Wafer-scale adhesive bonding with hard Benzocyclobutene anchors for wafer assembly and heterogeneous integration

Salim Abdi
Eindhoven Hendrik Casimir Institute (EHCI)
Eindhoven University of Technology
Eindhoven, the Netherlands
s.a.abdi@tue.nl

Tjibbe de Vries
Nanolab@tu/e
Eindhoven University of Technology
Eindhoven, the Netherlands
t.d.vries@tue.nl

Marc Spiegelberg
Eindhoven Hendrik Casimir Institute (EHCI)
Eindhoven University of Technology
Eindhoven, the Netherlands
m.spiegelberg@tue.nl

Kevin Williams
Eindhoven Hendrik Casimir Institute (EHCI)
Eindhoven University of Technology
Eindhoven, the Netherlands
k.a.williams@tue.nl

Yuqing Jiao
Eindhoven Hendrik Casimir Institute (EHCI)
Eindhoven University of Technology
Eindhoven, the Netherlands
y.jiao@tue.nl

2023 34th Annual SEMI Advanced Semiconductor Manufacturing Conference (ASMC) | 978-1-6654-5639-5/23/$31.00 ©2023 IEEE | DOI: 10.1109/ASMC57536.2023.10121131

***Abstract*—*Herein we present a novel method to improve the post-bonding alignment accuracy of substrates assembled via adhesive bonding with Benzocyclobutene (BCB). The method relies on hard BCB anchors to block misalignment. As a result, the alignment accuracy has been improved by an order of magnitude for a wide range of bonding BCB thicknesses (2-16 µm) without influencing the continuity of this adhesive layer.*

***Keywords*—*component, formatting, style, styling, insert* (*Heterogeneous integration, 3D integration, Adhesive bonding, BCB stress*)**

I. Introduction

Many adhesive bonding applications with Benzocyclobutene (BCB) polymer impose strict tolerances on the alignment accuracy, *e.g.*, monolithic co-integration of electronics and photonics, fabrication of photonic integrated circuits, and microelectromechanical devices [1]. For these applications, adhesive bonding using soft-baked polymers is mostly employed. During bonding, the polymer heats up and reaches a low viscous stage to reflow and accommodates for the substrates' topographies and particle defects, thereby achieving a void-free layer with high bond strength. However, the substrates shift with respect to each other after bonding. This is caused by the absence of solid mechanical support at the interface between substrates, the presence of inevitable residual shear forces during bonding from state-of-the-art bonding tools, and bond layer non-uniformities [2]. The resulting misalignment is on the order of tens of microns and it highly depends on the BCB thickness, where higher thicknesses lead to more reflow and therefore higher misalignment [2], [3].

The method described in this paper improves the post-bonding alignment accuracy by an order of magnitude by introducing pre-baked hard anchors of the same polymer to the bonding process (Fig.1). We comprehensively tested this method on patterned glass substrates and used BCB as the bonding material. The method is tested and applicable to other solid substrates as well such as 3" Indium-Phosphide (InP) substrates. The investigated range of anchors and bonding BCB thicknesses is 2-16 µm to encompass most applications. The anchor density is fixed at 20% relative to the wafer surface area and their distribution is uniform on the wafer scale. We studied the effect of including anchors on the alignment accuracy, and how the anchor:BCB height ratios play a role in the latter. The bond layer uniformity and mechanical properties are also characterized.

II. Experimental Details

A. Fabrication

A schematic illustration of the fabrication stages is shown in Fig. 1.a and 1.b. We comprehensively studied the effect of anchors on misalignment using identical 3" SiO_2 substrates. Before fabrication, we measured the bow values of the used substrates and paired those having close bow values for bonding to avoid introducing the effect of the initial bows on misalignment.

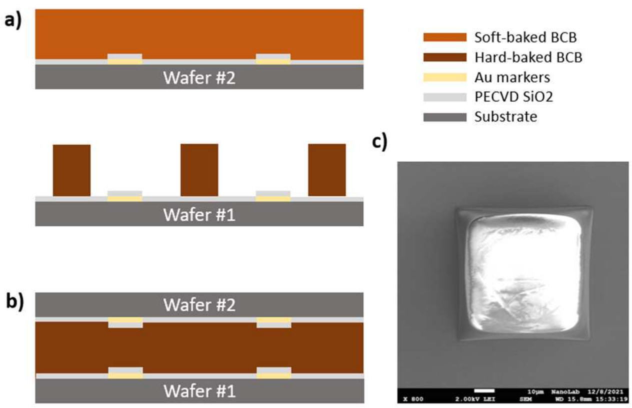

Fig. 1. Schematic illustration of the structures in wafer#1 and 2# a): before bonding, b): after bonding. c) Top-view SEM image of an 8µm BCB anchor before bonding.

The process flow starts by fabricating on both substrates Titanium-Gold stack markers with 10-100 nm thickness, respectively, then depositing 500 nm SiO_2 and AP3000 adhesion promotor to improve the adhesion to BCB. To fabricate anchors on wafer #1, we first spin and hard bake BCB at 280°C for 1h, then define anchors with photolithography using AZ9260 followed by dry etching in

O_2:CHF_3 20:4 plasma. The anchors' are distinguishable by their 37° sloped sidewall transferred from the resist during etching.

A top-view scanning electron microscopy (SEM) image of a BCB anchor before bonding is shown in Fig 1.c. For wafer 2#, BCB is deposited and soft-baked as normal. The wafers are then aligned and bonded at 280°C for 1h in <10^{-5} Torr vacuum and with an applied force of 700N. These bonding/hard-baking parameters correspond to a thermal budget equivalent of full cross-linking, required for high strength and durability [2]. The post-bonding BCB interface becomes uniform after this step, as illustrated in Fig .1.b since both anchors and the adhesive BCB are fully crosslinked. Further discussions on this point are found in Sec.III.

B. *Characterization*

The misalignment and quality of the bond layer are characterized using optical microscopy. SEM is employed to characterize the anchor/BCB interface. Profilometry is used to extract the residual stress of BCB at different baking conditions to measure the difference in stress between anchors and the bond layer.

III. Results and Discussions

A. *Improved post-bonding alignment accuracy*

The goal of adding these anchors is to suppress the misalignment by adding solid mechanical support to the two wafers during the reflow process of BCB. This happens briefly when the BCB becomes liquid during bonding, where the applied bonding force allows for the anchors to penetrate through the soft-baked BCB and reach the surface of the other substrate. This suppression acts against the lateral residual shear forces present during the bonding process regardless of its direction in the (x,y) plane of the substrates to be bonded. Therefore, we use the total misalignment as a metric for our study instead of separating the misalignment in the separate (x,y) directions. Plots of the total misalignment of the bonded stacks *vs* BCB thickness including/not including anchors are shown in Fig.2.

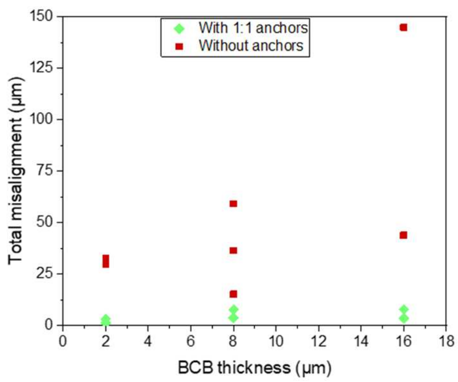

Fig. 2. Total misalignment *vs* BCB thickness including/not including BCB anchors.

The total misalignment values increase with the BCB thickness from 30, 59.2, and up to 140 µm for bonding BCB thicknesses of 2, 8, and 16 µm, respectively. The degree of variance in misalignment also becomes larger, making it difficult to predict and pre-compensate for misalignment values in real assembly applications. This is explained by the higher reflow of BCB for higher thicknesses where the presence of the same residual shear forces in the bonding tool causes higher misalignment [3]. However, by introducing hard anchors to the bonding process, both the misalignment and degree of variance in misalignment are reduced well below 10µm for all BCB thicknesses (green in Fig.2). This low variance in misalignment with added anchors signifies that a pre-bonding compensation of the alignment can be done to further improve the post-bonding alignment accuracy.

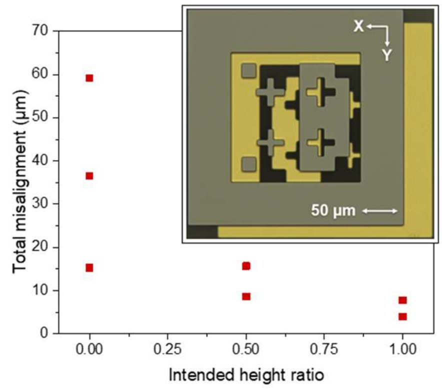

Fig. 3. Total misalignment *vs* anchors height BCB:thickness ratio for BCB thickness of 8µm. Inset: microscope image of misaligned markers after bonding where the dark gray (Titanium) corresponds to the top wafer.

Fig.3 shows the total misalignment *vs* anchors height:BCB thickness ratio for bonding BCB thickness of 8µm. The misalignment increases from 7.7, 15.5, and 59.2 µm with decreasing height ratio from 1:1, 1:2, to no anchors, respectively. This indicates that the height of anchors plays a key role in blocking misalignment. Here, the presence of BCB thickness non-uniformities during the reflow process results in a lower *effective* area where the BCB thickness is the same as the anchors' height. The anchors that reach up to the other substrate to block misalignment are those present in these effective areas only. The latter can be maximized by choosing matching anchors' height and bonding BCB thickness. Introducing taller anchors can lead to insufficient BCB volume to fill areas in between anchors, likely introducing voids in that manner.

B. *Physical properties*

We first inspected the bonded substrates for voids visually and then with optical microscopy. The concern is that adding anchors with the same height as the BCB thickness used for bonding could lead to void formation at the interface, and therefore lowers the yield. Fig.4.a shows a 3" post-bonding substrate with flower-like voids at the BCB interface resulting from the presence of defects. Fig.4.b shows a post-bonding substrate with wafer-scale and micro-scale (inset) void-free BCB bonding layer and having BCB anchors. It can be seen that the addition of BCB anchors to the process poses no risk of void formation regardless of the distance between anchors, where the smallest distance in the mask layout is around 10 µm. The slight difference in color between the BCB anchor and bonding BCB arises from the 5% higher refractive index of BCB inside of anchors relative to the bonding BCB. The latter results from hard-baking these anchors at 280 °C for 1h before bonding and can be optimized by lowering the hard-baking thermal budget.

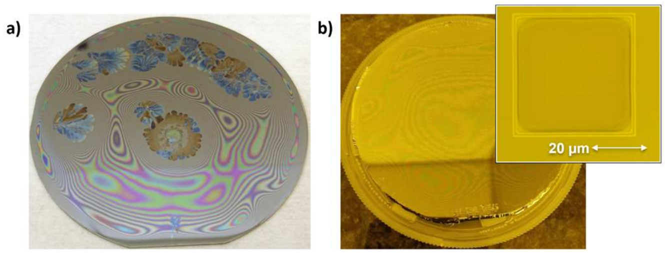

Fig. 4. Image of 3" post-bonding substrate: a): showing flower-like voids in the BCB interface, b): void-free BCB interface with BCB anchors embedded, inset: microscope image close-up of one of the BCB anchors post-bonding

Next, we inspected the interface between anchors and BCB with SEM. The cross-sectional view in Fig.5.a shows no voids at the anchor:BCB interface. This offers higher yield and flexibility in anchor placement compared to SiO_2-based anchors that introduce voids at the anchor:BCB interface [4]. Next, we partially dry-etched 2μm of the top of the bonded stack after substrate removal to inspect the interface from the top, as shown in Fig.5.b. Here, the BCB inside of anchors has a slightly denser pattern than the bond layer, which is likely related to the difference in thermal history between the two. The interface is void-free as well.

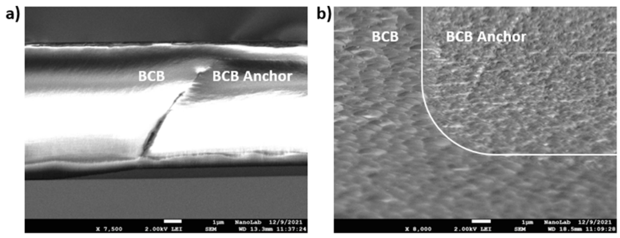

Fig. 5. Schematic illustration of the structures in wafer#1 and 2# a): before bonding, b: after bonding. c) Top-view SEM image of an 8μm BCB anchor before bonding.

C. *Mechanical properties*

Furthermore, for the mechanical properties, we evaluated the residual stress of anchors and BCB used for bonding. This is because a high-stress difference could result in the partial detachment of anchors from the matrix, leading to void formation at the interface. The residual stress of BCB *vs* baking temperatures was previously studied for 2.5 μm BCB **[5]**. However, a comprehensive study on the effect of BCB thickness and cure time is required to fully encompass the process parameters varied in our study. Here, the anchors are cured for 1h at 280 °C, and the bonding is carried out in the same conditions afterward. Hence, we fixed the temperature at 280 °C and cured BCB for 1h and 2h to investigate the stress difference. The studied BCB thicknesses are 1, 4, 8, and 16 μm. The thickness uniformity is above 95% after cure, therefore the effect of thickness non-uniformity on stress is negligible. The process flow consists of depositing and baking BCB on 3**"** Si and InP substrates for reproducibility. The wafer bow parallel and perpendicular to the major flat is tracked before BCB deposition and at each step of thermal treatment. The stress is then extracted from bow values using Stoney's formula **[6]**.

The average stress values are shown in Fig.6. The stress difference for BCB treated at 1h and 2h is below 2 MPa for all measurements, confirming that a bonding interface consisting of BCB anchors and BCB bond layer is continuous and almost uniform in terms of stress. The difference is low because the residual stress of BCB is mainly controlled by the difference in thermal coefficient expansion between BCB and the used substrate at a given temperature **[5]**. Moreover, since BCB as a polymer has a thermal expansion coefficient at least an order of magnitude higher than that of most solid-state substrates **[7]**, the residual stress is mainly dominated by the BCB being a polymer, and stress values are similar for different substrates (Fig.6). Therefore, we identify a low risk of stress-induced detachment at the interface as confirmed by SEM imaging (Fig.5), and this likely extends to most of the other solid-state substrates as well, and this likely extends to most of the other solid-state substrates as well.

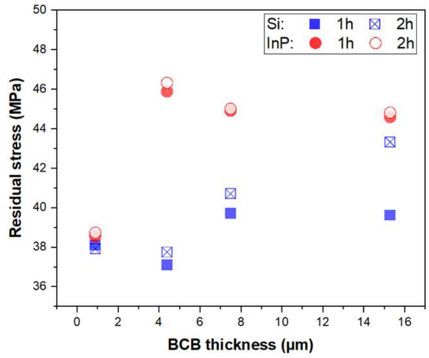

Fig. 6. Residual stress of BCB deposited on InP and Si and treated at 280 °C for 1h and 2h.

IV. CONLCLUSIONS

To conclude, the addition of BCB anchors in the bonding process improves the post-bonding alignment accuracy by an order of magnitude for a high thickness range (2-16μm) of BCB used for bonding. The post-bonding adhesive layer is uniform in terms of mechanical and physical properties and is void-free, signifying the flexibility of the design layout and fabrication of these anchors without increased dead space.

ACKNOWLEDGMENT

This research was performed in the NanoLab@TU/e cleanroom facility. This work was supported by the H2020 ICT TWILIGHT Project (contract No. 781471) under the Photonics PPP.

DECLARATION OF COMPETING INTEREST

Salim has patent "A method for bonding a first and second planar substrate" pending to Dutch provisional patent No. 2032112

REFERENCES

[1] X. Wang and F. Niklaus, "Polymer Bonding," in 3D and Circuit Integration of MEMS, John Wiley & Sons, Ltd, 2021, pp. 331–359. doi: 10.1002/9783527823239.ch15.

[2] F. Niklaus, R. J. Kumar, J. J. McMahon, J. Yu, J.-Q. Lu, T. S. Cale, and R. J. Gutmannet, "Adhesive Wafer Bonding Using Partially Cured Benzocyclobutene for Three-Dimensional Integration," J. Electrochem. Soc., vol. 153, no. 4, p. G291, Feb. 2006, doi: 10.1149/1.2168409.

[3] Z. Song, Z. Tan, L. Liu, and Z. Wang, "Void-free BCB adhesive wafer bonding with high alignment accuracy," Microsyst. Technol., vol. 21, no. 8, pp. 1633–1641, Aug. 2015, doi: 10.1007/s00542-014-2242-4.

[4] S. H. Lee, F. Niklaus, J.Jay McMahon, J.Yu, R.J. Kumar, H. Li1, R.J. Gutmann, T.S. Cale, and J.-Q. Lu, "Fine Keyed Alignment and

Bonding for Wafer-Level 3D ICs," MRS Online Proc. Libr. OPL, vol. 914, ed 2006, doi: 10.1557/PROC-0914-F10-05

[5] I. Yadav, S. Dutta, A. Katiyar, M. Singh, R. Sharma, and K. K. Jain, "Evolution of residual stress in benzocyclobutene films with temperature," Mater. Lett., vol. 158, pp. 343–346, Nov. 2015, doi: 10.1016/j.matlet.2015.06.032.

[6] D. Quirion, M. Manna, S. Hidalgo, and G. Pellegrini, "Manufacturability and Stress Issues in 3D Silicon Detector Technology at IMB-CNM," Micromachines, vol. 11, no. 12, Art. no. 12, Dec. 2020, doi: 10.3390/mi11121126.

[7] V. Kumar and B. s. r. Sastry, "Thermal Expansion Coefficient of Binary Semiconductors," Cryst. Res. Technol., vol. 36, no. 6, pp. 565–569, 2001, doi: 10.1002/1521-4079(200107)36:6<565::AID-CRAT565>3.0.CO;2-F.