BCB phases and the tensile strength of the samples of group B was merely limited by the adhesion forces of the BCB to the substrates.

It is interesting to observe that most of the adhesive failures of the samples of group B2 happened at the surface of the silicon wafer. That means that the adhesion of BCB to the polished silicon surface is despite the use of the adhesion promoter less strong than the adhesion of BCB to the glass surface. Also, the tensile strength tests of the samples of the groups B1 and B2

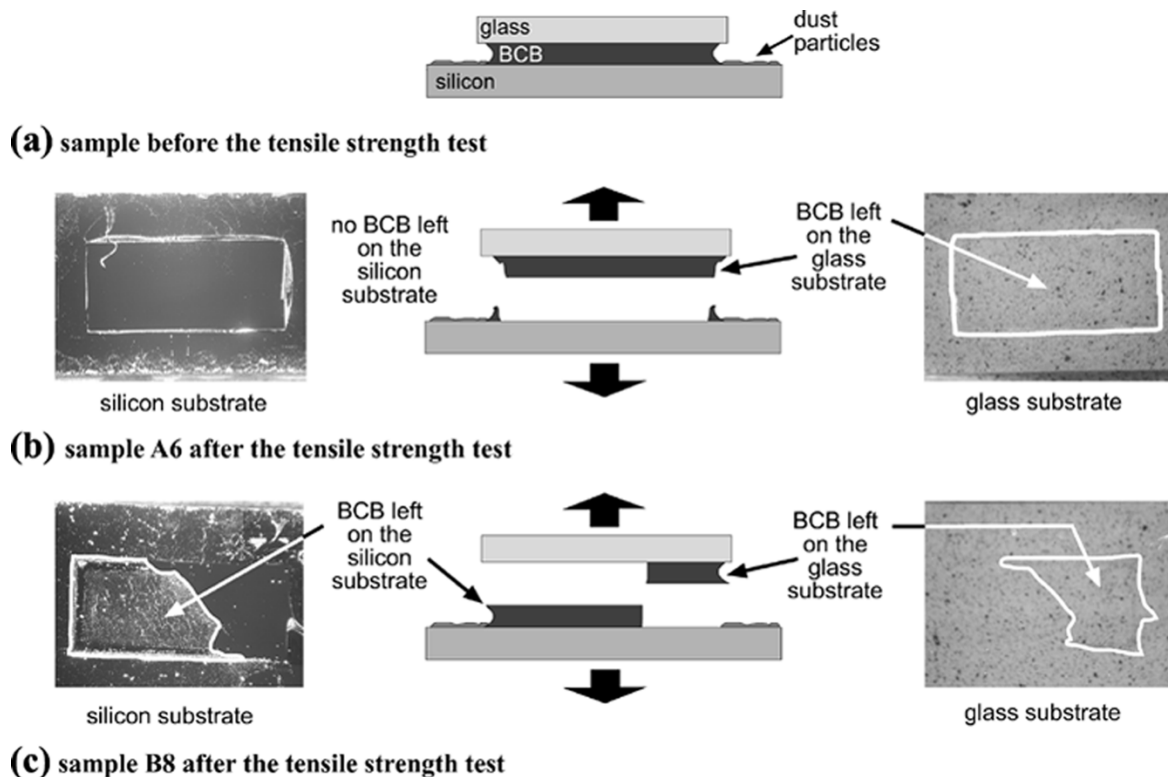


Fig. 9. Failure mode analysis of two samples of group B2 after the tensile strength tests.

show that the use of the adhesion promoter seems not to improve the adhesion of the spun-on dry-etch BCB to the silicon wafer.

In Table II, the bond strengths of various wafer bonding methods are compared with the bond strength of the BCB contact printing method.

#### IV. CONCLUSION

This paper described a contact printing method with viscous BCB as "ink" and using a soft-cured BCB pattern as stamp to improve the bond strength of full-wafer adhesive bonding with patterned BCB as intermediate bonding layer. The technology was successfully demonstrated for glass-lid encapsulations created by full-wafer bonding. The bond strength of samples fabricated with the new method was measured by tensile strength tests and compared with samples fabricated with the "conventional" patterned BCB bonding technique. The BCB contact printing method leads to an increased bond strength by a factor of at least 2, which even exceeds the adhesive strength of spun-on BCB to the substrate wafers.

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**Joachim Oberhammer** was born in Italy in 1976. He received the M.Sc. degree in electrical engineering from the University of Technology Graz, Austria, in 2000.

He was working with automotive electronics and RF identification systems both at the University of Technology Graz and Vienna University of Technology, Austria, before he joined the Microsystem Technology group at the Royal Institute of Technology, Stockholm, Sweden, as graduate student in March 2001. Here, his research focus lies in RF

MEMS and wafer-level packaging of MEMS components.



**Göran Stemme** (M'98) received the M.Sc. degree in electrical engineering in 1981 and the Ph. D. degree in solid-state electronics in 1987, both from the Chalmers University of Technology, Gothenburg, Sweden.

In 1981, he joined the Department of Solid State Electronics, Chalmers University of Technology, Gothenburg, Sweden, where in 1990, he became an Associate Professor (Docent) heading the silicon sensor research group. In 1991, he was appointed a Professor at The Royal Institute of Technology, Stockholm, Sweden, where he heads the Microsystem Technology group at the Department of Signals, Sensors and Systems. His research is devoted to microsystemtechnology based on micromachining of silicon. He has published more than 100 research journal and conference papers and has been awarded eight patents.

Dr. Stemme was a member of the International Steering Committee of the Conference series IEEE Microelectromechanical Systems (MEMS) between 1995 and 2001 and he was General Co-Chair of that conference in 1998. He is a member of the Editorial Board of the IEEE/ASME JOURNAL OF MICROELECTROMECHANICAL SYSTEMS and of the Royal Society of Chemistry journal *Lab On A Chip*. In 2001, he won together with two colleagues, the final of the Swedish Innovation Cup.