A Novel Design of Temporary Bond Debond Adhesive Technology for Wafer-Level Assembly

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Abstract— Heterogeneous integration gained significant momentum in the semiconductor industry as it compliments lithographic scaling and offers alternative pathways to device improvement. Temporary bond debond technology (TBDB) with a glass carrier provides a manufacturing platform for this heterogeneous assembly on the wafer level. This paper describes the material development of a silicone-based temporary adhesive to enable robust bonding of the device wafer to glass carrier, as well as a thermoset polymer based laser release layer that enables stress-free glass debond upon receiving UV irradiation. We found that thermoset based temporary bond adhesive offers robust thermal stability, low outgassing, and excellent mechanical stability, making it suitable for wafer level assembly with a temporary glass carrier. An innovative, solvent-based cleaning solution was also identified to efficiently break down the crosslinked adhesive network, offering a robust wafer cleaning process, post laser debonding at room temperature. Some preliminary results of heterogeneous wafer level assembly using this novel temporary adhesive with laser debond will also be discussed.

Keywords—Temporary bond, laser debond, glass carrier, wafer-level assembly, heterogeneous packaging

1. Introduction

Heterogeneous integration gained significant momentum in the semiconductor industry as it compliments lithographic scaling and offers alternative pathways to device improvement. Stacking of multiple chips manufactured from incompatible processes (heterogeneous integration) is required to build multifunctional chips to meet the latest demand of high connectivity, artificial intelligence, and autonomous driving. Successful examples include 2.5D and 3D packaging where sensing, photonics, and radio frequency communication units were incorporated into a single unit. The shortened interconnect leads to a reduced footprint and increased capacity, and holds promise for future packaging designs.

Temporary bond debond (TBDB) technology provides a manufacturing platform for heterogeneous assembly. The temporarily bonded carrier provides mechanical integrity to allow thin device wafer processing. Alternatively, it serves as a high coplanar substrate for redistribution layer build-ups such as in Fan-Out Wafer-Level Packaging (FOWLP) and embedded Wafer Level Ball Grid Array (eWLB). Opportunities to utilize the technology for die-level reconstitution were also explored to counter the low yields from an advanced silicon node. With the coalescence of multiple efforts, TBDB has been identified as a promising solution to die to wafer (D2W) assembly. In contrast to classic wafer-to-wafer (W2W) technology for stacked memories and image sensors, D2W allows bonding multiple dies, with various sizes and silicon nodes onto the same silicon base substrate [1].

The selection of TBDB adhesives, a carrier and the release mechanism is determined by the process requirements. Thermal release adhesives applied in a classic eWLB process, such as a heat activated release tapes, have a typical release temperature of <200ºC, rendering them unsuitable for high temperature dielectric deposition and assembly processes. Early attempts to increase adhesive thermal excursion budgets rely on applying mechanical or shear force to release the carrier. The former process separates the carrier by inserting a metal frame at the adhesive/carrier interface. The latter slides off the carrier at high temperatures when

the adhesive loses its mechanical integrity. Figure 1 summarizes commercially available debonding technologies.

wafer level assembly. Critical parameters for the LRL and the adhesive to function have been identified.
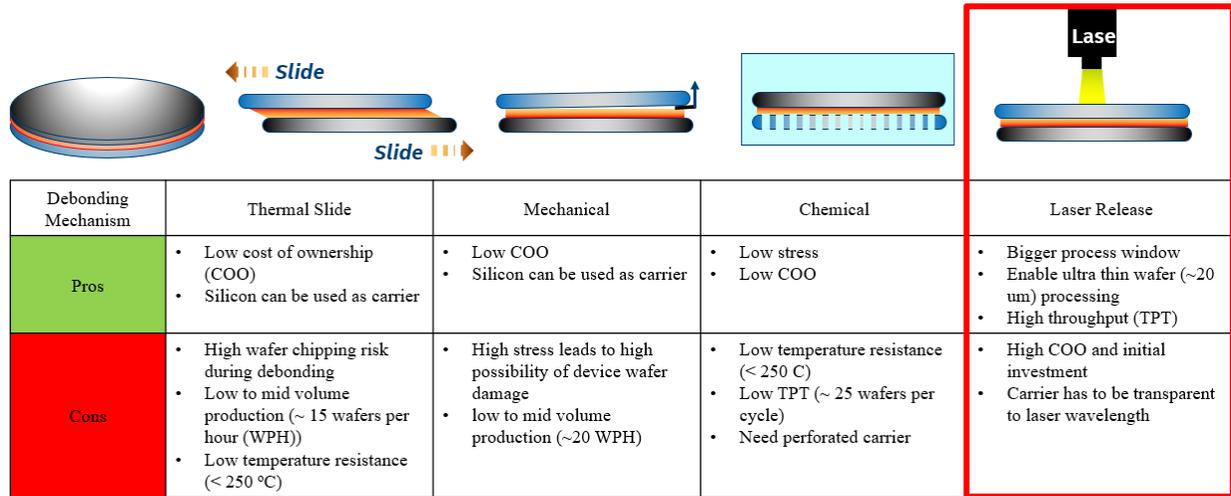

Figure 1. Various debonding approaches available in industry.

Thermal slide debonding (TSD), unfortunately, presents multiple process challenges and constraints. The glue used to attach the silicon carriers is designed to reduce its mechanical strength at high temperatures. It sets the upper temperature limit for nitrate deposition. The nitrate film deposited at lower temperatures is more sensitive to thermal stress. It is also very difficult to process bumped wafers. The undulated morphology prevents forming a good vacuum seal during the first carrier removal. This could lead to wafer chipping and low throughput.

Extendibility of the TBDB technology into future architectures and products should be considered in selecting a suitable carrier release strategy. As a key building block for heterogeneous packaging, the adhesives must be compatible with increasingly demanding process conditions. High heat tolerance and chemical resistant specifications drive selection away from thermal and chemical release systems. Mechanical and thermal slide release, on the other hand, induce stress during carrier removal and thus, constrain the tolerable device wafer thickness. To enable processing ultrathin wafers, laser release TBDB systems have been developed. By ablating away the few hundred nanometers of Laser Release Layer (LRL) at the glass interface, low debonding force (< 10 N) is sufficient to remove the carrier. This significantly reduces the risk of wafer chipping. Typically, laser releasable TBDB adhesives adapt a bilayer design where laser sensitive material (LRL) is deposited on a glass carrier and the adhesive is spin coated on the device to encapsulate the bumps (Figure 2). Such configuration allows vendors to address adhesion/warpage challenges separately from debonding performance. Consequently, this facilitates material optimization and customization. In this paper, we have successfully introduced a glass carrier in our

2. Temporary Bond Debond Material Sets

2.1. Laser Release Layer (LRL)

LRL is designed to absorb the laser energy to release the carrier by decomposition. This submicron layer is inserted between the glue and glass carrier to maximize laser absorption and facilitate debonding. As the adhesive layer is usually transparent to ultraviolet (UV)/visible wavelength, it is very critical for the LRL to have low transmittance to protect the device from laser damage.

Various models have been developed to describe the complex nature of the polymer UV-laser ablation [3]. Photochemical effect was first proposed to explain bond cleavage in polymers upon photon absorption. Assuming the Bouguer-Lambert-Beer intensity distribution inside the material, the etch depth per laser pulse (h_e) can be simplified as below (1):

$$h_e = \begin{cases} 0 & if \ \Phi < \Phi_{th} \\ \frac{1}{\alpha} \log \frac{\Phi}{\Phi_{th}} & if \ \Phi > \Phi_{th} \end{cases} \quad (1)$$

where α is the absorption coefficient, Φ is the laser fluence, and Φ_{th} is the threshold fluence required to initiate ablation. This expression, unfortunately, is limited to a scenario where the temperature at the ablation site is lower than the polymer thermal degradation temperature. In many cases, the relative high power density of the UV pulse causes significant heating. For example, based on the velocity of ejected atomic radicals, the temperature of poly(methyl methacrylate) (PMMA) was projected to reach 3200K at the ablation site [4]. In fact, research showed that as the

debonded LRL surface. Those patterns mirror the laser beam size and the corresponding rastering path.

The UV laser sources can be excimer laser operating at 308 nm or 248 nm, or a solid state laser operating at 355 nm. The excimer laser has high pulse energy, but lower repetition rate. The laser beam positioning mechanisms are typically in line scanning or step-and-repeat mode [6]. In step-and-repeat mode, a homogeneous rectangle-shaped beam of a few millimeters in length is exposed at the glass and LRL interface to cause the debonding.
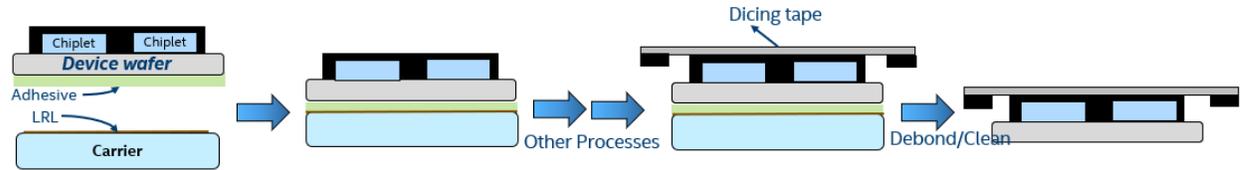

Figure 2. Bond process flow using the bilayer laser releasable TBDB material design.

irradiation wavelength increases, the ablation etch rate-fluence curves deviate from pure photochemical to photo-thermal behavior, obeying the Arrhenius law [5].

Photo-thermal reactions are considered more dominate at elevated temperature and high laser fluencies [3]. By considering thermal diffusion, Φ_{th} could be estimated as shown in (2):

$$\Phi_{th} \sim \left(\frac{1}{\alpha} + 2\sqrt{D_T t_p}\right)\frac{c_p \rho T}{(1-R)} \qquad (2)$$

where D_T is the polymer heat diffusivity, t_p is the duration of a laser pulse, c_p is the heat capacity, ρ is the density, T is the temperature at the ablation site, and R is the reflection coefficient. Any excess energy beyond Φ_{th} will be dissipated in the ablated fragment, ejecting at 2 - 5 times the speed of sound in air [4]. Fortunately, the heat is constrained in a very shallow depth within the surface of LRL that the thermal damage to the device wafer is considered negligible. Given a typical laser pulse ($\sim$ 20 ns) and a polymeric thermal diffusivity of $\sim 10^{-5}$ cm^2/s, the diffusion of the thermal energy to the unexposed depth of the adhesive would be < 10 nm, which is significantly smaller than the bulk adhesive thickness ($\sim 10^4$ nm).

Polymer degradation and localized heating during laser irradiation generates mechanical stress in the organic film [3]. The volatile species from chemical bond cleavage could exert an inner pressure, and thermal expansion and contractions could lead to thermal elastic stress. For example, a compression wave, followed by a rarefaction wave, were detected to propagate through PMMA film upon low fluence laser exposure [4]. The amplitude of the compressive signal increases with the fluence leading to onset of ablation. Such mechanical stress is suspected to form observed cracks on the

Compared with an excimer laser, a solid state laser typically has a relatively lower pulse energy but a much higher laser pulse repetition rate. It is often combined with a highspeed optical scanner to enable a highspeed debonding process. [6] The details regarding the laser used and the debonding pattern are shown in Figure 3.
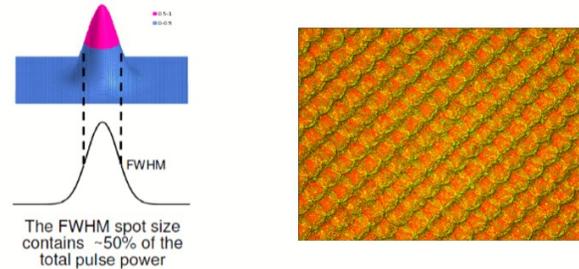

Figure 3. Ablated patterns observed on a laser debonded surface using a 355 nm Gaussian circular laser beam 120 um in diameter at 30% overlaps.

Development of polymeric LRLs is gaining momentum as it enables facile film preparation with lower cost of ownership. A simple spin coating setup can easily create a uniform LRL film with a target thickness at high throughput (TPT). In addition, such materials could also be extended to panel-level by using industrial standard slit coaters or film laminators.

Intel has extensively worked with Shin-Etsu Chemical for the development of a novel laser release material. A standard LRL (LRL-1) of Shin-Etsu and a newly developed LRL (LRL-2) were evaluated in this study. Both laser release materials are approximately 500nm when applied onto glass. The crosslink polymer has a rigid aromatic ring structure and the laser absorbing moieties are used for the design of the polymeric material. The crosslinked thermoset polymeric material was selected as it has better thermal stability (>300C),

high Tg, good chemical resistivity and higher adhesion to a glass carrier at RT to high temperature regions. Moreover, both LRLs have very low transmittances (less than 10%T) at 355nm which will protect the device from the laser damage. LRL-1 and LRL-2 differs in the overall rigidity of the polymer network structure that gives different solubility in the cleaning solvent. A special solvent mixture was developed to break the LRL polymer network into smaller segments.

2.2. Adhesive System

Several aspects must be considered when selecting a polymer adhesive system for wafer bonding applications. To achieve good adhesion, the material should provide good wetting to both the device wafer and glass carrier. In particular, the more complete the polymer adhesives flow and fill in the wafer surface profile, the better are the bond quality and long-term stability. It is often more desirable to prepare adhesive by spin coating the low viscosity varnish on the device side to ensure full bump encapsulation. Such an approach lowers the bonding process sensitivity towards wafer topology.

During bonding, the polymer adhesives needs to be in a viscoelastic phase in order to reach close contact with the glass carrier. Once the bonding is completed, it would then have to transform into a solid phase to confine the device wafer on the carrier. The transition could be achieved through different mechanisms that classify adhesives into 3 types [9]: (1) Drying adhesives: where removing solvent/water from the polymer system results in hardening and solidifying the adhesive; (2) Thermoplastic polymers: where bonding occurs at high temperatures in the melt state and solidifies upon cooling; (3) Thermoset material: where UV and heat trigger curing of soft polymer precursors form a mechanical robust 3D network. Drying adhesives are rarely considered because the residue solvent often yields voids and deteriorates the bond surface. As a consequence, industries focus on customizing thermoplastics and thermoset adhesive systems to meet various process demands.

Earlier adhesive material development centered on thermal slide and mechanical debonding applications. The former involves carrier removal by shearing softened adhesives at elevated temperatures. The latter lift off the handler wafer by initiating a defect at the adhesive/carrier interface. These adhesive systems typically have weak mechanical integrity at > 200 ºC, and consequently are incompatible with die bonding and reflow processes. However, the study of these systems laid the material design foundation for achieving high quality bonding. In general, the adhesive viscosity has to be < 10^4 Pa.s at the bonding temperature to flow and conform to the carrier surface. Otherwise, voids appearing at the bond interface will result in carrier delamination and poor total thickness variation (TTV). It

is possible to further increase the bond temperature to soften the adhesive, but this is often limited by tool capability. Higher bonding temperatures would also yield undesirable high stack warpage upon cooling to room temperature. Such tradeoffs between mechanical properties and bonding temperature are typically a dilemma for thermoplastic adhesives. In contrast, thermoset adhesives can be partially cured and bonded at low pressure and low temperature. A subsequent post bond cure can achieve high adhesive mechanical integrity, making the bonded stack robust against elevated processing temperatures, as shown in Table 1.

Table 1. Strength and weakness of thermoplastic and thermoset adhesives for TBDB applications.

Adhesive type	Thermoplastic	Thermoset
Pros	+ facile cleaning + easy to rework	+ good thermal stability
Cons	- poor mechanical strength at high temp.	- difficult to remove once fully cured

Based on the process requirements, the siloxane based crosslinked polymer was selected. As its resin is in a liquid form, it is easier to apply on the bump topography wafer and to get lower TTV. Siloxane has Si-O-Si linkage at the backbone, while the typical organic polymer mainly has C-C linkage. The Si-O links have higher bond energy and bond length than C-C linkage. The higher bond energy makes the siloxane based polymer more thermally stable than typical organic based polymer materials. Also, the higher bond length makes them more flexible at higher temperatures, which will be helpful in the dissipation of thermal stress that comes from various assembly processes. Moreover, siloxane linkage has good resistivity toward different harsh chemistry uses in the assembly process and lower absorption of moisture, which makes them the ideal candidate for our application. The siloxane chemistry was designed in such a way that the cross linked polymer does not flow (high glass transition temperature with wide tan(delta) peaks) nor delamination, even at higher temperatures.

2.3. Cleaning Solution for Debonded Wafers

Designing a good solvent system to clean the TBDB materials from the debonded wafer surface is critical. It is known that trace amounts of adhesive residue on the wafer surface can drastically alter the surface energy, potentially leading to underfill and mold delamination. With the typical adhesive thickness of 30 – 60 um, dry etch processes tend to be long and unsuitable for high volume manufacturing (HVM). In this work, we focus on using a solvent puddle to clean residue adhesives. Such a wafer-level tool configuration is similar to a photoresist developing module.

A typical laser debonded surface contains a submicron layer of LRL covering the bulk adhesives as shown in Figure 4. No organic solvent has been identified to

dissolve the crosslinked LRL-1. Instead, we rely on solvents to penetrate through defects in the LRL to dissolve the underneath adhesive. Once adhesive dissolution starts, the LRL will gradually release into the solvent puddle (Figure 5). The wettability of the solvent on the LRL should be tailored to facilitate penetration.
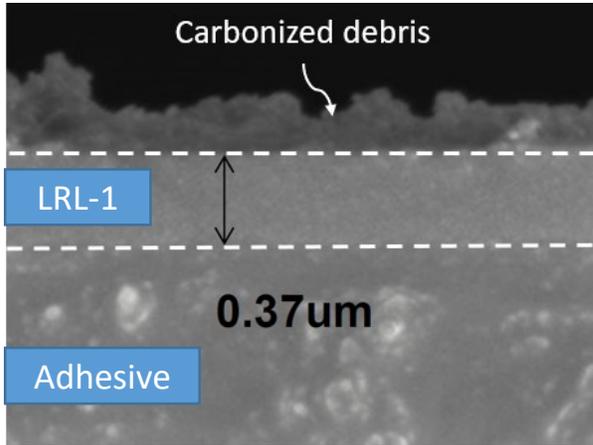

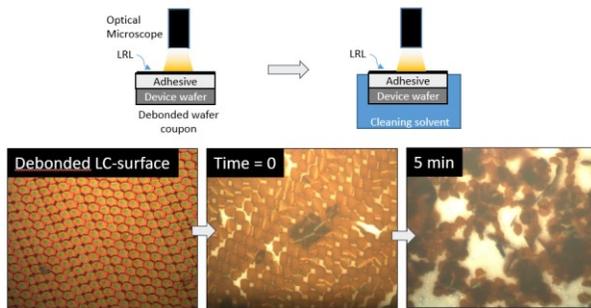**Figure 4.** Cross section SEM showing debonded surface of LRL-1.

Figure 5. *In-situ* study of debonded surface with LRL-1 after immersing in cleaning solvent.

It is most challenging to develop a cleaning solution for thermoset adhesives. The chemically crosslinked 3D polymeric network can only dissolve when the matrix is being broken down into smaller fragments. Cleaving the C-C bonds in acrylic and epoxy-based systems often requires highly oxidative chemistry (i.e., hot sulfuric acid). Not only would it be incompatible with commercial debonder configurations, but would also cause device/package damage.

Polysiloxanes network can be unzipped by proprietary additives, offering an unprecedented cleaning opportunity. The substitution of a Si-O bond with the additive drives the bond dissociation, followed by adhesive dissolution (Figure 6).
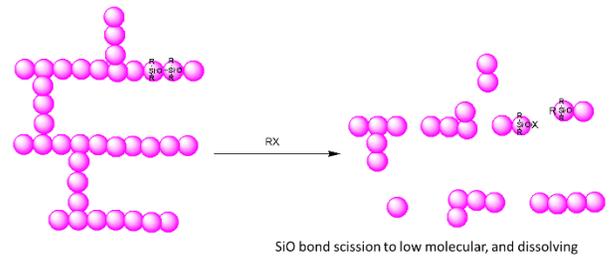

Figure 6. Solvation mechanism of adhesive.

3. Bonding/Debodning Evaluations

3.1 Bonding Glass and Debonding Silicon Wafer
Glass wafers were successfully bonded to a device wafer at Shin-Etsu in Japan. No voids were observed in the bond line as shown by the scanning acoustic microscopy (C-SAM) in Figure 7. Good TTV was achieved without significant adhesive squeeze-out at the wafer edge.
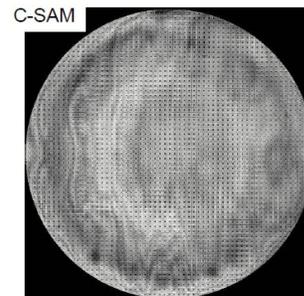

Figure 7. An example of C-SAM image for a bonded wafer stack.

Another merit of a thermoset TBDB adhesive is that stack warpage can be reduced by optimizing the post bond cure. We found final stack warpage can be reduced by initially curing the silicone adhesives at a higher pin height (slightly lower temperature) followed by a lower pin height bake (closer to the hot stage set temperature). The reduced warpage is possibly attributed to the wafer stack reaching thermal equilibrium before the adhesive starts to cure, lowering the internal stress in the bonded stack.

Siloxane based polymers may cause recurring reliability problems in packaging of microelectronic devices. Unreacted cyclic siloxane oligomers could outgas at elevated temperatures and deposit on other parts of the device. These contaminants have significantly lower surface energy that reduces adhesion strengths of assembly materials to the device wafer. Such risk is low in the hybrid bond flow because packaging was already completed prior to glass bonding. Moreover, the post laser debonding cleaning should be able to remove remnant siloxane, yielding pristine wafer surfaces and clean bumps. With due diligence, XPS was used to monitor possible siloxane contamination on the surface of the bonded stack after hammered thermal stress

conditions: 260C/10 min, followed by 175C/4h to simulate thermal exposure in the assembly processes. No organic Si-O signal was detected for adhesive systems, suggesting low out gassing risks (Figure 8).
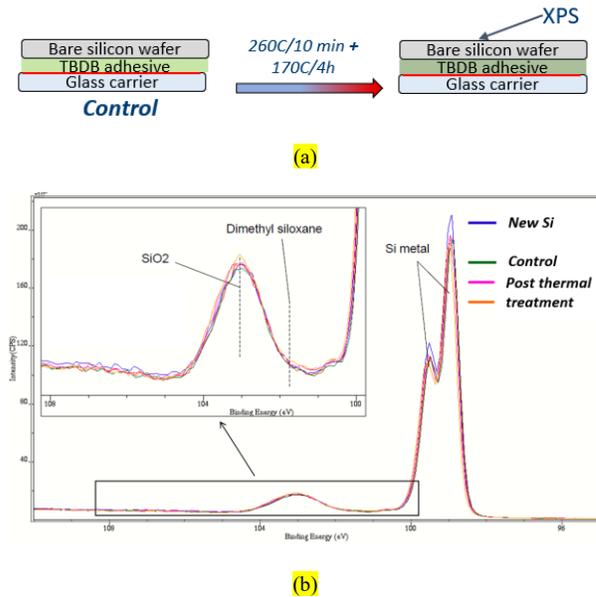

(a)

(b)

Figure 8. (a) XPS sample preparation to determine siloxane out gassing risks andnd (b) Wafer surface showed no Si-O signal post thermal treatment.

3.2 Laser debonding
Glass carriers with LRL-1 and LRL-2 were successfully debonded at 355nm. Typical laser debonding setting parameters investigated were: laser fluence level, laser spot size, degree of laser spot overlap, film thickness, and transmittance of the LRL at the laser wavelength. We found that while increasing the overlap reduces TPT, increasing the fluence causes significant material decomposition and easy debonding..

LRL preparation on the glass wafers was found to be sensitive to the glass surface quality and the dispense system. The non-uniform thickness causes transmittance variation which may lead to wafer damage during laser debonding. Since the adhesive has negligible absorption at 355 nm, the combined transmittance of glass and LRL at 355 nm should be zero to afford good laser protection. Transmittance of each layer prior to reaching the device wafer was measured by a UV/Vis spectrometer. We have validated that the glass wafer was successfully debonded from the device wafer at the laser release layer to the adhesive layer interface under a wider laser parameter window.

3.3 Cleaning Debonded Surface
To enable handling of the thin device wafer package post-glass debonding, the whole stack was mounted to a dicing tape frame. Another critical role of the dicing tape is to create the solvent puddle to clean the remnant LRL and adhesive on the debonded wafer. Figure 9 shows a typical cleaning procedure, where the solvent puddle was spun at a low rate for a couple of minutes to assist material dissolution, followed by a higher rotation (~1000 round-per-minute) to remove the puddle. Isopropyl alcohol is often used sequentially to speed up drying of residue solvent on the device wafer.
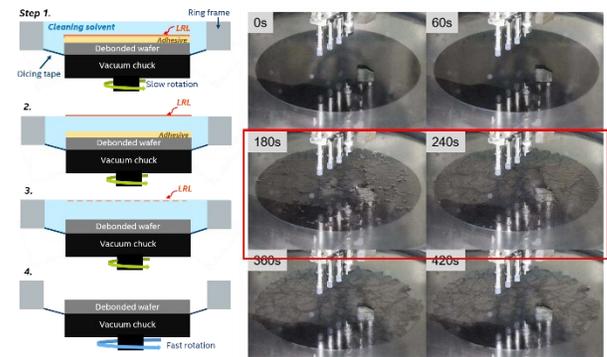

Figure 9. Schematics of the cleaning process and an actual cleaning progression of TBDB Material from Vendor S. The red box highlights the moment LRL-1 lift into the solvent.

LRL-1 was found to be much more difficult to clean. A closer examination revealed that the LRL-1 is more resilient and requires additional time for the solvent to completely penetrate through the cracks before being fully released into the puddle (Figure 5). Initial attempts to improve cleaning efficiency by increasing the overlap to induce more film defects was unfruitful. The most optimized laser and cleaning recipe still yields LRL debris on top of the device wafer post-cleaning, as shown in Figure 10.

To enable a healthy cleaning process window, devising a soluble LRL is necessary. Based on the LRL-1 learning, we reformulated the next generation LRL (LRL-2) by incorporating a siloxane backbone into the polymer precursor. Since the cleaning solvent is capable of breaking the Si-O bond, such LRL remains are projected to readily dissolve during cleaning. Preliminary trials showed significant improvement in solubility (Figure 11).
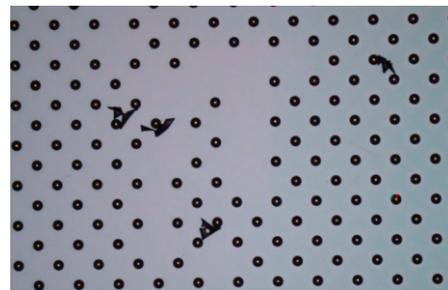

Figure 10. Trapped LRL-1 debris between the bumps on the edge of the wafer renders the device wafer not re-cleanable.

Figure 11. The pale yellow LRL-2 coated on glass readily dissolves in the cleaning solvent, which turned reddish brown.

4. Conclusions

Thermoset adhesives were found to meet all post-bonding process requirements with good reliability. Thermoplastic binders were not a good choice as they deformed under the process shear force and temperature, resulting in glass wafer sliding and wafer chipping. LRL-1 showed good debonding performance, but it is insoluble and acts as a barrier for good adhesive cleaning and the debris gets trapped between the solder bumps at the wafer edge. Soluble LRL was developed to truly ensure a healthy cleaning margin. Significant improvements in dissolution can be achieved by incorporating Si-O bond into the LRL backbone leading to a production worthy process.

Acknowledgements

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