A Novel Photosensitive Permanent Bonding Material Designed for Polymer/Metal Hybrid Bonding Applications

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Abstract

Wafer-level hybrid bonding techniques, which provide simultaneous bonding between metal-metal and dielectric-dielectric layers, have attracted more attention in recent years for fabricating 3D integrated circuits with high bandwidth and high interconnect density. However, there are some issues for conventional hybrid bonding using silicon oxide as the dielectric, such as the high stress and low tolerance to height difference of the bonding interface, which limits its applications for 3D heterogeneous integration.

In this paper, a novel negative-tone, photosensitive, polymeric bonding material is proposed that can be used as a dielectric enabling polymer/metal hybrid bonding. Compared to silicon oxide, the polymeric material with low Young's modulus is able to absorb thermally induced stress created during the bonding process and results in lower bow for the bonded substrates. The key features for the photosensitive permanent bonding material include 1) low dielectric constant and dissipation factor; 2) superior thermal stability up to 350°C; 3) excellent fine-pitch capability <10 µm; and 4) low processing and curing temperatures <200°C. The photosensitive permanent bonding material has also demonstrated good patternability with good adhesion when bonded to another Si or glass substrate without obvious defects. The details of the material characterization, process optimization, reliability, and preliminary polymer/polymer hybrid bonding results will be presented in this paper.

INTRODUCTION

As costs climb when moving to the next generation of silicon nodes, 2.5D and 3D IC heterogeneous integration is in the spotlight to provide an economic solution for the industry which will enhance the performance of final devices through scaling system-level interconnection. Heterogeneous integration in the industry exists in many formats, such as Chip-on-Wafer-on-Substrate (CoWoS) and Integrated Fan-Out (InFO) technologies from TSMC [1-2], Embedded Multi-Die Interconnect Bridge (EMIB) and Foveros technologies from Intel, and I-Cube technology from Samsung. One of the most promising solutions is hybrid bonding and chip stacking since it offers the ability to integrate several dies with small interconnection pitches below 10 µm which enables higher bandwidth through power and signal integrity improvement [3].

Wafer-level hybrid bonding simultaneously bonds metal to metal and between dielectric and dielectric, and has been applied to some applications, such as image sensors and non-volatile storage, proving to be an effective way to improve bonding quality and reliability. Generally, Cu is used as the metal for I/O pad metal conjunction and inorganic silicon dioxide is used as the dielectric for insulation. The biggest concern for the current approach is the use of inorganic silicon dioxide which requires high-quality surface planarization to obtain highly reliable bonding. Also, the hardness of silicon dioxide makes it difficult to tolerate height differences and particles on the bonding interface, which results in lower yield due to electrical failures [4].

To solve these issues, a novel photosensitive permanent bonding material is introduced in this paper, which exhibits fine-pitch patterning capability with <10 µm L/S resolution, excellent thermal stability for the thermal budget needed for Cu annealing, and good bonding quality with surface planarization. With all these merits, this material has the potential to replace silicon dioxide in hybrid bonding and solve the issues with current processing.

MATERIAL CHARACTERISTICS

Characterization of the photosensitive permanent bonding material (PBM) was conducted using both a solution and cured film that was created using molds or cast onto silicon wafers using standard processing conditions. Advantages associated with this novel negative-tone permanent bonding material are: high chemical resistance, photopatternability L/S <10 µm, high adhesion to various substrates, and low-temperature bonding with good thermal stability >350°C. For this paper, data will be presented and separated into two categories: product performance and product physical properties.

PRODUCT PERFORMANCE

Photosensitive Permanent Bonding Material Processing

Evaluation of product performance was conducted using flat silicon wafers of 100- to 200-mm diameter. In general, the permanent bonding material was manually coated using a static dispense process in a spin coater with minimal air flow and exhaust. A target film thickness of 5 µm was achieved using a spin speed of 700-850 rpm with an acceleration of 1000-3000 rpm/s for a spin time of 30 s. The coated wafer was then baked using a bake plate at 60°C for 5 min (contact), then further baked at 120°C for 8 min (contact) to remove residual solvent from the film. Baked wafers were then photo-exposed with broadband or i-line exposure tools using various exposure doses (100-500 mJ/cm^2). A post exposure bake was done using a bake plate set at 120°C for 3 min followed by a solvent develop process (for patterns only, develop was not done for flood exposure). Bonding to a silicon carrier wafer was done using an EVG® 510 bonder set at 150°C, 8000 N of force for 15 min. Thermal curing post-bond was done using a 200°C bake plate for 60 min contact.

Chemical Resistance

As a permanent bonding material which will remain with the final device over a lifetime, excellent chemical resistance is necessary. Testing was conducted on coated wafers and bonded pairs (silicon bonded to glass) which were prepared using the above process (no develop process). Each sample was then placed into a chemical bath using the desired conditions and time (Table I). Test wafers and bonded pairs were then visually inspected for possible film delamination, bond line edge attack or solubility after chemical exposure.

TABLE I

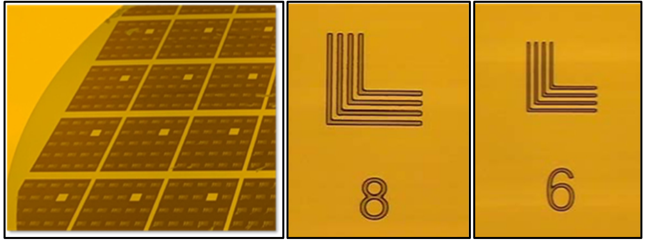
Chemical resistance data for exposed films and bonded pairs

Chemical	**Bath**	**Time**	**Film**	**Bond line**
Acetone	25 °C	25 min	No defects	No defects
Cyclohexanone	25 °C	5 min	No defects	No defects
Ethyl Lactate	25 °C	30 min	No defects	No defects
IPA	25 °C	30 min	No defects	No defects
PGMEA	25 °C	5 min	No defects	No defects
PGME	25 °C	5 min	No defects	No defects
Mesitylene	25 °C	5 min	No defects	No defects
TMAH 2.38%	25 °C	10 min	No defects	No defects
NMP	80 °C	10 min	No defects	Edge attack
H_2O_2 35%	50 °C	60 min	No defects	Edge attack
KOH 30%	85 °C	60 min	Delamination	Edge attack
Oxalic acid 0.25%	25 °C	10 min	No defects	No defects
Citric acid 0.25%	25 °C	10 min	No defects	No defects

Photolithography Performance

Beyond 40-µm pitches, hybrid bonding becomes an attractive alternative to microbumps. A typical hybrid bonding process targets CD sizes below 10 µm [5]. This material has been designed to be photopatternable using standard photolithography processing. Using standard processing conditions, 200-mm silicon wafers were coated with a 5-µm film of the permanent bonding material. An exposure dose matrix was conducted using a resolution reticle with various exposure tools. A post-exposure bake (PEB) was then performed at 120°C for 3 min. A solvent develop was performed on the wafers using cyclopentanone or mesitylene for <3 min in a SUSS MicroTec XBC300 debond and cleaning system (Fig 1).

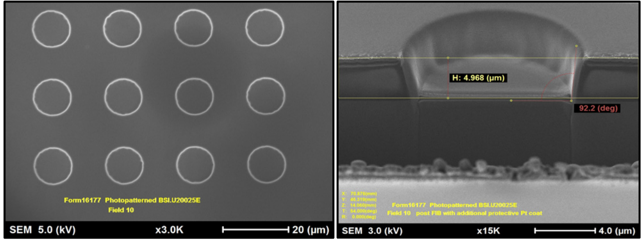
Fig. 1. Exposure matrix on silicon substrate



Exposure dose <200 mJ/cm^2 L/S

With additional optimization of the develop process, successful patterning of 10 µm vias has also been achieved (Fig. 2).

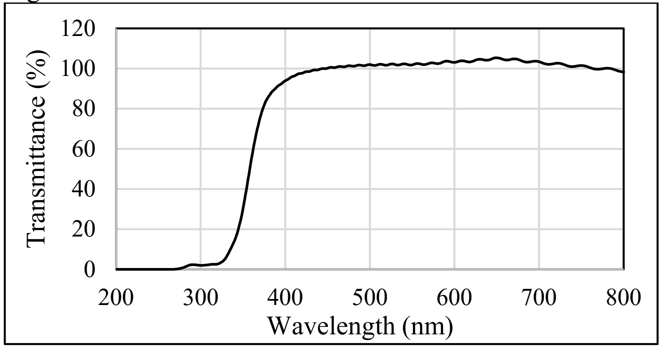
Fig. 2. SEM photos of 10 µm vias



Film transparency

A test sample was prepared using a quartz wafer. The permanent bonding material was then coated, baked, and flood exposed to fully cure the permanent bonding material. Using a Cary UV-Vis Spectrophotometer, the optical transparency (% Transmittance) of a 5 µm film through the visible spectrum was measured (Fig. 3.). Greater than 95% transmittance was obtained at 405-800 nm.

Fig. 3. Film Transmittance



Film Total Thickness Variation (TTV)

Copper-polymer and polymer-polymer hybrid bonding requires zero defects with co-planar bonding surfaces with minimal surface roughness. This improves the bond formation, yield and reliability which are critical to achieving interconnect functionality [6]. Achieving a polymer film with low TTV allows for uniform formation of the bond.

Using a 200-mm silicon wafer, film uniformity was determined using the standard processing conditions as outlined above for an unbonded wafer. This testing did not include an edge bead removal process which can be easily incorporated into the film casting process. Measurements were made using a FRT MicroProf® 300 metrology tool and include both a full wafer map and multiple line scans (Fig. 4). An average full wafer film thickness of 4.551 µm with a TTV of 5.103 µm was obtained. In this case, the thickness variation is a direct result of the high film edge bead. Using a 10-mm edge exclusion, an average film thickness of 4.767 µm was obtained with a TTV of 0.235 µm, which is <5% of the film thickness. Further coat optimization needs to be conducted using a fully automated dispense with improved air flow control in the coater.

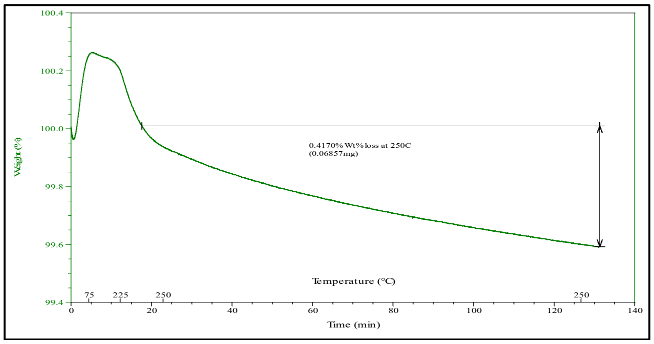
Fig. 4. FRT TTV measurement, full wafer line scan

Measurement location (mm) vs film thickness (µm)

Thermal Stability

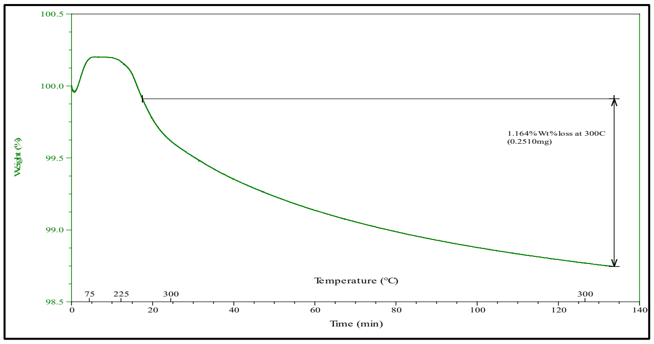
Good thermal stability of the permanent bonding material is a necessary requirement for successful implementation of a hybrid bonding process. To strengthen the bond and form electric contact of the interconnects, a thermal anneal process of bonded pairs is performed at temperatures >250°C under vacuum. Isothermal thermal gravimetric analysis (TGA) was conducted on fully cured films at various temperatures with a hold time at temperature of 2 hours in a nitrogen atmosphere (Fig. 5 & 6). Weight loss for each temperature was determined and samples compared.

Fig. 5. Isothermal TGA data (250°C for 2 hrs) for fully cured film



Weight loss (%) at temperature vs time (min) at temperature.

Fig. 6. Isothermal TGA data (300°C for 2 hrs) for fully cured film

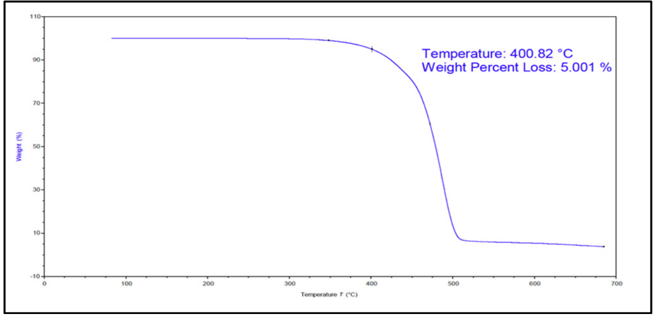


Weight loss (%) at temperature vs time (min) at temperature.

When heated at 250°C, weight loss was measured at 0.41% and at 300°C a weight loss of 1.16% was obtained. Further testing was conducted at 350°C with a measured weight loss of 8.26%.

Thermal gravimetric analysis was also conducted to determine the thermal decomposition temperature for fully cured films. At 350°C in N_2, a 2% weight loss was measured and at 400°C, a weight loss of 5% was observed (Fig. 7).

Fig. 7. TGA in N_2 fully cured film



Preliminary Hybrid Bonding Results

Various hybrid bonding test scenarios have been evaluated using the photosensitive permanent bonding material. Adhesion, bond quality and bond strength for chip-to-wafer (C2W), and chip-to-chip (C2C) using both silicon dioxide (SiO_2) to polymer (PBM) and polymer-to-polymer (PBM) have been tested. As of the writing of this paper, copper-(Cu) to-Cu and Cu-to-PBM hybrid bonding processes are pending evaluation.

Preliminary testing involved processing the PBM onto flat silicon wafers. For die shear tests, both SiO_2 and PBM were processed on silicon wafers and then diced into 2.5-mm x 2.5-mm dummy die, underwent plasma treatment, and were then bonded to the coated silicon wafers in a chip-to-wafer configuration (Fig 8). An anneal bake process was performed at 200°C for 1 hr. Using confocal scanning acoustic microscopy (CSAM), images were generated to evaluate the chip-to-wafer bond quality (Fig. 9). No voids or defects were found and no difference in bond quality was observed for wafers bonded to either PBM or SiO_2 chips.

Fig. 8. (C2W) PBM bonded to SiO_2 or PBM

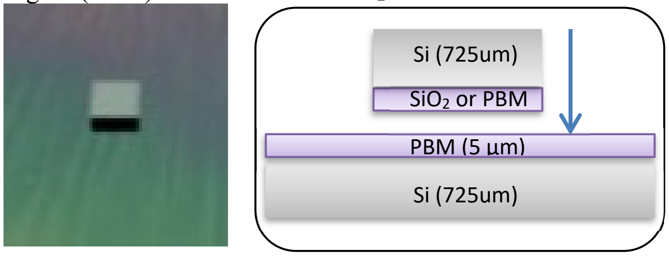
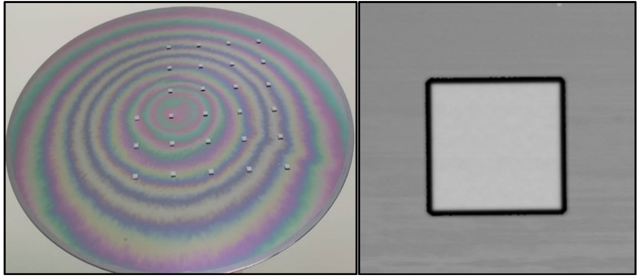
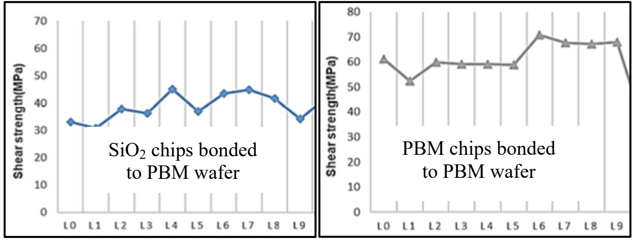


Fig. 9. PBM wafer (with Newton's rings) bonded to either SiO_2 or PBM chips with CSAM image of bonded chip.



Using an xyztec bond tester, the peak load (force) was measured and represents the maximum amount of shear force the bond line can handle before failure. Using a blade, increasing force is applied to the side of the chip attempting to induce a failure by fracture [7]. The amount of force required to cause a failure is known as shear strength (Fig. 10).

Fig. 10. Shear strength Results



These tests indicate a shear strength range of 30-40 MPa for SiO_2 bonded to PBM and a range of 50-70 MPa for PBM chips bonded to PBM wafers.

PRODUCT PHYSICAL PROPERTIES

As part of the characterization for the photosensitive permanent bonding material, various mechanical and film properties have been evaluated. This preliminary data has been generated using standard sampling techniques for each test (Table II).

The photosensitive permanent bonding material offers excellent dielectric properties, especially at higher frequencies which reduces the electrical loss seen in high-speed circuitries. Good elongation and tensile strength are measures of the film's fracture toughness which minimizes stress during multilayer build-up. Currently, further characterization such as moisture absorbance and reliability testing are on-going for this material.

TABLE II

Product Properties: This data is reported as preliminary results for this material and is subject to additional testing.

Dielectric Constant (D_k)	10 GHz 108 GHz	2.6 2.6
Dissipation Factor (D_f)	10 GHz 108 GHz	0.0016 0.0041
Volume Resistivity	Ω-cm	6.99×10^{16}
Young's Modulus	MPa	240.9
Tensile Strength	MPa	21.37
Elongation (max)	%	160.6
Glass Transition (T_g)	°C	30
CTE	ppm/°C	206
Optical Constants (n, k)	248 nm 365 nm 633 nm 1310 nm	1.696, 0.128 1.576, 0.002 1.528, 0.0003 1.515, 0.0007

CONCLUSIONS

Heterogeneous integration formats, such as Chip-on-Wafer-on-Substrate (CoWoS) and Integrated Fan-Out (InFO) technologies, Embedded Multi-Die Interconnect Bridge (EMIB) and Foveros technologies require new multifunctional materials which enable sub-10-µm interconnection pitches and higher bandwidth through power and signal integrity [1]. In this paper we have presented preliminary results using a novel permanent photosensitive bonding material developed for hybrid bonding applications. The PBM exhibits excellent performance characteristics including <10 µm L/S pattern ability, thermal stability <300°C, and high shear strength. Product properties also include low T_g, high modulus, and excellent dielectric performance at higher frequencies. Evaluation of film performance using a hybrid bonding application with copper and film reliability under various environmental conditions is on-going.

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