Photonic Debonding for Wafer-Level Packaging

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Abstract

Temporary bonding and debonding (TB/DB) processes have emerged as promising solutions in wafer-level packaging technology. These processes offer a pathway to wafer thinning and subsequent backside processing, which are crucial in enabling heterogenous integration using technologies such as 3D through silicon-vias and fan-out wafer-level packaging. These are critical for overall device miniaturization and increased performance. In this work, a novel photonic debonding (PDB) method and the corresponding bonding material are presented. PDB enhances the TB/DB process by overcoming many of the disadvantages associated with traditional debonding methods. PDB uses pulsed broadband light (200 nm – 1100 nm) from flashlamps to debond temporarily bonded wafer pairs with glass as the carrier wafer. These flashlamps generate high-intensity pulses of light (up to 45 kW/cm^2) over short time intervals (~300 µs) to facilitate the debonding.

INTRODUCTION

Recently, three-dimensional (3D) chip technologies have gained importance in the microelectronics industry because of their advantages including shorter circuit paths, faster performance, reduced power consumption and heat dissipation [1]. These technologies involve heterogeneously stacking several thinned silicon (Si) dies (<100 µm) and interconnecting them vertically to form a three-dimensional integrated circuit (3D-IC) [2]. Through-silicon vias (TSV), instead of classical wire-bonding technique, may be utilized to vertically interconnect between the silicon wafers in the modern 3D chip technologies. Thinned wafers further enable facile creation of these TSVs [3, 4].

In order to facilitate processing of thin Si wafers, temporary bonding of the Si wafer is utilized. In the temporary bonding process, a secondary carrier wafer acts as a rigid support for the primary device wafer and utilizes an adhesive layer between the two to bond the two wafers together. Once the wafers are bonded together, backside-grinding and subsequent backside processing can be performed. After the backside processing, the thinned wafer and the carrier stack are prepared for wafer debonding. Wafer debonding is the process of separating the thinned, already processed Si wafer from the carrier so that the IC on the processed wafer can be used for its intended application [4]. This makes wafer debonding an important processing step to implement 3D-ICs.

Many existing techniques for debonding the thinned wafer include, (a) using chemical solvents to dissolve the adhesive between the silicon wafer and the perforated carrier, (b) heating the adhesive between the silicon wafer and the carrier so it exhibits a large enough complex viscosity drop to the point where the silicon wafer can be separated by shearing, or (c) using mechanical means to peel the silicon wafer off the substrate [4-6]. However, in order to prevent any damage on the surface structure of the thinned wafers, room temperature and low stress debonding techniques are preferred. Use of harsh chemicals is also not desirable.

Laser assisted wafer debonding techniques have become increasingly attractive due to their ability to debond the wafer at room temperature [7]. Lasers operating in both excimer region [8] and infrared region [9] have demonstrated their ability to debond the thinned wafer from a transparent carrier. Conversion of optical energy by a laser release layer or a laser sensitive adhesive result in photo-chemical and/or photo-thermal breakdown of the polymer at the interface resulting in microlayer ablation of the polymers to promote adhesion loss at the adhesive-carrier interface. However, several disadvantages of this technique including (a) variation in the sensitivity of the laser beam's focal point with variation in the thickness of the wafer-carrier stack, (b) power fluctuation of the beam, (c) need for special beam focusing objectives, and (d) most importantly, throughput challenges due to beam width limitations, especially when processing a large wafer (300 mm), all contribute to the need to explore an alternative room temperature, low stress, high-throughput debonding technique.

In this work, a non-laser, photonic debonding (PDB) method for temporary bonding and debonding (TB/DB) will be presented. Characteristics of the compatible bonding adhesive, along with the material stack of the bonded wafer pair will be discussed. PDB process, utilizing broadband light-emitting flashlamps, to debond Si wafers from glass carriers in less than a millisecond (ms) debond time will be demonstrated. The post-debond cleaning process will also be evaluated.

EXPERIMENTAL

A bonding adhesive, Material A from Brewer Science, Inc., was chosen for the photonic debonding study of 200-mm full thickness wafer pairs due to its thermal properties, such as its glass transition temperature (T_g), thermal decomposition temperature (T_d), and melt viscosity of the material at 220°C. The physical properties of the material can be seen in Table 1 with the full melt viscosity profile shown in Figure 1.

Table 1. Thermal Properties of Material A.

Material	**Glass Transition Temperature**	**Thermal Decomposition Temperature**	**Melt Viscosity at 220°C**
A	98.3°C	400°	1974 Pa·s

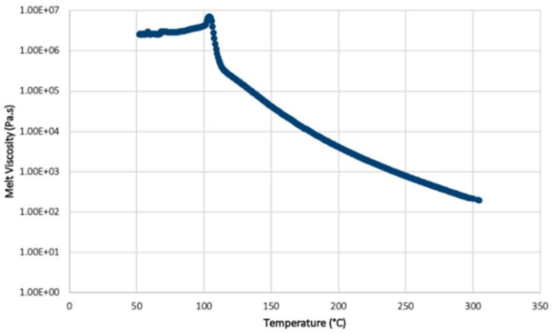

Fig. 1. Melt viscosity profile of Material A.

Material A was spin-coated at a target thickness of 50 µm on a 200-mm Si wafer and baked to remove solvent prior to thermocompression bonding of the Si wafer to the carrier using the parameters shown in Table 2.

Bonding for 200-mm wafers was performed utilizing a 0.7-mm Si wafer coated with Material A, to act as the device wafer, and a 0.7-mm Corning® Eagle XG® glass wafer was used as the carrier wafer and coated with a 200-nm light absorbing layer (LAL) on the Si wafer facing side. The two wafers were then bonded together via a thermocompression bonding method with conditions shown in Table 2 utilizing an EVG® 510 Bonder for the process.

Table 2. Process Parameters of Material A

Material	**Spin Conditions**	**Bake Conditions**	**Bond Conditions**
A	1000 rpm 3000 rpm/s 30 s	60°C, 5 min 160°C, 5 min 220°C, 5 min	220°C 2000 N 3 min

Six wafer pairs (200-mm diameter) bonded with Material A underwent PDB. A high, instantaneous power photonic debonding tool, (PulseForge® EX2-9510) from PulseForge, USA was used to demonstrate the PDB process. (Fig. 2) This tool uses a variable pulse length power system driving a 24-mm diameter flashlamp and is capable of emitting broadband light (200 nm – 1100 nm) with peak radiant intensity as high as 45 kW/cm^2. It has an irradiation area of 75 mm x 150 mm. The same tool has the capability to uniformly irradiate over an area larger than the beam size by automatically synchronizing the flash frequency to an automated X-translation stage. These particular tests required translation in both the X and Y directions, so there was a manual positioning component for proof of principle for processing of a 200-mm diameter pattern. This laid a path forward for a fully automated PDB tool at this larger size. A photograph of the debonded wafer pair is shown in Fig. 3. Eight indexed flashes, each 300 µs long, were required to completely debond the wafer. With a single lamp, this process would take < 20 seconds using an automated X-Y stage.

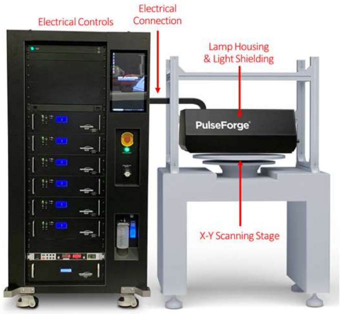

Fig. 2. Photonic debonding tool

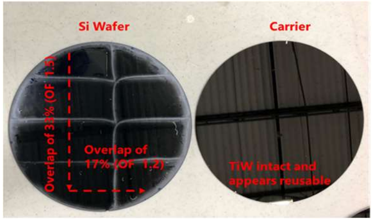

Fig. 3. Photograph of a 200-mm wafer pair debonded using the defined tool path.

Cleaning of the wafers was performed post debond using a CEE® spin coater with a pressure pot dispense apparatus. The cleaning process consisted of a continuous dispense of cyclopentanone as the solvent to dissolve the residual polymer while spinning the wafer. This was followed by a solvent dispense of isopropanol to assist in drying the wafer after the initial cleaning process. The wafer was then spin dried to finish the process. Process conditions for cleaning the debonded 200-mm device and carrier wafers are shown in Tables 3 and 4.

Table 3. Cleaning Procedure of Material A on 200-mm Si Wafer.

Step	**Spin Speed (rpm)**	**Time (s)**	**Solvent Dispense**
1	1000	145	Cyclopentanone

2	1000	15	Isopropanol
3	1000	15	No Solvent

Table 4. Cleaning Procedure of Material A on 200mm Carrier Wafer.

Step	Spin Speed (rpm)	Time (s)	Solvent Dispense
1	1000	15	Cyclopentanone
2	1000	15	Isopropanol
3	1000	15	No Solvent

RESULTS

From a materials perspective, the photonic debonding process consists of two critical pieces to make the process work well and be desirable as a debonding method.

The first critical piece for the photonic debonding method is having a robust bonding adhesive layer that enables the bonding portion of temporary bond and debond. Material A was chosen as this robust bonding material due to a few specific characteristics the material offers. The first important characteristic of the material is its moderate T_g of 98.3°C which allows for an ideal melt viscosity profile for a thermoplastic-based material for processing within the 200-250°C temperature range. In this temperature range the material will be able to bond efficiently at 220°C because its melt viscosity is below 3000 Pa·s which is considered a good limit for where the material begins to have enough flow to efficiently bond in a thermocompression bond process. The second important characteristic is the T_d. Material A offers a T_d of ~400°C which allows for efficient processing in the 200-250°C temperature range as well as good compatibility with the photonic debonding process.

Material A was spin coated on a Si wafer and then measured for film thickness utilizing a FRT MicroProf® 300 metrology tool giving an average film thickness of 51.6 µm. The post-coat film thickness map of Material A is shown in Fig. 4a.

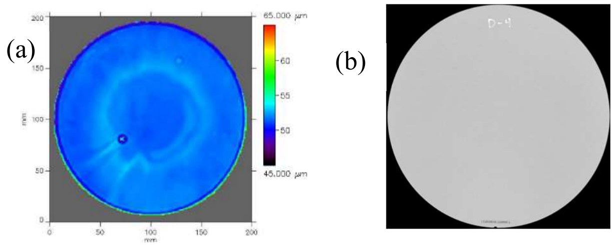

Fig. 4. (a) Material A after coating film thickness map. (b) CSAM of bonded wafer pairs.

After the spin coating, the coated Si wafer was then bonded with the LAL-coated glass wafer using the bond conditions shown in Table 2. Once the wafer was bonded, it was then measured for bond line voids utilizing a Sonix CSAM (confocal scanning acoustic microscope). The CSAM image of the bonded wafer pair can be seen in Fig. 4b, where it shows no voids in the bond line, which would generally appear as white spots in the image.

The second critical materials element for the PDB process is the LAL coating on the glass carrier. Its primary function is to convert the absorbed optical energy from the flashlamp into the thermal energy needed to facilitate the decomposition of the adhesive at the LAL-adhesive interface, which in turn creates the adhesion loss needed to debond the wafer pairs. Its secondary function is to block the penetration of the broadband light into the adhesive and the Si wafer. As such, optical measurements (Fig. 5) with light incident from the back of the glass substrate reveal that the absorber layer coating had 0% transmittance (T) over the spectral range of 200 nm to 1100 nm. The reflectance (R) of the LAL when measured through the glass was ≈ 45% over the same spectral range. Since A+R+T=100%, where A is the absorptance, R is the reflectance and T is the transmittance and T=0, the absorptance of the LAL is ≈55% of the incident light from the flashlamp.

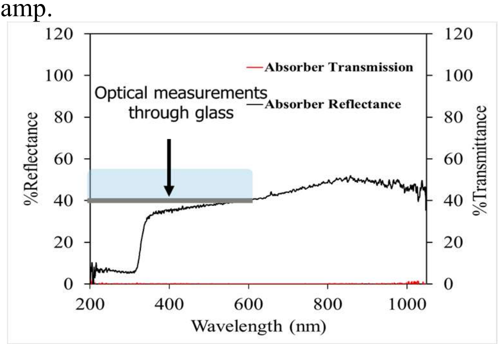

Fig. 5. Optical measurement of the LAL.

Thus, when irradiated through the glass carrier, which is mostly transparent, the light absorber layer absorbs the majority of the light and converts it to the heat needed to debond the carrier from the Si wafer.

All six bonded wafer pairs that went through PDB method, debonded successfully without any cracks or damage to the Si wafer. The pulse conditions that enabled PDB delivered fluence between 4.72 J/cm^2 (edge case) and 5.27 J/cm^2 (best case). The bonded wafer pairs were of 200-mm diameter and received 8 flashes which were indexed to cover the entire wafer pair. Each pulse of light was 300 µs in duration. The Si wafers remained intact without any cracks or damage.

Figure 6 (a) and (b) show photographs of the Si wafers and LAL-coated carriers debonded using the PDB method, for both best and worst-case conditions respectively. The LAL-coated carrier could be easily separated from the Si wafer by hand with no separation force needed after debonding. As seen in the photograph, there is no visual adhesive residue left behind on the LAL-coated carrier (Fig. 6 (a)) when processed under best-case PDB conditions. However, when processed using worst-case PDB conditions, which delivers noticeably lower fluence, the wafer-pairs required a slight force to separate. It is also evident from Fig. 6 (b) that there are still some residues from the adhesives on the LAL coated carrier responsible for the slight force needed to separate the wafer pairs.

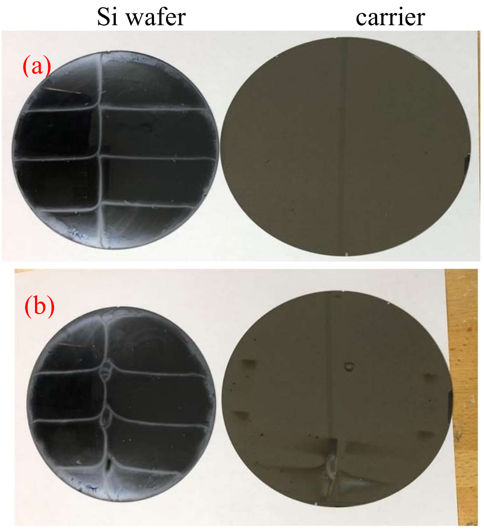

Fig. 6. Photonically debonded wafer-pairs (a) using best-case PDB condition (b) using worst-case PDB condition.

This indicates that PDB process can be optimized to result in a clean debond without any ashing or charring, which may otherwise occur with laser debonding [10]. Since the LAL coating prevents direct illumination of the bonding adhesive, PDB is a relatively cleaner debonding process than laser debonding. The sputtered LAL coating appears to be intact. Studies on reusing the LAL-coated carrier after the PDB and cleaning processes are underway.

Once debonding was performed on the wafer pair, the Si wafer and LAL-coated carrier underwent a spin cleaning process using the conditions shown in Tables 3 and 4. Once the wafers were cleaned, they underwent a visual inspection to ensure the polymer and ablation residues were fully removed from the surface, Fig. 7 shows the visually inspected wafers after cleaning. After cleaning, the wafers showed no polymer residue on either the Si wafer or the LAL coated carrier wafer.

Overall, these results demonstrate that PDB can offer new solutions to the TB/DB process by bringing in capabilities such as high-throughput, low thermal stress on a Si wafer, and low-ash/-residue debonding.

Fig 7. Si Device Wafer after spin cleaning process.

CONCLUSIONS

The photonic debonding method that has been developed together by Pulseforge Corp. and Brewer Science, Inc. is a relatively new technique to debond a Si wafer from a glass carrier wafer. It uses LAL-coated glass as the temporary carrier with a bonding adhesive material between the carrier and Si wafer. When an intense pulse of light from a flashlamp is shined through the glass carrier, the LAL absorbs the light and is heated to cause interfacial thermal degradation of the bonding adhesive at the interface between the LAL and bonding adhesive. The separation of the bonding adhesive results in no ash or charring and allows for easier cleaning of both the thinned silicon and carrier wafers. Photonic debonding offers high throughput with a debond time within seconds of loading the wafer. The photonic debonding method has been proven in the past using thinned 150-mm wafers. Here, we have shown that this method is also viable at the 200-mm wafer size. Photonic debonding appears to continue to be a viable high-throughput debonding method for future TB/DB.

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