Cleaning and Particle Challenges in the Temporary Bonding and Debonding Process

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Abstract
The demands of 5G, Internet of Things and other global technology trends, combined with the increasing cost of scaling down process nodes, have created a shift towards more integrated packaging requirements. The emergence of advanced packaging technologies, such as fan-out wafer-level packaging, 2.5D/3D IC packaging, and heterogenous integration, brings potential for smaller form factors with increased functionality and bandwidth. Backside processing or thinning of the device wafer is often needed for enabling these technologies. This requires the device wafer be adhered to a rigid carrier wafer using a temporary bonding material for mechanical support during handling and processing. Following carrier release, the temporary bonding material must be thoroughly removed and cleaned from the device wafer. Many of these adhesives are exposed to high-power lasers or elevated temperatures, making removal more challenging. Sub-micron particle level clean demands for temporary bonding material removal are also reaching standards typically reserved for front-end-of-line processing. This is especially crucial in 3D processes such as hybrid bonding where feature and pitch sizes are nearing < 1 µm and insufficient cleaning can lead to failures in subsequent bonding processes. Thus, careful consideration of all processing steps is necessary to meet stringent particle demands. This work investigates the removal of coated and baked temporary bonding material on silicon wafers, with an emphasis on processing conditions that obtain best particle results. Several chemistries were assessed at the beaker level by performing coupon-level studies and measuring surface properties. Based on these findings, studies with 300-mm wafers were performed using a customizable single-wafer processing tool.

Key words
Temporary bonding material, wet cleans, wafer level packaging, single wafer processing.

I. Introduction

While transistor and node scaling has continued to progress, the associated costs and complexity has mandated alternative routes for increasing performance. Most prominently, 2.5D/3D integration in advanced packaging has shown significant promise through the integration of different components with varying sizes and materials into a single device [1]. Several types of integrated technologies such as fan-out wafer-level packaging (FOWLP), 2.5D interposer, 3D through-silicon vias (TSVs), and package-on-package (PoP), have all been developed with expected advantages of high integration, low power consumption, miniaturization, and high reliability [1-3]. As many of these current integration process flows require backside processing or thinning of the device wafer, the use of temporary bonding and debonding (TBDB) systems have proven necessary for enabling these current technologies [4-10]. During TBDB, wafers are temporarily adhered to a more rigid carrier wafer using a temporary bonding material (TBM) for mechanical support during handling and processing [8, 11]. Once subsequent processing steps are complete, the two wafers must be separated and the TBM must be removed from the device wafer. (Fig. 1).

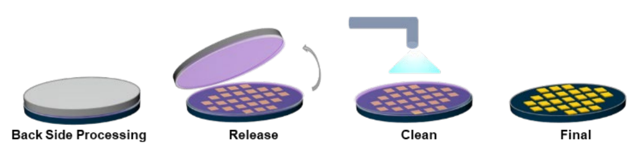

Figure 1: Schematic detailing the debonding process.

For release or debonding of the wafers, several methods exist depending on the physical properties of the TBM. These can include thermal slide, mechanical peel off, laser ablation, and chemical dissolution [8]. Overall, the selection of the appropriate debonding system is highly dependent on the application and process flow, which can vary widely. As a result, the TBDB space is currently occupied with several types of TBMs that require unique approaches for cleaning. Independent of the debonding system, TBM is typically still present on the wafer after the release step, and it is necessary to completely remove the adhesive.

Cleaning is predominantly done through wet processing, where chemical solvents are used to dissolve the adhesive directly [8, 10, 12]. The dissolution process for polymers typically follows the Arrhenius Equation as described in equation 1:

$$K = A * \exp\left(\frac{-E_a}{RT}\right) \quad (1)$$

The dissolution rate (K) is highly dependent on both the activation energy (E_a) and acceptable processing temperatures (T) that are predominantly influenced by solvent selection. In addition to the chemistry, tool-based processing parameters can also help increase the dissolution rate by increasing the collision factor (A). Providing agitation or physical force in the form of ultrasonics or sprays can increase mass transfer and accelerate liftoff, physical breakdown, and enhance solvation [13]. The use of sprays or agitation has been a common practice in the removal of thicker back-end-of-line (BEOL) photoresists [14]. Combining sprays with prolonged exposure to heated solvents has also proven effective for softening thick photoresist and increasing dissolution [10, 14]. As many TBMs approach similar thicknesses, it is therefore expected that comparable processing conditions would be necessary for complete removal.

Furthermore, particle level clean demands for TBM cleanings are reaching standards that were typically reserved for front-end-of-line (FEOL) processing. More aggressive particle specifications are being implemented to prevent downstream defects and complications. For example, in processes such as hybrid bonding, where the feature and pitch sizes are continuously decreasing, defects from insufficient cleaning in previous steps can lead to voids and failures [15, 16]. In particular, polymer residues and particles can create voids in the hybrid bond 30 times larger than the original defect [15]. Since all steps in wet processing (clean, rinse, dry) can introduce particles, careful consideration of each is necessary to meet stringent particle demands.

This study investigates the removal of two different types of TBMs from coupon studies to full wafer processing. Key parameters such as chemical selection, rinsing sequences, and processing methods are examined with the purpose of highlighting particle performance. Chemistries were evaluated by performing beaker-level experiments and measuring surface properties. Based on these findings, studies utilizing 300-mm wafers were performed with a customizable single-wafer processing tool. To maximize dissolution, a two-step approach combining an immersion process and a pressurized fan spray process is assessed for thick (> 20 µm) TBM materials. Meanwhile, a spray-only process is tailored for thinner (< 200 nm) TBMs.

II. Experimental

Studies were performed with two different TBM materials: (i) BrewerBOND® 230 and (ii) BrewerBOND® 701. Both adhesives target 3D wafer-level packaging applications but serve two different functions. (i) BrewerBOND® 230 material is coated at larger thickness and enables thinning and backside processing. The nominal thickness for this study was 20 µm. (ii) BrewerBOND® 701 material is a laser release layer that provides low-stress separation and enables selective debonding when combined with other TBMs. Wafers coated with BrewerBOND® 701 material had a nominal thickness of 200 nm and did not have any additional processing. More specifications regarding these TBMs and the processing conditions are reported in Table 1.

Table 1: Properties and processing of TBMs

TBM	BrewerBOND® 230	BrewerBOND® 701
TBDB Type	Thermal Slide	Laser Release
Thickness Range	20 – 150 µm	150 – 250 nm
Thermal Stability Range	≤ 250ºC	≤ 400°C
Spin Conditions	1150 rpm for 60s	1750 rpm for 30s
Bake Conditions	120˚C for 1 min followed by 220˚C for 2 min	210˚C for 3 min

Coated and baked 300-mm wafers were cleaved into coupons with dimension of 4 cm x 2.5 cm to assess potential chemistries for full wafer removal. Samples were immersed in a beaker with 200 mL of solvent. All solvents were heated to 10ºC below their respective flash points. Rinsing of samples was then performed in a separate beaker, followed by an N_2 dry. Surface properties and the effectiveness of the chemistry were assessed with an Osilla Contact Angle Goniometer. Once the desired chemistry was selected, full-wafer tests were performed on a Veeco WaferStorm® M3303 processing system equipped with ImmJET™ technology This unique technology allows for a combined batch immersion and single wafer spray processing in one tool. Wafers are loaded/unloaded from the immersion station in a buffered sequence that guarantees equal process time for each wafer. The immersion station holds approximately 6 gallons of chemistry and a secondary 3-gallon tank supplies chemistry to the single wafer station in the form of a lowpressure dispense (LPD) stream or high-pressure chemical (HPC) spray. The HPC spray can reach pressures of 3000 psi. A separate chamber was utilized for all spin, rinse, and dry (SRD) processes. It should be noted that the single-wafer processing tool was designed for manual processing, so particles related to manual handling and cleanroom exposure are expected.

Particle measurements were performed on a KLA Surfscan® SP2-XP with minimum particle size threshold ranging from 100 nm – 150 nm. Results for particle monitor (PMON) rinsing tests were performed with 100-nm threshold. BrewerBOND® 701 material and BrewerBOND® 230 material tests were run with 120-nm and 150-nm thresholds, respectively. Inspections were performed on 300-mm wafers with a 3-mm edge exclusion.

III. Results and Discussion

A. Chemistry Assessment

As many TBMs are engineered to be resistant to different chemistries, selecting the proper solvent to attack and dissolve the adhesive can be challenging. Additionally, when considering particle performance, selecting a chemistry with a compatible rinsing medium is important as a poor choice can lead to insufficient rinsing of the solvent in the form of precipitation or residues [17]. Therefore, it was necessary to not only select an appropriate chemistry that would dissolve and remove the TBM but also develop proper rinse procedures. The effectiveness of a chemistry was determined by examining the surface properties of the coupon post removal through contact angle.

Several chemistries were examined for BrewerBOND® 230 material, including DMSO- and NMP-based solvents typically used for photoresist strips, single-component hydrocarbon solvents, and surfactant-based chemistries. The contact angle of each coupon test is shown in Figure 2. NMP and DMSO chemistries were ineffective in removing the bulk TBM, even when paired with more aggressive components such as tetramethylammonium hydroxide (TMAH). Single-component hydrocarbon solvents, labeled "Solvent #", were more effective in removing the bulk TBM, dropping the contact angle from 90º to approximately 40º. Optical microscopy characterization (not shown) revealed clean surfaces with no visible residues on the coupon. The lowest contact angle was obtained with a surfactant-based chemistry, but concerns regarding etch rate of standard BEOL metals excluded it from further consideration. Ultimately, mesitylene was selected as the solvent for full-wafer testing as it showed full removal of the TBM with similar contact angle to the other hydrocarbon solvents. More importantly, observations and additional testing revealed a faster dissolution rate compared to the other chemistries tested.

A similar number of chemistries were tested with BrewerBOND® 701 material with far more demonstrating complete removal of the TBM. Due to the thinner TBM layer, 2-minute beaker tests were sufficient for most chemistries to remove the bulk. Similar to BrewerBOND® 230 material, the surfactant-based chemistry provided the best contact angle measurements, but tests run with AZ920 material (EMD Electronics) achieved comparable results. Due to metal etch rates of the surfactant-based chemical, AZ920 material was selected for full-scale testing with BrewerBOND® 701 material coated wafers.

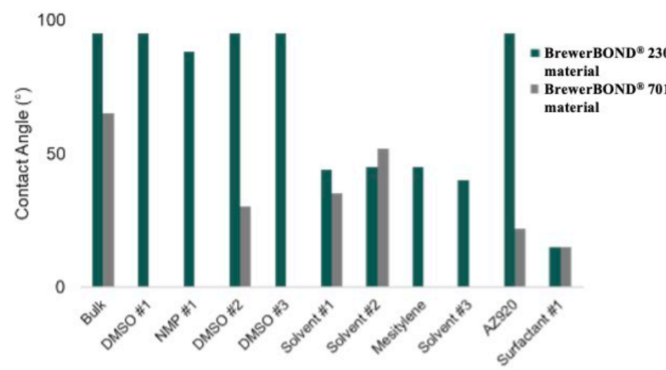

Figure 2: Chart comparing contact angle on the surface BrewerBOND® 230 material (dark green) and BrewerBOND® 701 material (grey) coupons surface after testing with several solvents.

It was quickly determined that achieving the best particle result on full 300-mm wafers was highly dependent on the rinsing medium in conjunction with sequencing. Thus, to continue development with the selected chemistries, rinsing recipes were tested on PMON wafers with incoming specification of 10 particles greater than 100 nm. Two rinsing mediums were used, which were referenced as Rinse A and Rinse B. All tool processing conditions were held constant to directly compare effects from the chemistries and the rinsing mediums. Particle results from these tests are illustrated in Figure 3.

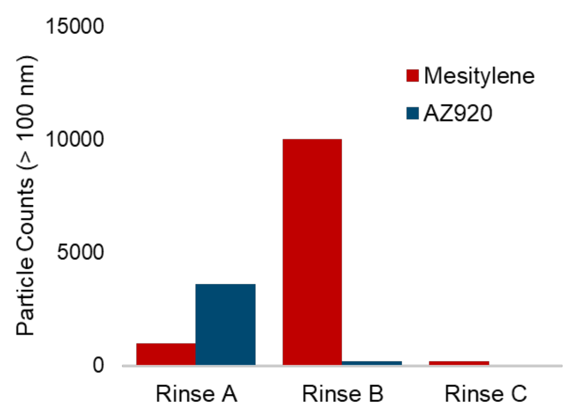

Figure 3: Graph showing particles counts as a result of rinsing method for mesitylene (Red) and AZ920 (Blue). Two mediums, Rinse A and B, were used for testing. Rinse C utilized both mediums.

Rinsing tests with mesitylene display a difference of nearly two orders of magnitude between Rinse A and Rinse B. Inversely, AZ920 was much more effectively rinsed with Rinse B than Rinse A. For particle counts, the difference between the two was roughly 100 times greater. The disparity between the respective solvents illustrates the importance of selecting the proper rinsing medium for achieving the desired particle specifications. A third rinse, Rinse C, was developed by combing both Rinse A and B in distinct sequences through tool-specific capabilities. In doing so, the particle counts were reduced even further than using only Rinse A. While further optimization was possible, TBM studies were conducted with Rinse C for BrewerBOND® 230 material and Rinse B for BrewerBOND® 701 material.

B. BrewerBOND® 230 material

After chemistry assessment, full-wafer studies with TBM-coated wafers were conducted on a Veeco WaferStorm® ML wet processing system. In particular, three different processing methods were utilized to compare effectiveness in removing BrewerBOND® 230 material and highlight particle results. Table 2 summarized the different testing conditions. Test-A consisted of a 45-minute soak step followed by a 90-s LPD stream process. The flow rate of the dispensed liquid was measured at 1000 mL/min. Test-B had similar processing conditions, but a 90-s HPC spray was utilized in place of the stream process. Test-C utilized a HPC spray-only process for a total time of 300 s. The pressurized spray for both Test-B and C was set to 1500 psi with a flow rate of 500 mL/min. The same arm scan was used for all dispenses to ensure complete chemical coverage on the wafer. Each wafer was rinsed using Rinse C as described in the previous section.

Table 2: Processing conditions for tests run on BrewerBOND® 230 material–coated wafers.

Test	Immersion	HPC Spray	LPD Stream	SRD
Test-A	45 minutes	-	90s	Rinse C
Test-B	45 minutes	90s		Rinse C
Test-C	-	300s	-	Rince C

The results from each processing condition are highlighted in Figure 4, where particles maps, haze maps and contact angle measurements are displayed. Figure 5 further summarizes the particle counts from the wafer maps in Figure 4. The map from Test-A reveals an overloaded condition as indicated by the saturated center and incomplete scan. Therefore, the number of particles has exceeded the threshold of 130,000 and should be greater than the values recorded in Figure 5 but cannot be accurately determined. Despite the SP2 indicating all sizes of particles are covering the wafer surface, the wafer appeared optically clean. Optical microscopy as seen in Figure 6, did not reveal any visible residues or large particles. In addition, the haze data from the SP2 reveals elevated average haze values for Test-A. Previous studies have shown that haze can be influenced by the presence of residual polymers [18, 19]. In addition, the surface of the wafers under Test-A conditions had the highest contact angle measurement, showing similar values to beaker-level tests. These results suggest the presence of residual defects that could not be captured with microscopic characterization. However, further wafer surface analysis is necessary to confirm. Overall, the results from Test-A indicate a 45-minute soak followed by a stream dispense was insufficient to get the desired particle level cleanliness of BrewerBOND® 230 material.

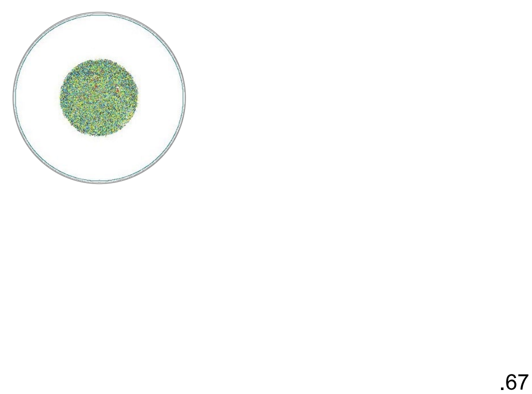

Figure 4: Particle maps for sizes greater than 150 nm, haze maps, and contact angle results for each test performed on BrewerBOND® 230 material–coated wafers.

There is substantial difference in all tests when comparing Test-A to Test-B. Switching from the LPD stream to a HPC spray results an approximately 200x reduction in particle counts, with the assumption that the particle counts for Test-A was 130,000. Additionally, the average haze values for Test-B are significantly lower than Test-A and comparable to that of a bare polished Si wafer, suggesting complete removal of the TBM. These results show that increasing the collision frequency factor in the form of a high-pressure spray provides significant benefits and may be a necessity to remove thicker TBMs.

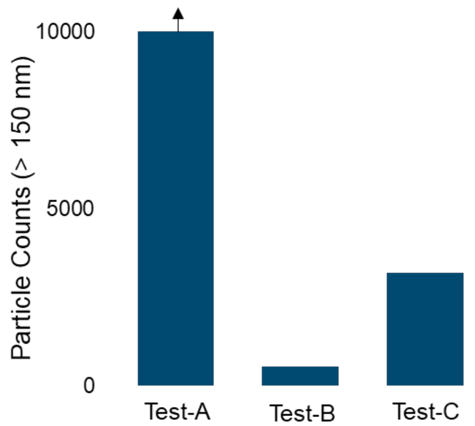

Figure 5: Particle counts based on particle maps from Fig. 5.

The longer spray-only conditions of Test-C resulted in a roughly 6x increase in particle counts when compared to Test-B. The particle maps display prominent signatures coming from the center of the wafer, including several clusters shown in red. These regions are further highlighted in the haze maps, signifying elevated haze values and potential residues on the wafer. Similar to Test-A, optical microscopy could not reveal the presence of any residues on the wafer surface. The contact angle from Test-C also supports the assertion of a less clean surface, with a value in between the other two processes.

These results indicate that the immersion step provides a substantial benefit in removing residues and achieving lower particle counts. The long chemical exposure is expected to dissolve and soften the TBM, allowing for rapid removal when exposed to the high-pressure spray. Along with an increase in performance, the throughput of Test-B compared to Test-C would be 2.5x for a WaferStorm® tool configured with ImmJET™ technology. In terms of practicality from a production and high-volume manufacturing level, the combined immersion and spray process produces the best results in the most efficient manner.

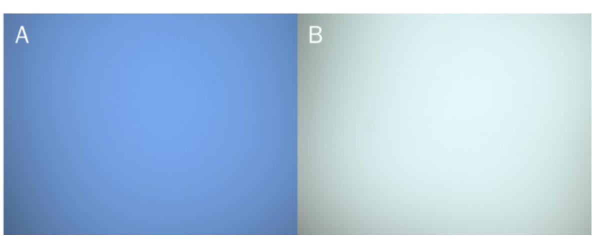

Figure 6: Optical images of TBM-coated wafer (a) prior to processing and (b) after processing.

C. *BrewerBOND® 701 material*

As indicated by the beaker tests, the coated BrewerBOND® 701 material wafers were expected to clean much more quickly than the thicker BrewerBOND® 230 material. As a result, an immersion step was not used for these wafers. Instead, the effects of the pressurized spray were compared with a LPD stream-only process using AZ920 material. Figure 7 displays the particle maps for both process at time intervals of 60 s and 120 s. Wafer maps for these tests had a minimum threshold of 120 nm and utilized Rinse A as discussed in the previous section.

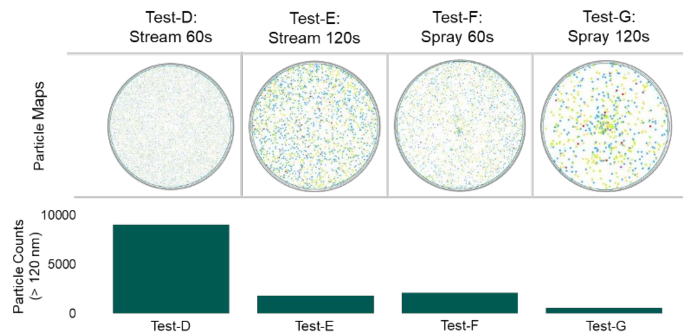

Figure 7: Particle maps for sizes greater than 120 nm, particle counts for tests performed on BrewerBOND® 701 material–coated wafers.

Haze value and contact angle were all comparable across the wafers, so complete removal of the TBM was expected for all tests. Test-D, a 60-s stream process, exhibited the highest particle counts but was reduced by more than 5x when extended to 120 s, as shown by Test-E. The counts for the 60-s HPC spray process, Test-F, were comparable to Test-E, despite the reduced processing time. A similar decrease in particle counts was observed with an extended processing time for HPC-processed wafers. Counts were reduced by more than 3x for Test-G, achieving less than 600 counts with a minimum threshold of 120 nm. While results show that both processes are capable of removing thinner TBM layers, the spray only process showed significant improvements in particle performance and efficiency. In addition to increasing the collision factor, previous studies have demonstrated that sprays can dispense droplets that can be effective in dislodging particles. There are also clear advantages in chemical consumption, as the flow rate of the high-pressure spray (500 mL/min) is half of the LPD stream dispense (1000 mL/min).

IV. Conclusion

The present study shows the ability a Veeco WaferStorm® wet processing system equipped with ImmJET™ technology to successfully remove both thin and thick TBMs, while meeting demands for low particle thresholds. It was found that selection of the solvent and rinsing sequence can significantly impact particle counts and requires careful tuning to minimize defects. In terms of tool-level parameters, tests with a high-pressure spray were most effective for TBM removal. For the thick TBM, an immersion step was effective in allowing for the HPC spray to effectively penetrate and remove any residues, which also improved particle results and potential throughput. In the soak process where the HPC spray was substituted with an LPD stream, particle and haze results indicate incomplete removal of the TBM. For the thin TBM, a spray-only process successfully removed the bulk TBM and obtained low particle counts. Compared to the LPD stream process, the HPC spray-only process reduced particles counts by more than 3x.

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