

PROCESS CONTROL TECHNIQUES FOR WAFER-TO-WAFER BONDING

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application Serial No. 63/529,538 entitled “Process Control Techniques for Wafer-to-Wafer Bonding,” filed on July 28, 2023, which is incorporated by reference herein in its entirety.

[0002] This application claims priority to U.S. Provisional Patent Application Serial No. 63/669,620 entitled “Methods for D2W and W2W Bonding,” filed on July 10, 2024, which is incorporated by reference herein in its entirety.

TECHNICAL FIELD

[0003] The present disclosure relates generally to wafer bonding, and more particularly to process control techniques for wafer-to-wafer bonding with high bonding yield.

BACKGROUND

[0004] Wafer bonding is crucial for compact and powerful devices. It involves coating a full thickness wafer with adhesive, bonding it to a support carrier wafer, and thinning it for downstream processes. Key factors impacting bonding quality include flatness (total thickness variation (TTV)), alignment, voids, temperature control, coefficient of thermal expansion (CTE) match, and bonding force. Addressing these factors ensures uniform bonding, precise processing, and high device yield, leading to reliable and high-quality semiconductor devices.

[0005] Over the past years, temporary substrate bonding gained popularity alongside the demand for smaller, more powerful devices. Thin substrates (<100 μm) pose challenges in handling, but a temporary wafer bonder solves this, reducing breakage risks.

[0006] In the bonding process, a full thickness wafer with devices is coated with a temporary adhesive to withstand downstream stresses. It is bonded to a support carrier wafer. After thinning and backside processing (e.g., through silicon via (TSV), metal-plating), the stack undergoes debonding, cleaning, dicing, and packaging.

[0007] After referring to the adhesive material manufacturer’s specifications, the bonder platens are heated to the temperature required for the bonding adhesive. This temperature is chosen based on the point that the material liquifies in order to maximize adhesion.

[0008] The device wafer is loaded onto the lower platen and centered using the built-in alignment fixtures. The carrier wafer is then placed and aligned on top of the device wafer. The mechanical alignment fixtures keep the carrier and device wafers separated at loading.

[0009] While the two wafers are held, the bonding chamber closes and vacuum is applied, evacuating air from the bonding chamber. Programmable piston force “squeezes” the wafers together for a specified period of time, planarizing the bonding adhesive and ensuring full wafer coverage.

[0010] Once complete, the chamber opens and the bonded wafer pair is removed and placed on a cooling plate. This allows the wafer stack to cool, setting the adhesive for maximum bond strength. The bonded wafer pair is then ready for the next downstream process step.

[0011] Unfortunately, the number of bonded wafer pairs created using current process control techniques is deficient.

SUMMARY

[0012] In one embodiment of the present disclosure, a method for bonding two wafers comprises dispensing droplets of interfacial liquid at pre-specified locations on a first bonding surface of a first wafer or on a second bonding surface of a second wafer, where the first bonding surface of the first wafer is facing a first direction, and where the second bonding surface of the second wafer is facing a direction opposite of the first direction. The method further comprises bringing the first wafer and the second wafer together so that both the first wafer and the second wafer contact the interfacial liquid. The method additionally comprises performing an overlay error correction between the first and second wafers with the interfacial liquid between the first and second wafers. Furthermore, the method comprises removing the interfacial liquid using evaporation thereby creating a bonding between the first and second wafers.

[0013] The foregoing has outlined rather generally the features and technical advantages of one or more embodiments of the present invention in order that the detailed description of the present invention that follows may be better understood. Additional features and advantages of the present invention will be described hereinafter which may form the subject of the claims of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] A better understanding of the present invention can be obtained when the following detailed description is considered in conjunction with the following drawings, in which:

[0015] Figure 1 illustrates a system for performing the substrate-to-substrate bonding process with in-liquid align and in-situ alignment metrology in accordance with an embodiment of the present disclosure;

[0016] Figure 2A illustrates the shroud concept for management of interfacial liquid evaporation prior to bonding in accordance with an embodiment of the present disclosure;

[0017] Figures 2B-2C illustrate the birefringence-based method for interfacial particle detection in accordance with an embodiment of the present disclosure;

[0018] Figure 2D illustrates the interferometry-based method for interfacial particle detection in accordance with an embodiment of the present disclosure;

[0019] Figure 3 illustrates a first embodiment for wafer-to-wafer (W2W) bonding equipment in accordance with an embodiment of the present disclosure;

[0020] Figure 4 illustrates a second embodiment for W2W bonding equipment in accordance with an embodiment of the present disclosure;

[0021] Figure 5 illustrates a third embodiment for W2W bonding equipment in accordance with an embodiment of the present disclosure;

[0022] Figure 6 illustrates an equipment architecture for die to wafer (D2W) hybrid bonding in accordance with an embodiment of the present disclosure;

[0023] Figure 7A illustrates a side view of the carrier substrate chucking system in accordance with an embodiment of the present disclosure;

[0024] Figure 7B illustrates a top view of the carrier substrate chucking system in accordance with an embodiment of the present disclosure;

[0025] Figure 8 illustrates a cross-sectional view of the indent of the chuck for the carrier substrate in accordance with an embodiment of the present disclosure;

[0026] Figure 9 illustrates the slots for an equipment front end module (EFEM) end effector on a potential configuration for the chuck in accordance with an embodiment of the present disclosure;

[0027] Figure 10 illustrates a side view of an exemplary pick-down configuration for die release in accordance with an embodiment of the present disclosure;

[0028] Figure 11 illustrates a side view of an exemplary pick-up configuration for die release in accordance with an embodiment of the present disclosure;

[0029] Figure 12 illustrates fiber optic guided (UV) light incident on a die in accordance with an embodiment of the present disclosure;

[0030] Figure 13 illustrates mirror guided UV light incident on a die in accordance with an embodiment of the present disclosure;

[0031] Figure 14 illustrates mirror guided UV light to be incident on the die with intermittent condenser, collimator, or lens units for collimating the incident light on the die in accordance with an embodiment of the present disclosure;

[0032] Figure 15 illustrates a first embodiment for the die pickup and transfer system in accordance with an embodiment of the present disclosure;

[0033] Figure 16 illustrates a second embodiment for the die pickup and transfer system in accordance with an embodiment of the present disclosure;

[0034] Figure 17 illustrates a third embodiment for the die pickup and transfer system in accordance with an embodiment of the present disclosure;

[0035] Figure 18 illustrates an example testing system for bonding in accordance with an embodiment of the present disclosure;

[0036] Figure 19A illustrates the undeformed configuration of a deformable die chuck in accordance with an embodiment of the present disclosure;

[0037] Figure 19B illustrates the deformed configuration of a deformable die chuck in accordance with an embodiment of the present disclosure;

[0038] Figure 20 illustrates an alternative embodiment of a deformable die chuck in accordance with an embodiment of the present disclosure;

[0039] Figure 21 illustrates a further embodiment of a deformable die chuck in accordance with an embodiment of the present disclosure;

[0040] Figure 22 illustrates a fourth embodiment of the deformable die chuck in accordance with an embodiment of the present disclosure;

[0041] Figures 23A-23B illustrate a fifth embodiment of the deformable die chuck in accordance with an embodiment of the present disclosure;

[0042] Figure 24A illustrates an air-bearing based short-stroke motion stage for a multi-die bond head in accordance with an embodiment of the present disclosure; and

[0043] Figure 24B illustrates a cross-section of an air bearing module of Figure 24A in accordance with an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0044] As stated above, wafer bonding is crucial for compact and powerful devices. It involves coating a full thickness wafer with adhesive, bonding it to a support carrier wafer, and thinning it for downstream processes. Key factors impacting bonding quality include flatness (total thickness variation (TTV)), alignment, voids, temperature control, coefficient of thermal expansion (CTE) match, and bonding force. Addressing these factors ensures uniform bonding, precise processing, and high device yield, leading to reliable and high-quality semiconductor devices.

[0045] Over the past years, temporary substrate bonding gained popularity alongside the demand for smaller, more powerful devices. Thin substrates ($<100\text{ }\mu\text{m}$) pose challenges in handling, but a temporary wafer bonder solves this, reducing breakage risks.

[0046] In the bonding process, a full thickness wafer with devices is coated with a temporary adhesive to withstand downstream stresses. It is bonded to a support carrier wafer. After thinning and backside processing (e.g., through silicon via (TSV), metal-plating), the stack undergoes debonding, cleaning, dicing, and packaging.

[0047] After referring to the adhesive material manufacturer's specifications, the bonder platens are heated to the temperature required for the bonding adhesive. This temperature is chosen based on the point that the material liquifies in order to maximize adhesion.

[0048] The device wafer is loaded onto the lower platen and centered using the built-in alignment fixtures. The carrier wafer is then placed and aligned on top of the device wafer. The mechanical alignment fixtures keep the carrier and device wafers separated at loading.

[0049] While the two wafers are held, the bonding chamber closes and vacuum is applied, evacuating air from the bonding chamber. Programmable piston force "squeezes" the wafers together for a specified period of time, planarizing the bonding adhesive and ensuring full wafer coverage.

[0050] Once complete, the chamber opens and the bonded wafer pair is removed and placed on a cooling plate. This allows the wafer stack to cool, setting the adhesive for maximum bond strength. The bonded wafer pair is then ready for the next downstream process step.

[0051] Unfortunately, the number of bonded wafer pairs created using current process control techniques is deficient.

[0052] As discussed herein, process control techniques have been developed for wafer-to-wafer bonding with high bonding yield.

[0053] The following published references are incorporated by reference herein in their entirety.

[0054] U.S. Patent No. 11,469,131 entitled “Heterogeneous Integration Of Components Onto Compact Devices Using Moiré Based Metrology And Vacuum Based Pick-and-Place,” is incorporated by reference herein in its entirety.

[0055] U.S. Patent No. 11,600,525 entitled “Nanoscale-Aligned Three-dimensional Stacked Integrated Circuit,” is incorporated by reference herein in its entirety.

[0056] U.S. Patent Application Publication No. 2021/0350061 entitled “Nanofabrication and Design Techniques for 3D ICS and Configurable ASICs,” is incorporated by reference herein in its entirety.

[0057] U.S. Patent Application Publication No. 2023/0163013 entitled “Processes and Applications for Catalyst Influenced Chemical Etching,” is incorporated by reference herein in its entirety.

[0058] International Publication No. WO 2023/056072 entitled “Tool and Processes for Pick-and-Place Assembly,” is incorporated by reference herein in its entirety.

[0059] International Publication No. WO 2023/137181 entitled “High-Precision Heterogeneous Integration,” is incorporated by reference herein in its entirety.

[0060] Bonding is a process for temporary or permanent attachment of one substrate to another substrate. The bonding could be bump bonding, micro-bump bonding, eutectic bonding, thermocompression bonding, hybrid bonding, anodic bonding, covalent bonding, fusion bonding, solder bump bonding, wire bonding, wafer-to-wafer (W2W) bonding, etc. In one embodiment, bonding includes one or more of the following: direct bonding, SiO₂-SiO₂ bonding, covalent bonding, fusion bonding, hybrid bonding, adhesive bonding, self-assembly, temporary bonding, and permanent bonding. The bonding could be between two silicon surfaces (hydrophobic bonding), two oxide surfaces (hydrophilic bonding), two SiCN surfaces, two SiCO surfaces, two surfaces with composition of the following form: SiC_xN_yO_z (where $x \geq 0$, $y \geq 0$, $z \geq 0$), etc.

[0061] Referring to Figure 1, Figure 1 illustrates a system 100 for performing the substrate-to-substrate bonding process with in-liquid align and in-situ alignment metrology in accordance with an embodiment of the present disclosure.

[0062] As shown in Figure 1, system 100 includes moiré microscopes 101 for in-situ real-time overlay metrology during bonding. In one embodiment, 4, 6, 8, 12, 16 or more of these assemblies (moiré microscopes 101) could be simultaneously deployed for high-precision distortion state measurement.

[0063] Additionally, system 100 includes infrared (IR)-based thermal actuation modules 102 based on a radiative-heating-based concept.

[0064] Furthermore, system 100 includes bridges 103, z actuators 104 (e.g., voice coils), a top wafer chuck 105, a top wafer 106, alignment marks 107, a bonding interface 108, a bottom wafer 109, wafer chuck with coarse grained temperature control 110, an XY motion stage 111, and a wafer chuck 112.

[0065] In one embodiment, during bonding, interfacial liquid 113 is dispensed onto top wafer 106 using an inkjetting-based approach. In one embodiment, top wafer 106 with its carrier is then brought into contact with the dispensed interfacial liquid. In one embodiment, in-liquid alignment is subsequently performed using alignment marks 107.

[0066] In one embodiment, the composition of interfacial liquid 113 includes one or more of the following: an aqueous solution, a hydroxyl group containing material, an alcohol, isopropyl alcohol, an acid, a base, water, citric acid, an adhesive, a silsesquioxane, acetone, methanol, ethanol, and a mixture of one or more of the foregoing.

[0067] In one embodiment, interfacial liquid 113 is dispensed to a larger height at an edge of a surface of top wafer 106 or bottom wafer 109 and to a lower height away from the edge of the surface of top wafer 106 or bottom wafer 109, respectively.

[0068] Figure 1 further illustrates optionally including lateral grooves and/or through holes 114 to improve interfacial liquid removal from bonding interface 108 prior to bonding. In one embodiment, interfacial liquid 113 is dispensed at an edge of the grooves and/or through holes at one of the surfaces of top and bottom wafers 106, 109.

[0069] In one embodiment, to enhance evaporation, counter-directional airflow is created using the wafer chuck (as shown by vertical arrows 115) to create localized regions of high airflow.

[0070] Furthermore, as illustrated in Figure 1, in one embodiment, ink-jetted interfacial liquid droplets 113 are used to facilitate in-liquid alignment. The in-liquid alignment provides the ability to correct overlay distortions between the wafers (top wafer 106 and bottom wafer 109) to be bonded with a thin intermittent film of interfacial liquid 113 between the two bonding wafers (top and bottom wafers 106, 109). This would allow for overlay correction all the way until bonding happens between the two wafers.

[0071] In one embodiment, inkjet drop volume tuning permits the creation of custom wafer bow during wafer bonding and evaporation control of interfacial liquid 113 would enable bond-wave optimization.

[0072] In one embodiment, one or more of the fluids utilized in the cleaning and/or hydration steps during bonding could be used to enable lubrication between the two surfaces being bonded (e.g., surfaces of top and bottom wafers 106, 109), immediately prior to the bonding. In one embodiment, the lubrication occurs once the two surfaces being bonded are close enough such that a residual amount of the cleaning and/or hydration fluids fills the gap (partially or completely) between the two surfaces, where the gap could be one of the following: sub-5 μm , sub-1 μm , sub-500 nm, sub-200 nm, sub-100 nm, sub-50 nm, sub-20 nm, sub-10 nm, sub-5 nm, and sub-2 nm. Once the required alignment (or overlay) specification has been achieved, a bonding wave could be initiated (by forcing contact between a central region of the two surfaces, for instance) creating a temporary or permanent bond between the two surfaces (surfaces of top and bottom wafers 106, 109). Any excess fluid that was used for lubrication could go into one or more of the following regions between the bonded surfaces: porosity in one or more of the bonding surfaces, porosity in oxide/SiCN/SiCO layers at one or more of the bonding surfaces (an example of porous oxide films is hydrogen silsesquioxane based dielectric materials), recesses in one or more of the bonding surfaces, nanowires in one or more of the bonding surfaces, high-aspect-ratio nanostructures in one or more of the bonding surfaces (where the nanostructures could be comprised of nanowires, line-spaces, etc.), where the recesses, nanowires, nanostructures could be created prior to the bonding step using one or more of the following techniques: etching, reactive ion etching, metal assisted chemical etching, and deposition techniques).

[0073] In one embodiment, the rate of excess fluid removal is modulated by lowering the local pressure around the bonding region (for instance, fluid removal could be enhanced by lowering the pressure in a local enclosed area around the substrates to be bonded). In one embodiment, the lowering of pressure is temporary, performed just prior to bonding. Alternatively, the lowering of pressure is permanent (where the tool is kept at a specific pressure at all, or a majority, of the time). Other factors that could be utilized to modulate the excess fluid removal are as follows: temperature of the bonding surfaces, and humidity of the air in the vicinity of the bonding surfaces.

[0074] In one embodiment, a shroud in the vicinity of top wafer 106 is used to arrest (i.e., stop) the removal of the residual interfacial fluid (through evaporation, for instance), if a defect at the bonding interface is detected (a particle at the bonding interface, for instance) as discussed in further detail below in connection with Figures 2A-2D.

[0075] Figure 2A illustrates the shroud concept for management of interfacial liquid evaporation prior to bonding in accordance with an embodiment of the present disclosure.

[0076] Figures 2B-2C illustrate the birefringence-based method for interfacial particle detection in accordance with an embodiment of the present disclosure.

[0077] Figure 2D illustrates the interferometry-based method for interfacial particle detection in accordance with an embodiment of the present disclosure.

[0078] Referring to Figure 2A, system 200 illustrating the shroud concept for management of interfacial liquid evaporation prior to bonding includes an in-situ particle detection sub-system 201. In one embodiment, sub-system 201 corresponds to a wafer-scale sub-system or a group of sub-systems, each covering a metrology region smaller than the wafer but together covering the entire wafer (either statically or using a scanning approach).

[0079] Furthermore, system 200 includes an alignment metrology sub-system 202, such as IR moiré metrology.

[0080] Additionally, system 200 illustrates dispensing interfacial liquid 113 via an inkjet 203.

[0081] Furthermore, system 200 illustrates z actuators 104 positioned on z-heads 204.

[0082] Additionally, Figure 2A illustrates chucking pressure 205 (p_{cd}) at the interface of the carrier substrate (in one embodiment, the carrier substrate may correspond to the bottom wafer or bottom substrate 109) and the top substrate (also referred to as the top wafer 106).

[0083] Furthermore, system 200 includes a transparent backing plate 206, which is transparent to IR or optical wavelengths.

[0084] Additionally, system 200 includes carrier substrate pins 207, a shroud 208, a space for an optional airflow 209, metal interconnects 210 in the top/bottom wafers (106, 109), and substrate chuck 211.

[0085] Furthermore, Figure 2A illustrates the shroud-to-bottom-wafer gap 212 as well as an interfacial particle 213 and the humidity (h_1 , h_2) and pressure (p_1 , p_2) at locations 214, 215, respectively.

[0086] Further, in connection with system 200 of Figure 2A, a wafer chuck could be used to attach to top substrate (also referred to as top wafer) 106. The chuck could contain pins in the region where the chuck interfaces with top substrate 106. In one embodiment, such pins have a high aspect ratio and have lateral dimensions that are microscale or even nanoscale. In one embodiment, the pins are designed to be compliant when a particle (e.g., interfacial particle 213) is present at the interface (e.g., bonding interface 108) between bottom wafer 109 and top wafer 106.

[0087] In one embodiment, the thickness of top wafer 106 along with the chuck stack could be changed to change the bending characteristics of the stack. For instance, a thicker chuck could be used to enhance the size of the exclusion zone created by a particle (e.g., interfacial particle 213) at bonding interface 108.

[0088] In one embodiment, shroud 208 is retractable using suitable z actuators 104 (e.g., voice coil, screw drive stage, linear motion stage, etc.) into z-head 204. In one embodiment, the ability to retract, elongate, and to generally actuate precisely in the z direction, is used to enable a precisely controlled shroud-to-bottom substrate gap 212 (for instance, less than 100 μm , 10 μm , 1 μm , 500 nm, or 100 nm).

[0089] In one embodiment, the pressure and humidity (e.g., see locations 214, 215) within the surrounding of shroud 208 are controlled to have a different value on different sides of the bonded wafers (e.g., top and bottom wafers 106, 109). This could be used to enhance or arrest interfacial liquid evaporation during bonding. For instance, if a particle (e.g., interfacial particle 213) is detected during bonding, one side of shroud 208 could be changed from a nominal pressure and

humidity of p_1 and h_1 (see location 214) to a higher pressure p_2 and higher humidity h_2 (see location 215). This would have the effect of setting up a cross flow from one area of shroud 208 to another area, creating enhanced humidity h_2 in the interfacial region as well, with the enhanced humidity arresting the interfacial liquid evaporation. In one embodiment, the shroud pressures and airflow dynamics are designed so that the time it takes for the interfacial humidity to go from h_1 to h_2 is less than one of 10, 5, 1, 0.5, 0.1, and 0.05 seconds.

[0090] In one embodiment the top and/or bottom wafers 106, 109 could either be monolithic substrates or reconstituted substrates/wafers (RW stands for reconstituted wafer). The bonding could therefore be of the following types: W2W, RW2RW, and RW2W.

[0091] As discussed above, system 200 includes an in-situ particle detection sub-system 201. An illustration regarding the birefringence-based method for interfacial particle detection performed by sub-system 201 is provided in Figures 2B-2C.

[0092] Referring to Figure 2B, Figure 2B illustrates the top view of birefringent film 216 showing a particle-like distortion signature.

[0093] Referring to Figure 2C, Figure 2C illustrates an exclusion zone 217 where no bonding occurs. In one embodiment, the lateral extent of exclusion zone 217 is over 1 μm , 10 μm , 100 μm or 1 mm. In one embodiment, the extent depends on the bulk thickness of the un-chucked top wafer 106, the pressure applied on top wafer 106 (for example, atmospheric pressure), and the material properties of top wafer 106.

[0094] Referring now to Figure 2D, optical interference between the bottom surface of a reference flat 218 and the top surface of top wafer 106 produces an interference signal which could be used to detect particle-like signatures by thin-film interferometer 219 (e.g., Fizeau interferometer).

[0095] Referring to Figures 2A-2D, in one embodiment, in-situ particle detection sub-system 201 is utilized to detect particles (e.g., interfacial particles 213) at bonding interface 108. In one embodiment, said particles (e.g., interfacial particles 213) can lead to exclusion zones 217 that prevent bonding in the exclusion zones. In one embodiment, the detection is performed in-situ in the bonding tool itself, such as shown in Figures 2C and 2D.

[0096] In one embodiment, the particle detection in in-situ particle detection sub-system 201 is performed using one or more of the following methods: (1) birefringence-based detection; (2) thin-film interference-based detection; and (3) alignment-based detection.

[0097] Concerning birefringence-based detection as shown in Figures 2B-2C, birefringent film 216 is coated on the un-bonded surface of a substrate to be used to detect particle-like signatures. In one embodiment, birefringent film 216 is also coated on top wafer 106. Alternatively, in one embodiment, a thick substrate made of birefringent material is temporarily, or permanently, bonded to the chuck or top wafer 106.

[0098] Concerning thin-film interference-based detection as shown in Figure 2D, a thin-film interferometer 219 is used to detect particle-like signatures in the interference pattern of the back surface of a substrate (e.g., top and bottom wafer 106, 109) that is being bonded and reference flat 218.

[0099] In alignment-based detection, arrays of alignment marks (see 107 of Figure 1) on the backside of a substrate (e.g., top and bottom wafer 106, 109) are measured with respect to a reference substrate with a corresponding array of alignment marks, such as alignment marks 107. In one embodiment, particles (e.g., interfacial particles 213) are detected by the presence of particle-like signatures in the misalignment of the alignment marks.

[00100] In one embodiment, an interconnect pitch at bonding interface 108 is one of the following: sub-50 nm, sub-100 nm, sub-250 nm, sub-500 nm, sub-1 μm , sub-2 μm , sub-5 μm , and sub-10 μm .

[00101] In one embodiment, the post-bonding overlay precision is one of the following: sub-5 nm, sub-10 nm, sub-25 nm, sub-50 nm, sub-100 nm, sub-200 nm, sub-500 nm, and sub-1 μm overlay precision.

[00102] Referring to Figure 3, Figure 3 illustrates a first embodiment for W2W bonding equipment 300 in accordance with an embodiment of the present disclosure.

[00103] As shown in Figure 3, W2W bonding equipment 300 is similar to system 100 except W2W bonding equipment 300 includes miniaturized moiré metrology assemblies 301 for in-situ sub-3 nm (3s) precision real-time overlay metrology during bonding along with integrated high-density fine-grain thermal actuation modules.

[00104] Furthermore, W2W bonding equipment 300 includes a top transparent plate 302, which is similar to transparent backing plate 206 of system 200.

[00105] Furthermore, top wafer chuck 105 of W2W bonding equipment 300 may alternatively correspond to a carrier substrate.

[00106] Referring now to Figure 4, Figure 4 illustrates a second embodiment for W2W bonding equipment 400 in accordance with an embodiment of the present disclosure.

[00107] As shown in Figure 4, W2W bonding equipment 400 differs from W2W bonding equipment 300 by including an aqueous solution inkjetting module 401 with pL-precision.

[00108] In one embodiment, during bonding, liquid 402 is dispensed by module 401 onto top wafer 106 using an inkjetting-based approach. In one embodiment, top wafer 106 is brought into contact with the dispensed liquid 402 as shown by element 403 and in-liquid alignment is subsequently performed.

[00109] Furthermore, W2W bonding equipment 400 includes optional grooves 404 to improve liquid removal from bonding interface 108 prior to bonding.

[00110] Referring now to Figure 5, Figure 5 illustrates a third embodiment for W2W bonding equipment 500 in accordance with an embodiment of the present disclosure.

[00111] As shown in Figure 5, W2W bonding equipment 500 differs from W2W bonding equipment 400 by performing in-liquid alignment using a liquid layer 501 outside the wafer periphery.

[00112] Furthermore, the following published references are incorporated by reference herein in their entirety.

[00113] International Publication No. WO 2018/119451 entitled “Heterogeneous Integration of Components Onto Compact Devices Using Moiré Based Metrology and Vacuum Based Pick-and-Place,” is incorporated by reference herein in its entirety.

[00114] International Publication No. WO 2019/126769 entitled “Nanoscale-Aligned Three-Dimensional Stacked Integrated Circuit,” is incorporated by reference herein in its entirety.

[00115] International Publication No. WO 2020/051410 entitled “Nanofabrication and Design Techniques for 3D ICS and Configurable ASICS,” is incorporated by reference herein in its entirety.

[00116] International Publication No. WO 2022/212260 entitled “Processes and Applications for Catalyst Influenced Chemical Etching,” is incorporated by reference herein in its entirety.

[00117] International Publication No. WO 2023/056068 entitled “Tool and Processes for Pick-and-Place Assembly,” is incorporated by reference herein in its entirety.

[00118] International Publication No. WO 2023/164251 entitled “Programmable Precision Etching,” is incorporated by reference herein in its entirety.

[00119] The following are definitions of the terms that are used herein.

[00120] D2W: Die to Wafer

[00121] Multi D2W Bonding: D2W bonding, where more than one die is bonded onto a product substrate simultaneously or in short time intervals between each other (for instance, sub-1 second, sub-0.5, 0.2, 0.1, 0.05, 0.02, 0.01 second time intervals)

[00122] W2W: Wafer to Wafer

[00123] RW: Reconstituted Wafer, where a reconstituted wafer contains only known good dies that have been diced, picked and placed, and bonded onto a carrier.

[00124] HB: Hybrid Bonding

[00125] FB: Fusion Bonding

[00126] Bonding: A method for attaching a substrate (wafer, silicon wafer, SiC, GaAs, GaN on Si, GaN, GaSb, CdTe, polymeric substrate, a III-V substrate, glass, SiO₂, fused silica, a crystalline material, an amorphous material, tape, tape on frame, back-grinding tape), or a portion of a substrate (die, chip, chiplet, dielet), to a second substrate or a portion of a substrate, where the attachment could be performed using one or more of the following methods: Cu-Cu hybrid bonding, hybrid bonding, oxide-oxide fusion bonding, benzocyclobutene (BCB) based bonding, SU-8 based bonding, adhesive bonding (where the adhesive could be a UV-curable adhesive, a UV-release adhesive, a light-to-heat-conversion release coating (LTHC) adhesive, etc.), anodic

bonding, eutectic bonding, thermal compression bonding (TCB), C4 bump bonding, indium bump bonding, glass frit bonding, etc.

[00127] Substrate: A substrate could include a wafer or a portion of a wafer (die, chip, chiplet, dielet).

[00128] Source substrate: This is the substrate that is either directly bonded to a product substrate or is the source for dies that are subsequently bonded to the product substrate. In one embodiment, the substrate includes one or more of the following: a wafer, a silicon wafer, a reconstituted wafer, a wafer comprised of SiC, GaAs, GaN on Si, GaN, GaSb, or CdTe, a polymeric substrate, a III-V substrate, glass, SiO₂, fused silica, a crystalline material, an amorphous material, tape, tape on frame, back-grinding tape, dies on a carrier, where the carrier could be one or more of the following: a tape, a tape on a frame, a glass wafer, a silicon wafer, etc.

[00129] Product wafer: This is the substrate onto which bonding of a source substrate, or dies from a source substrate, is performed. In one embodiment, the product substrate after having undergone bonding, could be used to create system-in-packages (SiPs) of one or more of the following types: stacked logic, logic-on-memory stack, logic-on-SRAM stack, logic-on-DRAM stack, SRAM memory, DRAM memory, flash memory, high bandwidth memory (HBM), imagers, photonics devices, augmented reality devices, biomedical devices, quantum computing devices, thermal management devices, RF devices, power devices, which could further be utilized for applications including: high performance computing, consumer devices, mobile computing, edge computing, cloud AI, energy, defense, medicine, telecommunication, transport, automotive applications, etc.

[00130] Face-up orientation: This is the orientation in which the bonding surface of a substrate to be bonded (die or a wafer) faces away from the item in relation to which the face-up orientation is being defined (for instance, a carrier substrate or a product substrate). In one embodiment, said item could also be an equipment (for instance, a bonding equipment), in which case the face-up orientation is defined to be one where the bonding surface of the substrate of interest faces the upward direction.

[00131] Face-down orientation: This is the orientation in which the bonding surface of a substrate to be bonded (die or a wafer) faces towards the item in relation to which the face-down orientation is being defined (for instance, a carrier substrate or a product substrate). In one embodiment, the

item could also be an equipment (for instance, a bonding equipment), in which case the face-down orientation is defined to be one where the bonding surface of the substrate of interest faces the downward direction.

[00132] Chuck: This is a system for holding a substrate (a die or a wafer), against the forces of gravity and/or acceleration and/or internal stresses in a substrate that try to deform/warp it. Chucks can be fabricated out of one or more of the following materials: aluminum (with optionally a coating of alumina), steel, alumina (or sapphire), silicon carbide (which could be in amorphous, or crystalline form), polymers (such as polytetrafluoroethylene (PTFE), polycarbonate, Delrin, polyperfluoroalkoxyethylene (PFA), etc.). The chuck could additionally be used to maintain stability of a mechanical nature (against vibration, distortion, slippage) or thermal nature (against high temperature excursions, and localized temperature hot-spots). Chucks can maintain contact with the chucked substrate using one or more of the following mechanisms: vacuum, electrostatic, electromagnetic, and mechanical clamping.

[00133] Referring now to Figure 6, Figure 6 illustrates an equipment architecture 600 for D2W hybrid bonding in accordance with an embodiment of the present disclosure.

[00134] As shown in Figure 6, equipment architecture 600 includes a base 601, XY motion stage 602 for product wafer 618 (shown in a non-bonding position), a chuck 603 for product wafer 618, a mechanically-stable bridge 604, mini environment and mechanism 605 for evaporation control, dispenser 606 for dispensing fluid for in-liquid alignment, bonded dies 607, precision alignment metrology 608, a bond head 609 (contains die chuck), a die path 610 (pickup from die carrier 613, transfer to bond head 609, and lastly bonding onto product substrate 618), a die ejection mechanism 611, a die carrier chuck 612 (also referred to herein as die chuck 612), a die carrier 613, dies 614, a chuck 615 for die transfer, a die transfer mechanism 616, a motion stage 617 for die transfer mechanism 616, and product substrate (also referred to as a product wafer) 618.

[00135] Referring to Figure 6, in one embodiment, dies 614 are brought-in into the equipment mounted on one or more of the following source substrates (or alternatively referred to as a carrier substrate, such as die carrier 613): tape frame (metal or plastic annular frame with a thin polymeric film supported near its edges by said frame), glass wafer, and silicon wafer. Dies 614 could be on the source substrate at a SiP pitch (which is the pitch, in the X and/or Y directions, of the SiPs

defined on the product wafer), such that they are picked and placed on to a set of bond heads 609, which are also at a SiP pitch, without any pitch reconfiguration.

[00136] The dies (e.g., dies 614) on the carrier substrate (e.g., die carrier 613) could be mounted “face-up,” or “face-down.”

[00137] In one embodiment, the carrier substrate (e.g., die carrier 613) is mounted face-down, or face-up in the equipment. Figure 6 describes a face-down carrier substrate architecture. In the face up architecture, a flipper mechanism would flip dies 614 onto bond head 609.

[00138] In one embodiment, the bond-head assembly is comprised of one or more bond heads 609, each of which handles a single die 614, and bonds said die 614 to a prespecified position on product wafer 618. In the case in which the bond head assembly has multiple bond heads 609, each bond head 609 could be used to independently and in-parallel bond dies 614 to product substrate 618. Furthermore, each bond head 609 could have actuation mechanisms to move die 614 in one or more of the X, Y, Z, θ_x , θ_y , and θ_z axes in an active or passive manner.

[00139] In one embodiment, alignment metrology modules are used to monitor and/or provide feedback regarding die-to-substrate misalignment during bonding in-situ, and optionally in real-time.

[00140] In one embodiment, equipment 600 includes distortion control mechanisms for die 614 and/or product substrate 618, including: thermal actuators, thermoelectric cooler based thermal actuators, global thermal actuators, local thermal actuators, fluidic thermal actuators, microchannel based thermal actuators, light based thermal actuators (where the light could be in the visible, ultraviolet (UV), infrared, short-wave infrared spectrums, etc.), actuators that enable distortion control by direct application of contact forces using piezoelectric, pneumatic, thermal electromagnetic, and/or electrostatic actuators.

[00141] The following outlines a system for die release from carrier substrates, including, but not limited to tape frames, silicon, glass, and polymeric (polycarbonate, for instance) wafers/substrates. The system incorporates one or more of the following sub-systems: carrier substrate chucking and orientation, carrier substrate rotation, and die release.

[00142] In one embodiment, carrier substrate chucking includes vacuum, electromagnets, or clamps to secure the carrier substrate on the chuck. In one embodiment, the chuck is on a z

translation, tip, and tilt stage to allow the carrier substrate to align with the die release and die pick-up mechanisms. In one embodiment, the system integrates flexures to allow for tip and tilt along desired axes while providing needed stiffness in other degrees of freedom as shown in Figures 7A and 7B.

[00143] Figure 7A illustrates a side view of the carrier substrate chucking system 700 in accordance with an embodiment of the present disclosure.

[00144] As shown in Figure 7A, carrier substrate chucking system 700 includes a chuck and carrier substrate 701 (combination of chuck 612 and carrier substrate 613) along with flexures 702 and z actuators 703.

[00145] In one embodiment, the carrier substrate is mounted upside down on a chuck and actuatable in the z-tip-tilt directions.

[00146] Figure 7B illustrates a top view of the carrier substrate chucking system 700 in accordance with an embodiment of the present disclosure.

[00147] In one embodiment, the surface of the chuck has a depression that the carrier substrate lies on, to allow for reduced required z-travel of the die pick-up mechanism as shown in Figure 8.

[00148] Figure 8 illustrates a cross-sectional view of the indent of chuck 612 for carrier substrate 613 in accordance with an embodiment of the present disclosure.

[00149] In one embodiment, chuck 612 includes slots to accommodate an equipment front end module (EFEM) end effector to allow carrier substrate 613 to be released closer or directly at the chucking surface as shown in Figure 9.

[00150] Figure 9 illustrates the slots 901 for an EFEM end effector on a potential configuration for the chuck in accordance with an embodiment of the present disclosure.

[00151] Furthermore, Figure 9 illustrates an exemplary positioning of carrier substrate 613 along with an indented surface 902 on chuck 612.

[00152] Chuck 612 could be of various shapes and form factors, including, but not limited to, circular, oval, rectangular, triangular, and a combination of the foregoing. Limit switches, other motion limiting systems, or sensors (ex: proximity sensors), could be utilized to prevent collision of the die pick-up system with the carrier substrate chuck.

[00153] In one embodiment, carrier substrate rotation is used to make die pick-up more space efficient, where a limited motion range die pickup system picks up a portion of dies 614 on carrier substrate 613 in a first orientation (for instance, greater than half of the dies, or a third, or a quarter, or a fifth), and a carrier substrate rotation is subsequently performed to move carrier substrate 613 to a second orientation (for instance, 90 degrees rotated from the first orientation, or 60 degrees, or 45, 30, 15, etc.) bringing new dies 614 in the regions where the die pickup system can reach. In one embodiment, a rotation stage is integrated into the carrier substrate chucking system or it could be a separate system. In one embodiment, rotation occurs at multiples of 90 degrees, 45 degrees, 22.5 degrees, or lower.

[00154] Referring now to Figure 10, Figure 10 illustrates a side view of an exemplary pick-down configuration 1000 for die release in accordance with an embodiment of the present disclosure.

[00155] As shown in Figure 10, pick-down configuration 1000 includes a gantry 1001 (meticulously designed to minimize vibrations, thermal expansions, and other disturbances, ensuring that movements are consistent to the scale of micrometers or even nanometers), x stages 1002, a y stage 1003, a die release system 1004, a chucked carrier substrate 612, and a die pick-up system 1005.

[00156] Referring now to Figure 11, Figure 11 illustrates a side view of an exemplary pick-up configuration 1100 for die release in accordance with an embodiment of the present disclosure.

[00157] Referring to Figures 10 and 11, in one embodiment, the die release system has X, Y, Z, and theta degrees of freedom. In one embodiment, the mechanism is mounted on a bridge or gantry system (e.g., gantry 1001) allowing the die (e.g., die 614 of Figure 6) to get released and picked down, or in a flipped configuration to allow the die (e.g., die 614) to get picked up. Both of these methods can be seen in Figures 10 and 11.

[00158] In one embodiment, the die release mechanism is based on incident light (for instance, laser based release, or UV light based release), or pin push mechanism(s). In one embodiment, limit switches, other limiting systems, or sensors (ex: proximity sensors), are used to prevent collision along X, Y, and Z axes with systems, such as the carrier substrate chuck (e.g., chuck 612). In one embodiment, the carrier substrate chuck (e.g., chuck 612) is designed with rectilinear edges (in contrast to curved edges) in a manner that only two sets of limit switches, corresponding to the X and Y axes, are required to eliminate collision risk.

[00159] Die release through UV light could be implemented in several ways. For example, one or multiple fiber optic guided UV lights could be routed through the die release system to end behind the die at an optimal working distance to allow the light to disperse over a desired area with a desired intensity and uniformity as shown in Figure 12.

[00160] Figure 12 illustrates fiber optic guided (UV) light incident on die 614 in accordance with an embodiment of the present disclosure.

[00161] As shown in Figure 12, UV light 1201 is guided via an optical fiber 1202 to be incident on die 614, which is on carrier substrate 613 that is not shown in Figure 12. Furthermore, Figure 12 illustrates the various dimensions, such as the bend radius (R_b) of optical fiber 1202, the distance (L) between die 614 and when UV light 1201 exits optical fiber 1202, the diameter D_0 of optical fiber 1202 as well as the angle, θ , that extends from the outer width of UV light 1201 to the diameter of optical fiber 1202.

[00162] In one embodiment, the fiber optic guided UV light could also be directed to the back of the die (e.g., die 614) using flat or curved mirrors to achieve a desired irradiated area, intensity, and uniformity, such as seen in Figure 13.

[00163] Figure 13 illustrates mirror guided UV light 1201 incident on die 614 in accordance with an embodiment of the present disclosure.

[00164] As shown in Figure 13, UV light 1201 is guided to be incident on die 614 using mirror 1301.

[00165] Condensers, collimators, or lenses could be used with a fiber optic guided UV light source and potentially mirrors (e.g., mirrors 1301), to direct the light (e.g., UV light 1201) directly behind the die (e.g., die 614) over a desired area with a desired intensity and uniformity as shown in Figure 14. Alternatively, a UV light emitting diode (LED) light source may be used instead, which could be positioned in close proximity to the die release location, and where light guiding could be free-space propagation along with one or more flat or curved mirrors and/or lenses.

[00166] Referring to Figure 14, Figure 14 illustrates mirror guided UV light 1201 to be incident on die 614 with intermittent condenser, collimator, or lens units for collimating the incident light on die 614 in accordance with an embodiment of the present disclosure.

[00167] As shown in Figure 14, a condenser, collimator or lens 1401 is used to collimate fiber optic guided UV light 1201 (P_1) to be incident (see P_2) on die 614 via mirror 1301.

[00168] The following discusses the die pick and transfer system.

[00169] This system comprises of mechanisms that allow precise pickup of one or more dies 614 from the source substrate (e.g., carrier substrate 613) and transfer/placement of said one or more dies 614 to corresponding locations on one or more bond-heads 609, or alternatively one or more locations on a substrate or wafer.

[00170] In one embodiment, the die pick and transfer system includes a base 601 (single or more than single bases) that moves on its own (in one or more of X, Y, Z, θ_x , θ_y , and θ_z axes) using suitable actuators or motion stages; or alternatively, is parasitic to another system (for instance, the product wafer motion stage) while being supported by some type of bearings in the non-actuated axes (for instance, air bearings). An example motion specification for said system is X and/or Y direction travel of 300 mm in less than or equal to 1 second, 0.5, 0.2, 0.1, 0.05, 0.02, 0.01 seconds (where the X direction is the direction along which the separation between the source substrate chucking location and the bond head assembly are the longest). Suitable bearing methods are utilized (for instance, vacuum pre-loaded air bearings) to counter unwanted vibrations during the previously mentioned motion. Another example motion specification is X and/or Y direction motion precision (repeatability and/or stability) of less than 25 μm , 10 μm , 5 μm , 2 μm , 1 μm , 500 nm, 200 nm, 100 nm, 50 nm, 20 nm, and 10 nm.

[00171] Furthermore, in one embodiment, the die pick and transfer system includes one or more chucks to hold dies 614 during pickup and transfer/placement. In one embodiment, the chuck is placed on a rotary stage, which could have a precision of less than one or 0.1 milliradians, or 50 microradians, or 20 microradians. In one embodiment, the chuck is placed on a flexure-based actuation stage that can move up and down and has tip-tilt capabilities.

[00172] Thus, the system would have the capability of moving and aligning in all 6 degrees of freedom.

[00173] Additionally, in one embodiment, the chuck picks up the die (e.g., die 614) through vacuum or electrostatic. The die would be chucked with minimal contact or no contact at all (e.g., Bernoulli's chuck, electromagnetic levitation, electrostatic levitation, etc.).

[00174] In one embodiment, the chuck is designed such that it is easily interchangeable for a different chuck. This could be enabled by having a secondary chucking surface for the primary chuck. The secondary chucking surface could release the primary chuck, which could subsequently be replaced with a second chuck using a robot manipulator, or a separate dedicated chuck swapping mechanism.

[00175] In one embodiment, the system has sensors, such as a laser displacement sensor, an air gauge, an optical camera system, a microscope lens or a combination of the sensors listed above to determine the location/orientation of the picked substrate (die or wafer) or wafer in one or more of the following directions: X, Y, Z, roll, pitch, and yaw directions.

[00176] In one embodiment, laser displacement or an air gauge sensor is used to determine the height at which the die (e.g., die 614) or substrate would be located. In one embodiment, the tip-tilt location of the die (e.g., die 614) is also determined using one or more of these sensors.

[00177] Additionally, in one embodiment, the die pick and transfer system includes an optical system, such as a microscopic lens or telecentric lens with sufficient magnification capability that would be able to determine the X, Y and θ_z location of the die (e.g., die 614) by looking at fiducial markers present on the substrate (die or wafer).

[00178] In one embodiment, the die pick and transfer system creates a mini environment (e.g., mini environment 605) to facilitate proper conditions required to pick up the die. In one embodiment, the environment required to pick up the die is made inert or devoid of oxygen and water vapor by supplying nitrogen or other inert gas. This is to address the challenge of oxygen poisoning that can prevent effective release of the adhesive layer that attaches the die (e.g., die 614) to the carrier substrate (e.g., carrier substrate 613).

[00179] Referring now to Figure 15, Figure 15 illustrates a first embodiment for the die pickup and transfer system 1500 in accordance with an embodiment of the present disclosure.

[00180] As shown in Figure 15, die pickup and transfer system 1500 includes X-Y stage 602, bearings 1501, an optical system 1502, a z-tip-tilt stage 1503, a rotation stage 1504, a z-actuator 703, a gas outlet 1505 for a suitable environment, inert gas which creates an inert mini-environment 1506 around a die during pickup, chuck 612, substrate 613, and a height sensor 1507.

[00181] Referring now to Figure 16, Figure 16 illustrates a second embodiment for the die pickup and transfer system 1600 in accordance with an embodiment of the present disclosure

[00182] As shown in Figure 16, die pickup and transfer system 1600 enables substrate 613 to be fixed in the air using electrostatic or Bernoulli's effect as shown by element 1601.

[00183] Referring now to Figure 17, Figure 17 illustrates a third embodiment for the die pickup and transfer system 1700 in accordance with an embodiment of the present disclosure

[00184] The following discusses the testing system for bonding.

[00185] Referring now to Figure 18, Figure 18 illustrates an example testing system 1800 for bonding in accordance with an embodiment of the present disclosure.

[00186] As shown in Figure 18, testing system 1800 includes a multi-axis movement stage 1801, a die picking mechanism 1802, a die holding mechanism 1803, and an environmental control device 1804.

[00187] In one embodiment, system 1800 is a multi-purpose platform that allows the testing, verification, and validation of high precision die and wafer handling equipment. The assembly will be able to measure alignment, and bonding/delamination/debonding behavior of the assemblies or components simultaneously or respectively.

[00188] In one embodiment, multi-axis movement stage 1801 is a set of motion stages, either powered or manual, aligned either in series or in parallel, that allows up to 6 degrees of freedom (DoF) movement over a range of up to 300 mm for prismatic joints or up to 360 degrees for rotational joints. This allows die picking mechanism 1802 and die holding mechanism 1803 to move synchronously or independently with the intention of maintaining alignment between specific points on die picking mechanism 1802 and die holding mechanism 1803, respectively. This alignment is detected and confirmed with one, two, or three oblique cameras and associated optical assemblies that allow perpendicular imaging at the interface of die picking mechanism 1802 and die holding mechanism 1803.

[00189] In one embodiment, die picking mechanism 1802 is a mechanism that, through the use of series motors, parallel motors, or flexures, moves a picking device with up to 5 DoF and a range of 10 mm for prismatic joints or 360 degrees for rotational joints. The picking device can manipulate dies, wafers, and/or tape frames using contact methods, such as mechanical clamping

or vacuum, or non-contact methods, such as Bernoulli or electrostatic chucking. These picking devices are easily interchangeable and can be a wide variety of sizes and materials, such as aluminum, steel, sapphire, silicon carbide, or similar, to accommodate dies, wafers, or tape frames of any commercially available or custom size less than or equal to 400 mm in diameter. In one embodiment, die picking mechanism 1802 is also instrumented in each DoF to determine displacement and force applied in each direction.

[00190] In one embodiment, die holding mechanism 1803 is a device that supports and positions dies, wafers, and/or tape frames of any commercially available or custom size less than or equal to 400 mm in diameter. In one embodiment, die holding mechanism 1803 uses any of the contact or non-contact methods described for die picking mechanism 1802. Further, the dies, wafers, and/or tape frames may be loaded or unloaded from die holding mechanism 1803 either by hand or using a robotic device colloquially known as an EFEM.

[00191] In one embodiment, environmental control device 1804 is a device that controls the environment around the previous 3 components. In one embodiment, environmental control device 1804 manages the temperature and/or humidity by using any combination of nitrogen, clean dry air, or full control feedback.

[00192] The following is a discussion regarding bond heads 609 and die chucks (e.g., die carrier chucks 612).

[00193] Referring to Figure 19A, Figure 19A illustrates the undeformed configuration of a deformable die chuck (e.g., die carrier chuck 612) in accordance with an embodiment of the present disclosure.

[00194] As shown in Figure 19A, in the undeformed configuration, there are vacuum vias 1901 leading to pneumatic connectors 1902, that joins vacuum vias 1901 to a vacuum generator 1903 in a pressurized, dry-air system.

[00195] Furthermore, as illustrated in Figure 19A, there is a pressure zone 1904 connected to a pressure regulator 1905 via pneumatic connector 1906.

[00196] Additionally, as illustrated in Figure 19A, die chuck (e.g., die carrier chuck 612) is connected to die 614 via pin 1907.

[00197] Referring now to Figure 19B, Figure 19B illustrates the deformed configuration of a deformable die chuck (e.g., die carrier chuck 612) in accordance with an embodiment of the present disclosure.

[00198] As shown in Figure 19B, the pressure in pressure zone 1904 exceeds the atmospheric pressure (see element 1908) thereby deforming die chuck 612.

[00199] A die chuck, such as die chuck 612, is an apparatus which is used to hold a die (e.g., die 614). In one embodiment, the dimensions of die 614 can vary from 300 x 300 x 1 mm to 10 x 10 x 0.05 mm. In one embodiment, the die chuck (e.g., die chuck 612) consists of several cylindrical protrusions referred to as pins 1907. In one embodiment, the die (e.g., die 614) rests on these pins 1907.

[00200] In one embodiment, the air between the surface of die chuck (e.g., die chuck 612) and the die (e.g., die 614) is removed by vacuum generator 1903 via vacuum vias 1901 resulting in the atmospheric pressure applying a force on the surface of the die (e.g., die 614) and holding it against pins 1907.

[00201] In one embodiment, the die chuck (e.g., die chuck 612) has a cored-out portion in its center referred to as pressure zone (e.g., pressure zone 1904). In one embodiment, pressure zone 1904 is pressurized via pressure regulator 1905. In one embodiment, pressure zone 1904 applies force on a portion of the die chuck (e.g., die chuck 612) resulting its deformation. The deformation of the die chuck (e.g., die chuck 612) leads to the deformation of the die (e.g., die 614).

[00202] Figure 20 illustrates an alternative embodiment of a deformable die chuck in accordance with an embodiment of the present disclosure.

[00203] As shown in Figure 20, deformable die chuck (e.g., die chuck 612) is made up of two parts, part 1 2001, and part 2 2002.

[00204] In one embodiment, parts 1 and 2 (2001, 2002) are fabricated from metals, such as aluminum, steel, titanium, etc. or ceramics, such as silicon carbide, sapphire, fused silica, etc.

[00205] In one embodiment, parts 1 and 2 (2001, 2002) are joined rigidly using bolts and nuts, rivets, adhesives, or using other joining methods.

[00206] In one embodiment, part 1 2001 consists of pressure zone 1904, vacuum vias 1901 and pins 1907.

[00207] In one embodiment, the purpose of part 2 2002 is to route the pressure and vacuum from pneumatic connectors 1902 to pressure zone 1904 and die 614 in part 1 2001.

[00208] Referring now to Figure 21, Figure 21 illustrates a further embodiment of a deformable die chuck in accordance with an embodiment of the present disclosure.

[00209] As shown in Figure 21, the embodiment of the deformable die chuck (e.g., die chuck 612) shown in Figure 21 is the same as the embodiment of the deformable die chuck (e.g., die chuck 612) shown in Figure 20 except that parts 1 and 2 (2001, 2002) are rigidly joined via vacuum force.

[00210] In one embodiment, parts 1 and 2 (2001, 2002) are rigidly joined via vacuum force by creating an annular groove in part 2 2002. The annular groove in part 2 2002 along with part 1 2001 forms a vacuum pocket 2101.

[00211] In one embodiment, vacuum pocket 2101 is attached to vacuum generator 1903 which creates a vacuum in vacuum pocket 2101. Due to the formation of this vacuum, the atmosphere pushes part 1 2001 and part 2 2002 against each other thereby rigidly joining them. This is the same method used to rigidly join die 614 to pins 1907 discussed above in connection with Figures 19A-19B. This is referred to herein as “vacuum chucking.”

[00212] Referring now to Figure 22, Figure 22 illustrates a fourth embodiment of the deformable die chuck in accordance with an embodiment of the present disclosure.

[00213] In the fourth embodiment, the deformable die chuck (e.g., die chuck 612) is made up of 4 parts, parts 1 and 2 (2001, 2002), part 3 2201, and part 4 2202.

[00214] In one embodiment, part 4 2202 is fabricated from any metal and has a thru hole in its center to allow infrared light to pass through. In one embodiment, pneumatic connectors 1902 are joined to part 1 2001 via bolted joint, adhesive etc.

[00215] In one embodiment, parts 1, 2 and 3 (2001, 2002, and 2201) are fabricated from any material that is transparent to infrared light, such as silicon carbide, sapphire, etc.

[00216] In one embodiment, the purpose of parts 2 and 3 (2002, 2201) is to route the vacuum and pressure from vacuum generator 1903 and pressure regulator 1905, respectively, to die 614 and pressure zone 1904 in part 1 2001. In one embodiment, such routing of the vacuum and pressure in the manner discussed above is achieved by machining grooves in parts 2 and 3 (2002, 2201).

[00217] In one embodiment, parts 1, 2, 3, and 4 (2001, 2002, 2201, and 2202) are rigidly joined to each other by any joining method which also includes “vacuum chucking” discussed above.

[00218] Referring now to Figures 23A-23B, Figures 23A-23B illustrate a fifth embodiment of the deformable die chuck in accordance with an embodiment of the present disclosure. In particular, Figure 23A illustrates the undeformed configuration of the deformable die chuck (e.g., die chuck 612); whereas, Figure 23B illustrates the deformed configuration of the deformable die chuck (e.g., die chuck 612).

[00219] In the embodiment shown in Figures 23A-23B, pressure is not used to deform the chuck (e.g., die chuck 612). Instead, vacuum is used to deform the chuck (e.g., die chuck 612) and therefore the die (e.g., die 614) as shown in Figure 23B.

[00220] In one embodiment, vacuum pocket 1 (element 2301), which is similar to vacuum pocket 2101, is connected to vacuum generator 1903 and creates a vacuum between part 1 2001 and part 2 2002. This leads to the rigid attachment of part 1 2001 and part 2 2002. This is referred to as “vacuum chucking” as discussed above. It is noted that parts 1 and 2 (2001, 2002) can be attached via other techniques, such as using nuts and bolts, adhesive etc.

[00221] In one embodiment, vacuum pocket 2 (element 2302), which is similar to vacuum pocket 2101, creates a vacuum between part 1 2001 and part 2 2002. As a result, the atmospheric pressure pushes part 1 2001 towards part 2 2002. However, since part 1 2001 is thin at this location it deforms (bends) towards part 2 2002 as shown in Figure 23B. As a result, the middle section of part 1 2001 deforms (bends) away from part 2 2002.

[00222] In one embodiment, the deformation of the middle portion of part 1 2001 leads to the deformation of the die (e.g., die 614) as shown in Figure 23B. Vacuum via 1901 in part 1 2001 creates a vacuum between part 1 2001 and the die (e.g., die 614), which leads to “vacuum chucking” of the die (e.g., die 614) with respect to part 1 2001.

[00223] Furthermore, Figure 23A illustrates an annular hole 2303 created from parts 1 and 2 (2001, 2002) being rigidly joined via vacuum force.

[00224] Referring now to Figure 24A, Figure 24A illustrates an air-bearing based short-stroke motion stage 2400 for a multi-die bond head (e.g., bond head 609) in accordance with an

embodiment of the present disclosure. Figure 24B illustrates a cross-section of an air bearing module of Figure 24A in accordance with an embodiment of the present disclosure.

[00225] As illustrated in Figure 24A, air-bearing based short-stroke motion stage 2400 includes an XY motion stage 2401, an electromagnetic (EM) actuator mover 2402, an EM actuator stator 2403, air bearing surfaces 2404, an air bearing module 2405, and ground 2406. In one embodiment, air bearing based XY motion stage 2401 is made up of four identical air bearing modules 2405.

[00226] In one embodiment, each air bearing module 2405, the cross-section of which is depicted in Figure 24B, includes two parts: ground 2406 and EM actuator mover 2402. Ground 2406 is a solid rectangular part whose four surfaces are machined to act as ground air bearing surface 2407. In one embodiment, ground air bearing surfaces 2407 are porous, orifice type, groove type or a combination of these.

[00227] In one embodiment, EM actuator mover 2402 is an annular rectangular part whose inner four surfaces are machined to act as mover air bearing surfaces 2408 as illustrated in Figure 24B. Figure 24B further illustrates the fly height (gap between ground air bearing surface 2407 and moving air bearing surface 2408) 2409.

[00228] As a result of the foregoing, process control techniques have been developed for wafer-to-wafer bonding with high bonding yield.

[00229] The descriptions of the various embodiments of the present disclosure have been presented for purposes of illustration, but are not intended to be exhaustive or limited to the embodiments disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the described embodiments. The terminology used herein was chosen to best explain the principles of the embodiments, the practical application or technical improvement over technologies found in the marketplace, or to enable others of ordinary skill in the art to understand the embodiments disclosed herein.

CLAIMS:

- 1 1. A method for bonding two wafers, the method comprising:
2 dispensing droplets of interfacial liquid at pre-specified locations on a first bonding surface
3 of a first wafer or on a second bonding surface of a second wafer, wherein said first bonding surface
4 of said first wafer is facing a first direction, wherein said second bonding surface of said second
5 wafer is facing a direction opposite of said first direction;
6 bringing said first wafer and said second wafer together so that both said first wafer and
7 said second wafer contact said interfacial liquid;
8 performing an overlay error correction between said first and second wafers with said
9 interfacial liquid between said first and second wafers; and
10 removing said interfacial liquid using evaporation thereby creating a bonding between said
11 first and second wafers.
- 1 2. The method as recited in claim 1, wherein an interconnect pitch at an interface between
2 said first and second bonding surfaces is one of the following: sub-50 nm, sub-100 nm, sub-250
3 nm, sub-500 nm, sub-1 μm , sub-2 μm , sub-5 μm , and sub-10 μm .
- 1 3. The method as recited in claim 1, wherein a post-bonding overlay precision is one of the
2 following: sub-5 nm, sub-10 nm, sub-25 nm, sub-50 nm, sub-100 nm, sub-200 nm, sub-500 nm,
3 and sub-1 μm overlay precision.
- 1 4. The method as recited in claim 1, wherein said interfacial liquid comprises one or more of
2 the following: an aqueous solution, a hydroxyl group containing material, an alcohol, isopropyl
3 alcohol, an acid, a base, water, citric acid, an adhesive, a silsesquioxane, acetone, methanol,
4 ethanol, and a mixture comprising one or more of the foregoing.
- 1 5. The method as recited in claim 1, wherein said bonding comprises one or more of the
2 following: direct bonding, SiO_2 - SiO_2 bonding, covalent bonding, fusion bonding, hybrid bonding,
3 adhesive bonding, self-assembly, temporary bonding, and permanent bonding.
- 1 6. The method as recited in claim 1 further comprising:

2 dispensing said interfacial liquid to a larger height at an edge of one of said first and second
3 bonding surfaces, and to a lower height away from said edge of said one of said first and second
4 bonding surfaces.

1 7. The method as recited in claim 1 further comprising:
2 dispensing said interfacial liquid at an edge of grooves or at an edge of holes at one of said
3 first and second bonding surfaces.