# Benefits of Live View of Bond Formation and Alignment for Adhesive Bonding Characterisation

A. Draisey[a], T. Rogers[a], A. Malik[a]

[a] Applied Microengineering Limited (AML), Unit 8 Library Avenue,
Harwell Campus, Didcot, Oxfordshire, OX11 0SG, United Kingdom

Adhesive bonding can be quite problematic in many aspects such as application of the intermediate material and its adhesion to the substrate, establishing precise photolithography or pre-curing parameters, controlling the flow/bond line broadening and maintaining alignment thorough the bonding process.
We are sharing our work on characterisation of PermiNex 1005 adhesive that can offer a simple solution to those problems for some applications like capping of BAW and SAW devices or Microfluidic devices (1). Using AML Aligner Wafer Bonder that allows in-situ alignment and live view of bond formation we have established a void free and <1μm accuracy bonding process for PermiNex 1005.
We are also presenting data from attempted BCB bonding, as an example of a more challenging material. We are showing how much knowledge the real time information gives and how much easier and more effective it can be to qualify any adhesive bonding process, when using our system.

## Introduction

The importance of high accuracy adhesive bonding has grown with mobile phone and virtual reality headset applications and is still widely used in Microfluidics, MEMS/MOEMS, Wafer Level Packaging and 3D integration. The well-known advantages of this bonding technique are: relatively low temperature process, no need for voltage or current, possibility of joining any types of material, possible low cost and even, to some extent, more tolerance for particles which presence doesn't necessarily mean a failure as it would in the unforgiving direct bonding. There is a large variety of adhesives that can be used in wafer bonding, including thermal cure and UV cure epoxies, photoresists (e.g. SU-8), BCB and many more.
For some materials it may be straightforward to establish a reliable bonding process as we did for PermiNex 1005, where based on the manufacturer's data and guidelines (1) we achieved high accuracy and strong void-free bonding in as little as two iterations. However other materials can be more problematic due to excessive flow that can affect the bond line broadening or cause challenges in keeping the wafers in good alignment throughout the process. Outgassing and void control is another common issue and can contribute to process failure.
For those reasons, for efficient process development and qualification it is incredibly useful to be able to observe behaviour of the adhesive live, in-situ during all stages of the

bonding process i.e. during alignment, contact, while force is being applied and while the adhesive is heated.
It is very useful to have data on material properties, curing temperatures, times and pressures, viscosity changes with temperature and photolithography guidelines but it will most certainly be necessary to adjust these parameters further for particular tooling, thickness of the material and other factors.
We therefore show the benefits of our tool for characterization of any new adhesive and share our work on "easy to use" PermiNex1005, with recommendations for the users whose applications can accept this material, but also talk about challenges of BCB bonding and conclusions we have drawn from observing the process live.
All tests have been performed on AML Aligner Wafer Bonders (AWB) described below.

## Bonding System Configuration

AML AWB systems are capable of bonding wafer sizes 3"- 6" (AWB-04) or 6" - 8" (AWB-08) and also chips to wafers and chips to chips, with maximum wafer stack thickness of 30 mm. The entire alignment and bonding process is performed in-situ, without being disturbed at any time and can be observed live. Also, the process can be run step by step manually or automatically through a recipe that can include automatic alignment and post-bond alignment check.

### Bonder Overview

AML Aligner Wafer Bonder schematic is shown in Figure 1 below.

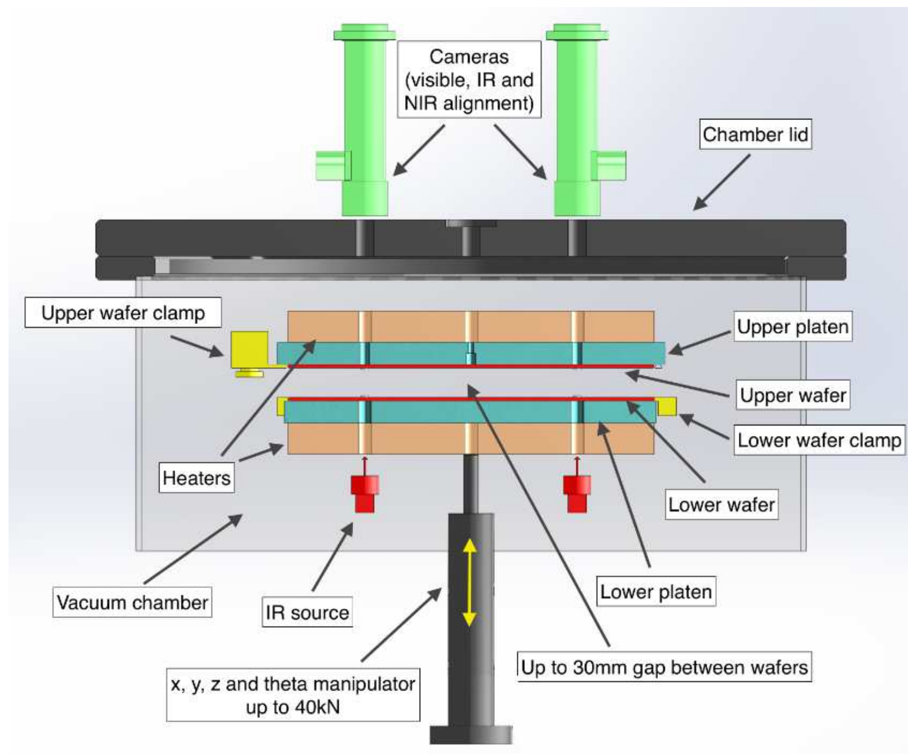


Figure 1. Schematic of AML Aligner Wafer Bonder.

The lower wafer is loaded onto the lower platen and held in place by a wafer retainer or clamp that can firmly keep the wafer in place during the process. The platen can have two 6 mm diameter openings for IR alignment if required and in such case the IR source is located underneath it. The platen can move in x, y and Θ for alignment and up and down in z for bringing the wafers into contact and applying force.

The upper wafer is loaded onto the upper platen (that is mounted onto the bonder lid) and clamped with a knife edge system. Important benefits of this clamping system are the possibility to keep the wafers in separation until the wafer contact step and the bond surfaces never being in contact with any tooling. This is especially important in adhesive bonding where any additional tooling may disturb the intermediate layer and/or become contaminated. Also, there are no flags that, when being released, may cause the wafers to shift relative to each other.

The upper platen has two 5 mm diameter openings that match the view ports in the lid and align with camera lenses that are mounted on the lid, directly above. The openings are the windows for observing the alignment, adhesive flow and bond formation. If the top wafer is transparent, visible illumination is used and if opaque, IR alignment is used (with possibility of using Short Wave IR cameras for highly doped Si wafers or alignment at high temperatures).

Both platens have independent heaters with heating rates 1°C/min - 90°C/min and controlled cooling option (this feature is useful in controlling wafer expansion). For processes that prefer large temperature differential between the wafers (e.g. for getter activation), it is achievable by keeping the wafers at large separation (max 30 mm) and platens being heated to different temperatures. Up to 350°C temperature differential is possible for 4” tooling at 15 mm wafer separation.

Bonding pressure/force can be controlled very accurately with ±3N resolution of the load cell and maintained automatically, compensating for tooling expansion and chamber pressure changes, e.g. it may be important to keep the force stable while cooling the wafers.

The process can be run in vacuum down to $10^{-8}$ mbar or in a gas environment controlled up to 2 bar absolute.

For UV adhesives the system is adapted by replacing the lower metal platen with transparent quartz platen. The UV LED array is located directly underneath the platen. This system is described in more detail in another AML publication (2).

In-situ Alignment

Upper and lower platens are levelled using a high precision LED jig to an angle < 0.006 degree (depending on tooling size) to ensure very good parallelism of the platens. This is very important especially for highly flowing adhesives where the alignment may be disturbed when the adhesive’s viscosity reduces and acts like a lubricant. Should the system be not levelled, the wafers may shift at contact and will slide against each other under force. Alignment is usually performed at 100 µm separation where depth of focus of the cameras allows clear image of both upper and lower marks. This assumes that the marks are located on the bonding faces but in case where back side alignment is needed, an image capture option can be used. Unfortunately even very accurately levelled system can’t guarantee the bond faces being perfectly parallel to each other. This is because of potential non-uniformity of the adhesive layer and wafer warp/bow, especially when using highly processed wafers like in 3D integration. To minimise this problem, AML system is equipped with a central pin that introduces

deliberate bow from the centre of the upper wafer outwards. This helps overcome the existing wafer bow, giving more control over the initial wafer contact and also provides a “grip” point to prevent wafers shifting. The spring force of the pin is very low (~40N) so can’t damage the wafers in any way - when the wafers come into contact, the hydraulic force moving the lower platen overcomes the pin force in a controlled way and hence removes the bow from the upper wafer, clamping the wafers flat in precise alignment. The schematics for wafer alignment in AML bonder is shown on Figure 2 below.

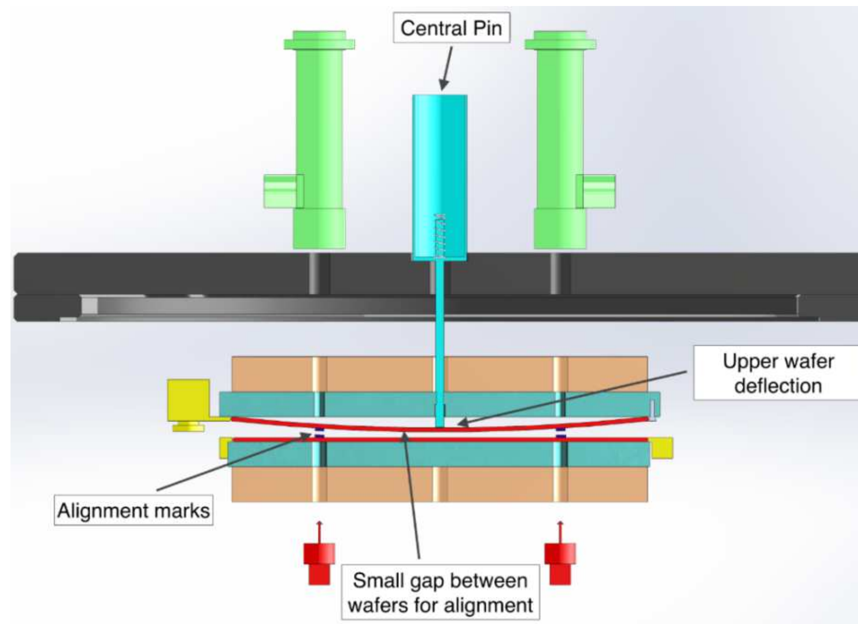


Figure 2. Schematic of wafer alignment in AWB.

## PermiNex 1005 Bonding Characterisation

PermiNex 1000 series is an epoxy based, negative photo – patternable, thermal cure adhesive, manufactured and recommended to us by MicroChem. This material features (1):

a) Low temperature process < 200°C

b) Superb adhesion to Glass and Silicon

c) Film thicknesses of 1 to > 25 µm available

d) Only one wafer a pair needs to be coated

e) High quality, void free bonding

Application and patterning

In our work we used PermiNex 1005 that was spun directly onto the wafers, giving a 5 - 6 µm thick layer. Because of its very good adhesion to glass and Si, we didn’t use any adhesion promoters. The wafers were then exposed on MA6 Karl Suss Mask Aligner with doses of 500 - 800 mJ/cm$^2$. We’ve found that the pattern definition was very good for a wide range of exposure times and the process didn’t require much adjustment.

Bonding

Bonding was performed on our Aligner Wafer Bonder using 100 mm dia glass and Si wafers. Tests included non-aligned and aligned bonds with one substrate coated with PermiNex (PermiNex to wafer bond) and both substrates coated (PermiNex to PermiNex bond). Process steps were as follows:

a) Load wafers and pump down to <1e$^{-4}$ mbar
b) Align wafers
c) Start heating with ramp rate 10°C/min - 40°C/min
d) Once at ≤ 70C contact the wafers and apply bonding pressure of 2.5 – 3 MPa
e) Heat to 150°C
f) Dwell for 1 – 5 min.

Minimum bond cycle is 15 minutes for non-aligned bond. A typical bond cycle is shown on graph below (Fig. 3). Additionally, for maximum bond strength it is recommended to perform a hard bake at 180°C for 1 hour (1) but this can be done in an external oven for a batch of wafers so doesn't add to the bonding cycle time.

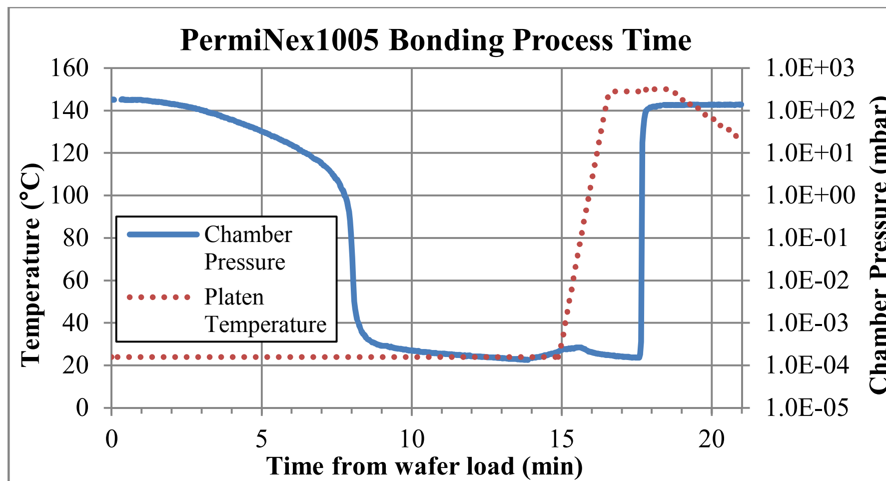


Figure 3. Parameters for a typical bonding process with PermiNex 1005.

Alignment during bonding. The wafers were aligned inside the AML bonder that allows live view and last minute correction of the alignment before bringing wafers into contact, as described on Figure 2. Figure 4 shows alignment marks just before contact (a) and at full bonding force and temperature (b) - large crosses are on the lower wafer and smaller crosses on the upper wafer. No contact shift or adhesive sliding was observed during the process. In this case only one of the wafers was patterned in PermiNex and the marks were fabricated in metal.

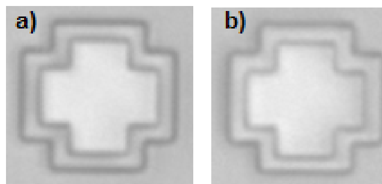


Figure 4. Proximity alignment before contact (a) and alignment at full bonding force and curing temperature (b).

Bond formation. On our very first, non-aligned bonding attempt we observed voids forming in some areas of the PermiNex features. These samples were put on top of each other before pumping (a piece of a patterned wafer on top of another wafer, without leaving a gap outgassing). To address this problem we have performed a post develop bake (after supplier's recommendation) and left the wafers in separation for pumping and heating up to 70°C. The wafers were then brought into contact and bonded void free. This experiment indicates that there were some volatile substances in the material that were trapped at the bond interface. After performing post develop bake at 70°C and further outgassing in the bonder in vacuum and with wafers separated by few millimeters, these components were sufficiently removed, allowing void-free bond. Figure 5 shows comparison of bond quality in both cases.

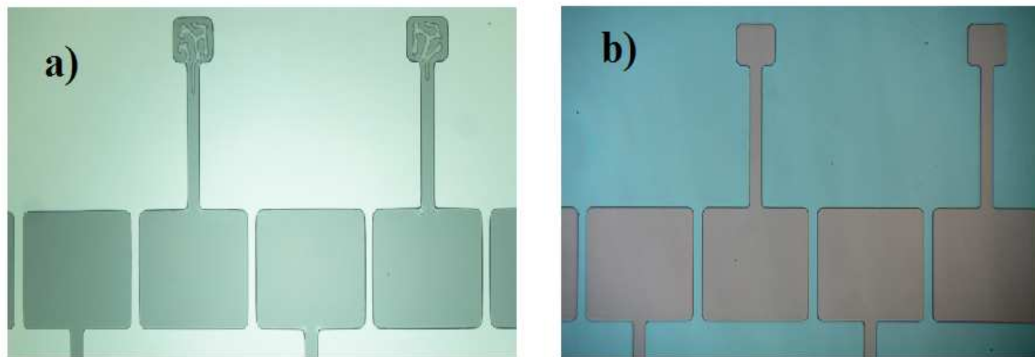


Figure 5. Samples bonded after contact in atmosphere (a) and samples after post develop bake and outgassed in the bonder before contact (b).

Using our live view, we were able to capture the exact moment of bond formation while the temperature was ramping up. Figure 6 shows how rapidly PermiNex starts flowing and seals nearly fully between 90°C and 100°C. Any remaining small voids sealed by temperature of 150°C which is the curing temperature.

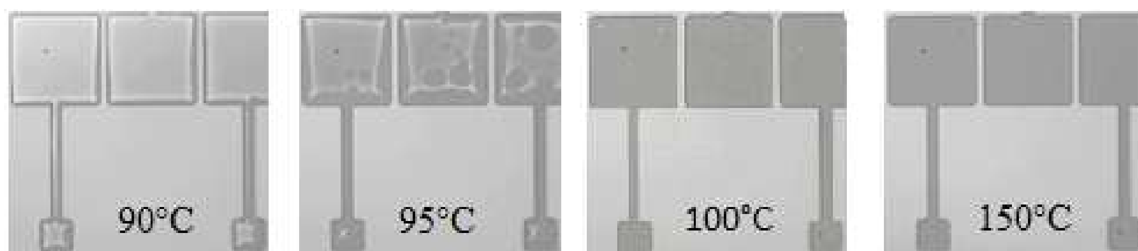


Figure 6. Live view of bond formation in PermiNex.

Post Bond Metrology

Alignment accuracy. Alignment accuracy in x and y directions was measured using optical microscopy. An example of ≤ 1 µm alignment accuracy is shown on Figure 7 a), b) and c), on a PermiNex coated wafer to uncoated wafer bond. Figure 7 d) shows 1 µm alignment on PermiNex to PermiNex bond.

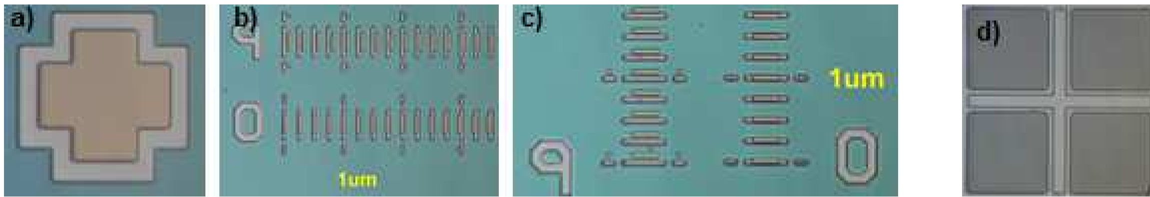


Figure 7. Microscope inspection of PermiNex to wafer bond: alignment marks (a), x vernier (b) and y vernier (c); microscope inspection of alignment mark on PermiNex to PermiNex bond (d).

Bond quality. Optical microscope and Scanning Acoustic Microscope inspection of bond interface showed good quality, void-free bonding (Fig 8).

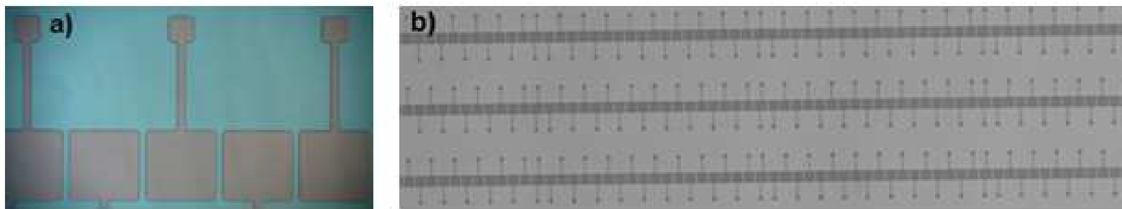


Figure 8. Bond interface imaged under a microscope (a) and using SAM (b).

Bond Strength. For maximum bond strength all bonded pairs were hard baked at 180°C for 60 min. Bond strength was measured with AML automated Maszara tool (IRIS) and the results showed the bond strength to be ≥ the fracture strength of Pyrex glass – i.e. the wafers fractured before the PermiNex seal was broken.

## BCB Bonding Challenges

BCB bonding was performed with two types of the material: photosensitive 4022 – 4000 and dry-etch BCB 3022-57. The wafers were pretreated in $O_2$ plasma for cleaning and promoting the adhesion. BCB was spun onto 3" InP, 3" glass and 4" glass wafers with thicknesses 3 µm – 4 µm and various wafer pair configurations were bonded, including bonding with both wafers of a pair coated and one wafer coated. In all cases, the full wafer area was bonded. Bonding parameters were: 0.4 MPa pressure and curing at 280°C for 1 hour.

Outgassing

Live view of outgassing problem is shown on Figure 9 below. In this experiment only lower wafer was coated with dry-etch 4 µm thick BCB and the wafers were separated by 7 mm for pumping. While pumping the chamber, with the BCB coated wafer being at 70°C, we observed bubbles forming on the upper wafer. This was clearly a condensation of solvents that were not fully removed during the pre-curing of the BCB. Outgassing can be a potential problem for any adhesive and if the wafers are contacted with gases being trapped at the interface, they are very likely to form voids while the adhesive is cured. It is therefore beneficial to keep the wafers in large separation for pumping and heating (if possible) to allow the remaining adhesive components to be removed from the material.

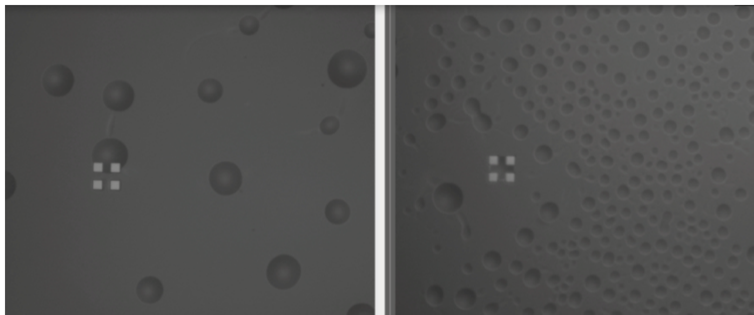

Figure 9. Outgassing of BCB components onto the upper wafer at 70°C and < $10^{-4}$ mbar chamber pressure.

Alignment

Alignment accuracy depended on the type of BCB used and the results are described for dry-etch and photosensitive BCB.

Dry-etch BCB. BCB was spun onto a glass wafer and bonded to an uncoated glass wafer. The wafers were contacted at room temperature and no alignment shift was observed at contact or when full bonding force was applied. However while the wafers were being heated and the viscosity of BCB begun to drop, alignment shift started appearing. This occurred at temperatures between 100°C and 220°C with a ramp rate 10°C/min. Figure 10 shows a total shift of 25 µm between room temperature and the end of cross-linking process. This phenomenon is known and believed to be unavoidable if the BCB is not pre-cured. It is caused by shear forces acting parallel to the bond line and causing the wafers to shift against each other when the adhesive is in the liquid state (3).

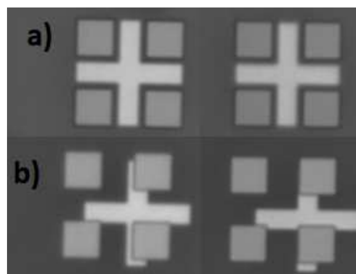


Figure 10. Left and Right alignment marks at 0.4 MPa bonding pressure at room temperature (a) and after dry-etch BCB bonding (b).

A solution to this problem has been investigated and described in publication (7) where the author has proven that if the dry-etch BCB undergoes a pre-curing at 190°C for 30 minutes, the alignment shift can be eliminated. This is because the BCB is then partially cured to a level of about 43% and doesn't reflow as significantly during the bonding process (7).

Photosensitive BCB. BCB layer of 3 µm was spun onto a glass or InP wafer and bonded in the same conditions as the dry-etch BCB. There was no shift observed during any of the bonding steps. We understand that this type of BCB had higher level of crosslinking than the dry-etch BCB. It has been reported that the optimum cross-linking level for a successful bond is 50-60% and the photosensitive BCB is typically crosslinked to about 55% after photolithography, thus doesn't require further pre-curing (4). Figure 11 shows the alignment accuracy on wafers under bonding force at room temperature and after BCB curing at 280°C.

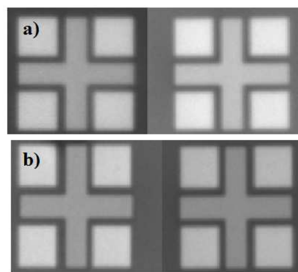


Figure 11. Left and Right alignment marks at 0.4 MPa bonding pressure at RT (a) and after 1 hour at 280°C bonding (b).

Bond formation

Live view of photosensitive BCB bonding is shown in Figure 12 below.

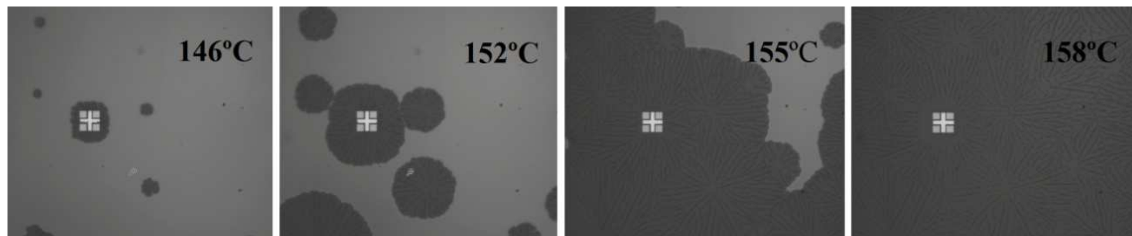


Figure 12. Live view of BCB flow and bond formation.

It was possible to observe the exact moment of BCB flow and bond formation that started at 145°C and very quickly spread within the next 15°C. This stage of the process is incredibly informative, similarly to the alignment described before. We can see how viscous the material becomes, if and how voids form and what the impact of bonding pressure is. It is possible to increase or decrease the bonding force and the heating rates as we watch the behaviour of the adhesive.

In this study we didn't investigate the appearance of voids that can be visible on those images. This is because we used customer supplied samples and had no control over the sample preparation. Void-free BCB bonding has been widely described and proven in the work of Frank Niklaus et al. (3), (4), (5) and (6).

## Other Benefits of Live View

CTE mismatch

For wafers with different Coefficient of Thermal Expansion it can be very useful to observe the mismatch at various temperatures. Figure 13 below shows alignment at 400μm separation between InP wafer and a glass wafer. CTE of InP is 4.60 ppm/°C and CTE of borosilicate glass is 3.3 ppm/°C so as we would expect we can see that the InP wafer (squares alignment mark) expands more than the glass wafer (crosses alignment mark). It was interesting to see that at temperature 285°C the marks met again and then after additional 10 minute dwell at 285°C the glass appeared to have expanded more (however thermal conductivity will also contribute here).
This type of information can greatly help to find a good moment for alignment, while the wafers are being heated, if the CTE mismatch hasn't been accounted for in the mask design.

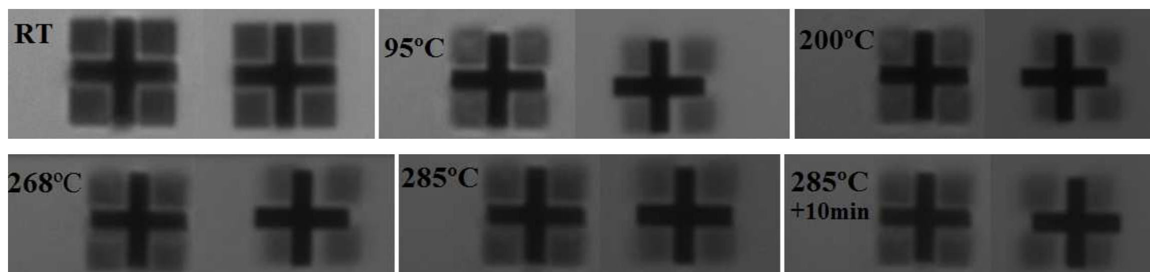


Figure 13. CTE mismatch between InP wafer (square boxes) and glass wafer (cross) at different temperatures.

## Summary

In this study we have presented our work with two different types of adhesives – PermiNex 1005 and BCB. In both cases we have shown how beneficial live view on the AML bonder is. Most of all it allows in-situ alignment that can be observed throughout the whole process. This allows for last minute correction and even reclaiming the wafers if problems arise.
Secondly, by observing the adhesive flow we can gather data on viscosity changes with temperature that can not only impact the alignment but also will contribute to bond line spread if patterned adhesive is used - with the direct and dynamic feedback the user has the opportunity to control bond line broadening by adjusting bonding force. Temperature and heating rates that will define the curing point can also be controlled and fine-tuned at any time.
Observing the process live helps to understand which part of the process needs further development - if it is the adhesive layer preparation or any of the bonding steps. If voids occur, it is likely that the adhesive needs baking out before bonding or wrong bonding force is used; if alignment shift occurs, it may mean that a higher level of adhesive cross - linking is required.
In our experience, the information obtained from the live view can speed up process development significantly from months to only days.

One may question that the openings in the platens are essentially areas with no direct temperature and force applied and so may not be representative of the full wafer area. We however know from our wide experience that those areas imitate the conditions across the whole wafer quite closely. This is because there is still heat and force being transferred "sideways" through the wafers and the temperature and pressure difference in the view port areas are minimal. Within the 7 mm diameter view ports, the force decreases slightly so that in the centre of the view port it is 20% lower than across the whole wafer area (measured with a pair of 525 μm thick wafers).


## Acknowledgments

We would like to thank Karl Otto Velthaus and his team from Fraunhofer HHI, Berlin for providing the BCB samples and for being very enthusiastic about the live view feature of our tool.

We would also like to thank Aurélie Mayeux and her technical team from MichroChem for providing data on PermiNex and fantastic support in our development work.


## References


1. *PermiNex 1000 Data Sheet,* MicroChem Corp 200 Flanders Road, Westborough, MA 01581 USA.
2. N. Aitken, T. Rogers, *Alignment Accuracy Adhesive Wafer Bonding – Thermal and UV cure*, Wafer Bond, Grenoble (2009)
3. F. Niklaus, P. Enoksson, E. Kälvesten and G. Stemme, *A method to maintain wafer alignment precision during adhesive wafer bonding*, Submitted for journal publication
4. J. Oberhammer, F. Niklaus, G. Stemme, *Selective Wafer-Level Adhesive Bonding with Benzocyclobutene for Fabrication of Cavities*, Submited for journal publication
5. F. Niklaus, H. Andersson, P. Enoksson, G. Stemme, *Low temperature full wafer adhesive bonding of structured wafers,* Sensor and Actuators A, Vol 92/1-3, p. 235-241 (2001)
6. F. Niklaus, P. Enoksson, E. Kalvesten and G. Stemme, *Low-Temperature Full Wafer Adhesive Bonding*, Journal of Micromechanics and Microengineering, Vol.11, No.2, p. 100-107 (2001)
7. F. Niklaus, R. J. Kummar, J. J. McMahon, J.Yu, J.-Q. Lu, T. S. Cale and R. J. Gutmann, *Adhesive Wafer Bonding Using Partially Cured Benzocyclobutene for Three-Dimensional Integration,* J. Electrochem. Soc., **153** (4) G291-G295 (2006).