

AREA-SPECIFIC CLEANING METHODS FOR BONDING APPLICATIONS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application Serial No. 63/470,673 entitled “Area-Specific Cleaning Methods for Bonding Applications,” filed on June 2, 2023, which is incorporated by reference herein in its entirety.

TECHNICAL FIELD

[0002] The present disclosure relates generally to wafer bonding, and more particularly to area-specific cleaning methods for bonding applications.

BACKGROUND

[0003] Since its inception over three decades ago, wafer bonding has been an important technique for material and microsystem integration. Many wafer bonding methods have been developed over the years enabling a wide range of semiconductor applications, such as the formation of silicon on insulator (SOI) wafers. In recent years, the importance of wafer bonding has also been realized in the development of multi-layered micro/nano electromechanical systems (MEMS/NEMS) and three-dimensional integrated circuits (3D IC) integration aiming at creating more compact and complex systems with improved functionality. This enables semiconductor devices to be fabricated separately and bonded together at a later stage and therefore provides more freedom in design and allows more advanced semiconductor systems to be fabricated. Wafer bonding has been identified as a promising technique to enable 3D IC which features in the International Technology Roadmap for Semiconductors (ITRS). However, with line widths in CMOS (complementary metal-oxide semiconductor) manufacture already below 100 nm and the shrinkage of electromechanical systems into the nanometer range, the lack of effective techniques for achieving bonding alignment with sub-micrometer precision has become a critical stumbling block hindering device realization in many fields where super accurate bonding alignment is required.

[0004] Optical alignment is by far the most commonly used method to achieve bonding alignment. This is achieved by positioning one wafer with respect to another and aligning them using alignment marks observed through optical objectives. A variety of optical methods have been implemented so far; however, alignment accuracy of 1 μm at best is obtained due to the large

optical structural loop. Although 0.5–1 μm alignment has been claimed, complicated and expensive optical machines are required to guarantee micrometer-range results. Such techniques are fundamentally limited by the wavelength of light and practically limited by the mechanical positioning systems required to match the two wafers.

[0005] Recently a mechanical passive wafer alignment method has been reported exploiting kinematic and elastic averaging. However, the alignment accuracy was obtained by optically observing the alignment marks located on the nonbonded sides of the wafer pair. This inevitably introduced optical and double-side alignment errors during the fabrication of the alignment marks, which could be well above 1 μm , and thus they were not able to assess the actual alignment accuracy at the bonded interface. Furthermore, wafer bonding was not achieved in this case due to the roughening of the bonding surface introduced by the fabrication processes.

[0006] Hence, there is not currently a means for effectively achieving nano-precision alignment accuracy for wafer bonding.

SUMMARY

[0007] In one embodiment of the present disclosure, a method for bonding with precision alignment comprises dispensing droplets of volatile liquid at pre-specified locations on a first bonding surface or a second bonding surface, where the precision alignment is enabled by lubricated relative motion due to the volatile liquid being deployed between the first and second bonding surfaces. A first portion of the droplets of the volatile liquid is dispensed at a center of the first bonding surface or the second bonding surface, and a second portion of the droplets of the volatile liquid is dispensed at an edge of one or more of the first bonding surface and the second bonding surface, where the second portion of the droplets of the volatile liquid is greater than the first portion of the droplets of the volatile liquid. Furthermore, the first and second portions of the droplets of the volatile liquid enable bowing of the first bonding surface with respect to the second bonding surface such that evaporation of the droplets of volatile liquid causes a center of the first and second bonding surfaces to make contact with each other.

[0008] In another embodiment of the present disclosure, a method for bonding with precision alignment comprises dispensing droplets of a volatile fluid at pre-specified locations on a first bonding surface or a second bonding surface, where the precision alignment is enabled by lubricated relative motion due to the volatile fluid being deployed between the first bonding surface and the second bonding surface. The volatile droplets are maintained in a first environment during the dispensing of the droplets, the volatile droplets are maintained in a second environment during performance of the lubricated relative motion, and the volatile droplets are maintained in a third environment during contact initiation with one or more of the first and second bonding surfaces and subsequent bonding.

[0009] 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

[0010] 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:

[0011] Figures 1A-1B illustrate lubricating fluid films at the bonding interface in accordance with an embodiment of the present disclosure; and

[0012] Figure 2 illustrates the shroud concept for management of interfacial liquid evaporation prior to bonding in accordance with an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0013] As stated above, since its inception over three decades ago, wafer bonding has been an important technique for material and microsystem integration. Many wafer bonding methods have been developed over the years enabling a wide range of semiconductor applications, such as the formation of silicon on insulator (SOI) wafers. In recent years, the importance of wafer bonding has also been realized in the development of multi-layered micro/nano electromechanical systems (MEMS/NEMS) and three-dimensional integrated circuits (3D IC) integration aiming at creating more compact and complex systems with improved functionality. This enables semiconductor devices to be fabricated separately and bonded together at a later stage and therefore provides more freedom in design and allows more advanced semiconductor systems to be fabricated. Wafer bonding has been identified as a promising technique to enable 3D IC which features in the International Technology Roadmap for Semiconductors (ITRS). However, with line widths in CMOS (complementary metal-oxide semiconductor) manufacture already below 100 nm and the shrinkage of electromechanical systems into the nanometer range, the lack of effective techniques for achieving bonding alignment with sub-micrometer precision has become a critical stumbling block hindering device realization in many fields where super accurate bonding alignment is required.

[0014] Hence, there is not currently a means for effectively achieving nano-precision alignment accuracy for wafer bonding.

[0015] As discussed herein, the principles of the present disclosure provide an effective means for achieving nano-precision alignment accuracy for wafer bonding.

[0016] The following published international patent applications are incorporated by reference herein in their entirety.

[0017] 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.

[0018] International Publication No. WO 2019/126769 entitled “Nanoscale-Aligned Three-Dimensional Stacked Integrated Circuit,” is incorporated by reference herein in its entirety.

[0019] 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.

[0020] International Publication No. WO 2022/212260 entitled “Processes and Applications for Catalyst Influenced Chemical Etching,” is incorporated by reference herein in its entirety.

[0021] Bonding is a process for temporary or permanent attachment of one die/substrate to another die/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, 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 $x \geq 0$, $y \geq 0$, $z \geq 0$). In one embodiment, the bonding is performed in one of the following manners: a face-to-face, a face-to-back, a back-to-face, and a back-to-back manner. A pre-bonding plasma activation step could optionally be used. In one embodiment, said plasma activation is performed using plasma including one or more of the following components: Ar, He, hydrogen, nitrogen, oxygen, chlorine, chlorine containing components, fluorine, fluorine containing components, fluoropolymers, organic compounds, methane, ammonia, etc. In one embodiment, a pre-bonding cleaning step is utilized, where the cleaning step is a wet clean, a dry clean, a clean using water, an aqueous solution, acids, citric acid, organic acids, etc. In one embodiment, a pre-bonding hydration step is utilized, where the hydration step includes dispensing water, an aqueous solution, acids, citric acid, organic acids, acetone, ketone, methanol, ethanol, isopropyl alcohol, an alcohol, a liquid with a low vapor pressure (for instance, 1/2, 1/5, 1/10, 1/50 of the vapor pressure of water), or a combination of the prior liquids. In one embodiment, the prior hydration step is also performed using a liquid mixture comprised of miscible components chosen from water, an aqueous solution, acids, citric acid, organic acids, acetone, ketone, methanol, ethanol, isopropyl alcohol, an alcohol, a liquid with a low vapor pressure (for instance, 1/2, 1/5, 1/10, 1/50 of the vapor pressure of water), etc. In one embodiment, the dispensing of the liquids utilized in the cleaning and/or the hydration steps is performed in one or more of the following ways: inkjetting, spin-coating, drop casting, slot die coating. In one embodiment, the fluid

dispensed for the cleaning and/or hydration steps has a thickness that is one of the following (in one or more of the locations that said fluid is dispensed in): 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.

[0022] In one embodiment, the fluid dispensed for the cleaning and/or hydration steps is dispensed in a uniform manner or a non-uniform manner (for instance, increasing thickness in a radial direction and constant thickness in a circumferential direction). In one embodiment, said non-uniform dispensing is performed using an inkjet, for instance, and could be utilized to help bow the die, for instance. Alternatively, said non-uniform dispensing is also used to provide dynamic control of in-liquid align to achieve zero residual layer thickness of said fluid. In one embodiment, the rate of evaporation of the dispensed fluids at the bonding interface is modulated (for instance, to retain a pre-specified distribution and amount of fluid at the interface during the bonding step) using one or more of the following factors: local/global air pressure, air flow in the vicinity of the bonding interface, additives in the dispensed fluid (which work to increase or decrease the rate of fluid evaporation), and initial volume and distribution of the dispensed fluid. Alternatively, to retain a pre-specified distribution and amount of fluid at the interface during the bonding step, an evaporation model is incorporated in the fluid dispensing scheme and an evaporation-compensated amount of dispensing is performed (for instance, using inkjetting-based techniques). In one embodiment, the measurement of the evaporation characteristics of the tool for a specific wafer and interfacial liquid is performed on a test wafer using one or more microscope assemblies.

[0023] In one embodiment, one or more of the fluids utilized in the cleaning and/or hydration steps are used to enable lubrication between the two surfaces being bonded immediately prior to said bonding. In one embodiment, said 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 is 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, sub-2 nm. In one embodiment, once the required alignment (or overlay) spec has been achieved, a bonding wave is initiated (by forcing contact between a central region of the two surfaces, for instance) creating a temporary or permanent bond between the two surfaces. 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 an 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 are comprised of nanowires, line-spaces, etc.), etc. In one embodiment, the recesses, nanowires, and nanostructures are created prior to the bonding step using etching, reactive ion etching, metal assisted chemical etching, and/or deposition techniques. In one embodiment, the rate of excess fluid removal is modulated by lowering the local pressure around the bonding region (for instance, fluid removal is enhanced by lowering the pressure in a local enclosed area around the substrates to be bonded). In one embodiment, said lowering of the pressure is temporary, performed just prior to bonding. Alternatively, in one embodiment, said lowering of the pressure is permanent (where the tool is kept at a specific pressure at all, or a majority, of the time). Other factors could be utilized to modulate the excess fluid removal, such as temperature of the bonding surfaces, humidity of the air in the vicinity of the bonding surfaces, etc.

[0024] Referring now to Figures 1A-1B, Figures 1A-1B illustrate lubricating fluid films at the bonding interface in accordance with an embodiment of the present disclosure.

[0025] As shown in Figure 1A, Figure 1A illustrates bonding one die/substrate 101A to another die/substrate 101B. In connection with such bonding, a pre-specified amount of fluid 102 is dispensed at the bonding interface (interface between die/substrate 101A and die/substrate 101B) at pre-specified locations between the top and bottom bonding surfaces (between surfaces of die/substrate 101A and die/substrate 101B, respectively). In one embodiment, fluid 102 is one or more of the following: an aqueous solution, a hydroxyl group containing a material, an alcohol, isopropyl alcohol, an acid, a base, water, citric acid, an acid, an adhesive, a thermally curable adhesive, a UV-curable adhesive, a light switchable adhesive, a light-to-heat-conversion adhesive, a spin-on dielectric, a silsesquioxane, a hydrogen silsesquioxane based spin-on dielectric, acetone, methanol, and ethanol.

[0026] In one embodiment, precision alignment is enabled by the lubricated relative motion due to the volatile liquid (e.g., fluid 102) being deployed between the surfaces of die/substrate 101A and die/substrate 101B, where a first portion of the droplets of the volatile liquid (e.g., fluid 102) is dispensed at a center of die/substrate 101A or die/substrate 101B and where a second portion of the droplets of the volatile liquid (e.g. fluid 102) is dispensed at an edge of die/substrate 101A

and/or die/substrate 101B, where the second portion of the droplets of the volatile liquid is greater than the first portion of the droplets of the volatile liquid.

[0027] In one embodiment, the volatile droplets (e.g., fluid 102) are maintained in a first environment during the dispensing of the droplets. In one embodiment, the volatile droplets (e.g., fluid 102) are maintained in a second environment during performance of the lubricated relative motion. In one embodiment, the volatile droplets (e.g., fluid 102) are maintained in a third environment during contact initiation with the surface of die/substrate 101A and/or die/substrate 101B and subsequent bonding. In one embodiment, the pre-specified environmental variables for the first, second, and third environments include humidity and/or temperature. In one embodiment, the first environment or the second environment has a humidity value that exceeds 40%, 50%, 60%, 70%, 80%, 90% or 95% relative humidity. In one embodiment, the third environment includes a humidity value that is below 50%, 40%, 30%, 20%, 10%, 5% or 1% relative humidity. In one embodiment, the first and second environments are substantially the same.

[0028] In one embodiment, volatile fluid 102 is dispensed to a larger height at an edge of a surface of die/substrate 101A and/or die/substrate 101B and to a lower height away from the edge of the surface of die/substrate 101A and/or die/substrate 101B.

[0029] In one embodiment, volatile fluid 102 is dispensed at an edge of a surface of die/substrate 101A and/or die/substrate 101B.

[0030] In one embodiment, an initial contact with volatile fluid 102 is made at an edge of a surface of die/substrate 101A and/or die/substrate 101B. In one embodiment, the initial contact with volatile fluid 102 is created by a back pressure applied on the surface of die/substrate 101A and/or die/substrate 101B, where the edge dispensed fluid enables contact of volatile fluid 102 with the center of the surface of die/substrate 101A and/or die/substrate 101B. In one embodiment, the contact is initiated between the surface of die/substrate 101A and the surface of die/substrate 101B, where the contact is subsequently expanded to a full extent of the surfaces of die/substrate 101A, 101B as discussed below.

[0031] In one embodiment, the amount of dispensed liquid 102 as well as the wetting properties of liquid 102 with regards to the top and bottom bonding surfaces (surfaces of die/substrate 101A and die/substrate 101B, respectively) are controlled, such as by using inkjetting for controlling the amount of dispensed fluid 102 and performing plasma treatment of the surface (e.g., surface of

die/substrate 101A, 101B) for controlling the contact angle, to limit the extent of spreading of liquid 102 in local regions to one or more of the following values: sub-1 mm, sub-500 μm , sub-200 μm , sub-100 μm , sub-50 μm , sub-30 μm , sub-20 μm , sub-10 μm , sub-5 μm , sub-2 μm , sub-1 μm , and sub-500 nm.

[0032] Furthermore, as illustrated in Figure 1A, bowing 103 is created by pressurizing the top surface 104 of die/substrate 101A, such as by using air pressure 105, or alternatively, by pressurizing a backside of a chuck that attaches to the top device (that includes the top bonding surface 104).

[0033] In one embodiment, bowing 103 is used to ensure that the first contact between die/substrate 101A and interfacial liquid 102 is near the center of die/substrate 101A.

[0034] In one embodiment, bonding is initiated by bowing (see bowing 103) die/substrate 101A beyond its existing bow amount or by bringing die/substrate 101A closer to die/substrate 101B while keeping the bow profile similar so that a central region of die/substrate 101A contacts a central region of die/substrate 101B. Alternatively, bowing 103 is modulated so that a non-central region of die/substrate 101A contacts a non-central region of die/substrate 101B.

[0035] Referring now to Figure 1B, in one embodiment, bonding is initiated at the first contact point 106. In one embodiment, fluid 102 near the center (e.g., center of die/substrate 101A) evaporates completely first, and subsequently an evaporation wave 107 propagates from the center (e.g., center of die/substrate 101A) outwards toward the edge of the top/bottom bonding surfaces/substrates (e.g., die/substrates 101A, 101B).

[0036] In one embodiment, an optional bowing force 108 is maintained during bonding. Such a bowing force (e.g., bowing force 108) may not be required in case the interfacial forces are sufficient to propagate bonding wave 107 all the way across the entire interface between die/substrates 101A, 101B.

[0037] Referring now to Figure 2, Figure 2 illustrates the shroud concept for management of interfacial liquid evaporation prior to bonding in accordance with an embodiment of the present disclosure.

[0038] As shown in Figure 2, mechanism 200 for managing the interfacial liquid evaporation prior to bonding includes a z-head assembly 201 with z-axis actuation using voice coils. Furthermore, z-head assembly 201 includes a chuck 202 (holds substrate during processing).

[0039] Furthermore, as shown in Figure 2, shroud 203 is around top substrate 204 (e.g., die/substrate 101A of Figures 1A-1B), incorporated for instance in chuck 202, to create localized regions of high humidity (e.g., over 50%, 60%, 70%, 80%, 90%, 95%, and 99% relative humidity) to prevent or reduce evaporation of the dispensed interfacial liquid (e.g., liquid 102 of Figure 1A) prior to bonding. Furthermore, as shown in Figure 2, there is an optional directed flow of air 205 with controlled humidity.

[0040] Additionally, as shown in Figure 2, top substrate 204 (e.g., die/substrate 101A of Figures 1A-1B) is attached to chuck 202 on z-head assembly 201 ready to be bonded.

[0041] Furthermore, as shown in Figure 2, bottom substrate 206 (e.g., die/substrate 101B of Figures 1A-1B) is to be bonded on a motion stage 207.

[0042] Additionally, mechanism 200 includes an inkjet assembly 208 for dispensing interfacial fluid 209 (e.g., fluid 102 of Figure 1A) for cleaning and/or surface activation.

[0043] In one embodiment, the distance between inkjet assembly 208 and the bonding location is optimized to reduce the time available for interfacial liquid 209 (e.g., liquid 102 of Figure 1A) to evaporate.

[0044] In one embodiment, mechanism 200 further includes a shroud 210 around inkjet assembly 208 to create localized regions of high humidity (e.g., over 50%, 60%, 70%, 80%, 90%, 95%, and 99% relative humidity) to prevent or reduce evaporation of the dispensed interfacial liquid 209 prior to bonding.

[0045] In one embodiment, the recesses described above are present near (or at) the edge (or kerf) of a die. In one embodiment, the recesses enable faster removal of the volatile fluid (e.g., fluid 102) from a bonding interface during and after bonding. In one embodiment, for wafer-to-wafer bonding, or substrate to substrate bonding, recesses near the die kerf could be used to enable in-liquid alignment during bonding, and subsequent evaporation of the interfacial liquid. In one embodiment, the recesses described above are present only near (or at) the edge (or kerf) of a die. In one embodiment, the recesses described above are present within one or more of the following

distances from the edge of a die: sub-5 μm , sub-10 μm , sub-20 μm , sub-50 μm , sub-100 μm , sub-200 μm , sub-500 μm , and sub-1 mm. In one embodiment, the recesses have sufficient depth that the volatile fluid (e.g., fluid 102) does not completely fill the recesses during the bonding. In another embodiment, metal pads or vias present on one or more of the two surfaces to be bonded (e.g., surfaces of die/substrates 101A, 101B of Figures 1A-1B, surfaces of substrates 204, 206 of Figure 2) are located alongside and interspersed with recesses as shown in Figure 2.

[0046] In one embodiment, the previously described in-liquid (or in-fluid) align is performed as the two bonding surfaces (e.g., surfaces of die/substrates 101A, 101B of Figures 1A-1B, surfaces of substrates 204, 206 of Figure 2) are urged together. In one embodiment, the in-liquid align happens in one of the following timeframes: sub-1, sub-0.5, sub-0.2, sub-0.1, sub-0.05 seconds.

[0047] In one embodiment, one or more of the following methods are utilized to compensate for overlay or alignment errors created due to temperature variation (cooling, for instance) resulting due to the evaporation of the interfacial liquid after in-liquid align: thermal actuation, and model-based pre-compensation of overlay in the mask layout of the electrical patterns in one or more of the top and bottom surfaces (e.g., surfaces of die/substrates 101A, 101B of Figures 1A-1B, surfaces of substrates 204, 206 of Figure 2) to be bonded.

[0048] In one embodiment, a post-bonding overlay precision is one of the following: sub-5 nm, sub-10 nm, sub-50 nm, sub-100 nm, sub-200 nm, and sub-500 nm overlay precision. In one embodiment, the overlay precision is achieved using nanometer overlay metrology scheme. In one embodiment, the overlay precision is achieved using a moiré metrology scheme. In one embodiment, the overlay precision is achieved using an infrared moiré metrology scheme.

[0049] In one embodiment, the methods described herein could be utilized for die to wafer (D2W) bonding, or wafer to wafer (W2W) bonding. In one embodiment, one or more of the said die or wafer could be bonded to a second substrate. In one embodiment, the second substrate could be a carrier wafer. In one embodiment, the carrier wafer could be comprised of one or more of the following materials: silicon, glass, fused silica, quartz, sapphire, or silicon carbide. In one embodiment, the carrier wafer could be of the following sizes: 300 mm diameter wafer, 200 mm diameter wafer, 150 mm diameter wafer, 100 mm diameter wafer, or 50 mm diameter wafer. In one embodiment, the second substrate could also be a carrier die, where the die could be equal in size or larger in size compared to the carried die. In one embodiment, the carrier die could be

rectangular in form, and have one or more sides that are in the following range of dimensions: 1-5 mm, 5-10 mm, 10-15 mm, 15-20 mm, 20-25 mm, 25-30 mm, 30-50 mm, 50-100 mm, 100-150 mm, 150-200 mm, or 200-300 mm. In one embodiment, the carrier die could be comprised of one or more of the following materials: silicon, glass, fused silica, quartz, sapphire, or silicon carbide.

[0050] In one embodiment, a die or a wafer is attached to a suitable carrier (die carrier or wafer carrier), and thermal actuation is performed on the sandwich of die/wafer and carrier, when the sandwich is being bonded onto a target substrate. In one embodiment, thermal actuation could be performed using a non-contact approach such as one utilizing incident light (which could optionally be spatially modulated, for instance, using a digital micromirror device), or using a contact-based thermal actuation method (for instance, a die/wafer chuck with embedded peltier or thermoelectric devices). In one embodiment, the target substrate onto which the sandwich is being bonded could be made of a material that has a substantially different coefficient of thermal expansion than the carrier substrate utilized in the sandwich. For instance, the carrier substrate could be glass (with a thermal expansion coefficient of less than 1ppm), and the target substrate could be silicon (with a thermal expansion coefficient of ~3ppm). This would allow the sandwich to have an effective coefficient of thermal expansion that is substantially different from that of the target substrate, which further would permit relative thermal expansion of the target substrate vs the sandwich, which would subsequently permit high-precision overlay control (for instance, overlay control of better than 50 nm, 30 nm, 25 nm, 15 nm, 10 nm, 5 nm, 2 nm Mean + 3*Standard Deviation). In one embodiment, the overlay control could be performed using an in-liquid approach. In some embodiment, the die or wafer in the above sandwich could be a thinned substrate wherein the thickness of the die or wafer could be in the following ranges: 100 nm-500 nm, 500 nm-1 um, 1-2 um, 2-5 um, 5-10 um, 10-20 um, 20-50 um, 50-100 um, 100-250 um, 250-500 um, 500-750 um, or 750-1000 um.

[0051] In one embodiment, in-situ moire-based overlay metrology could be performed during bonding (see Moon, Euclid Eberle. "Interferometric-spatial-phase imaging for sub-nanometer three-dimensional positioning." (2004) for a moire based alignment technique). In one embodiment, metrology could be done in a manner wherein multiple moire alignment marks are processed simultaneously. In one embodiment, this could be enabled by an optical arrangement which has multiple light sources sending light (in one or more of visible, infrared spectrums) towards the moire marks at an angle (Littrow angle, for instance), and where the back-diffracted

light (containing alignment information) is sent upwards, orthogonal to the surface of the target substrate, towards pickoff mirrors that allow two closely-spaced beams to be reflected in close spatial proximity to each other (one of 5 μm , 10 μm , 50 μm , 100 μm , 500 μm , or 1 mm apart), where the pickoff mirrors integrate alignment information from one or more of 2, 4, 8, 16 alignment marks, located at multiple locations on the sandwich and target substrate, such that a single (or two) centrally placed camera(s) can be used to simultaneously image one or more of 2, 4, 8, or 16 alignment marks.

[0052] As a result of the foregoing, the principles of the present disclosure provide an effective means for achieving nano-precision alignment accuracy for wafer bonding.

[0053] 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 with precision alignment, the method comprising:
2 dispensing droplets of volatile liquid at pre-specified locations on a first bonding surface
3 or a second bonding surface, wherein said precision alignment is enabled by lubricated relative
4 motion due to said volatile liquid being deployed between said first and second bonding surfaces,
5 wherein a first portion of said droplets of said volatile liquid is dispensed at a center of said first
6 bonding surface or said second bonding surface, wherein a second portion of said droplets of said
7 volatile liquid is dispensed at an edge of one or more of said first bonding surface and said second
8 bonding surface, wherein said second portion of said droplets of said volatile liquid is greater than
9 said first portion of said droplets of said volatile liquid, wherein said first and second portions of
10 said droplets of said volatile liquid enable bowing of said first bonding surface with respect to said
11 second bonding surface such that evaporation of said droplets of volatile liquid causes a center of
12 said first and second bonding surfaces to make contact with each other.
- 1 2. The method as recited in claim 1, wherein said first bonding surface is a top bonding
2 surface, wherein said second bonding surface is a bottom bonding surface.
- 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-50 nm, sub-100 nm, sub-200 nm, and sub-500 nm overlay
3 precision.
- 1 4. The method as recited in claim 3, wherein said overlay precision is achieved using a
2 nanometer overlay metrology scheme.
- 1 5. The method as recited in claim 3, wherein said overlay precision is achieved using a moiré
2 metrology scheme.
- 1 6. The method as recited in claim 3, wherein said overlay precision is achieved using an
2 infrared moiré metrology scheme.
- 1 7. The method as recited in claim 1, wherein said volatile fluid comprises one or more of the
2 following: an aqueous solution, a hydroxyl group containing a material, an alcohol, isopropyl
3 alcohol, an acid, a base, water, citric acid, an acid, an adhesive, a thermally curable adhesive, a

4 UV-curable adhesive, a light switchable adhesive, a light-to-heat-conversion adhesive, a spin-on
5 dielectric, a silsesquioxane, a hydrogen silsesquioxane based spin-on dielectric, acetone, methanol,
6 and ethanol.

1 8. The method as recited in claim 1, wherein said bonding comprises one or more of the
2 following: direct bonding, SiO₂-SiO₂ bonding, covalent bonding, fusion bonding, hybrid bonding,
3 adhesive bonding, self-assembly, temporary bonding, and permanent bonding.

1 9. The method as recited in claim 1 further comprising:
2 dispensing said volatile fluid to a larger height at an edge of one of said first bonding
3 surface and said second bonding surface and to a lower height away from said edge of said one of
4 said first bonding surface and said second bonding surface.

1 10. The method as recited in claim 1 further comprising:
2 dispensing said volatile fluid at an edge of one of said first bonding surface and said second
3 bonding surface.

1 11. The method as recited in claim 10, wherein an initial contact with said volatile fluid is
2 made at said edge of one of said first bonding surface and said second bonding surface.

1 12. The method as recited in claim 11, wherein said initial contact with said volatile fluid is
2 created by a backpressure applied on said one or more of said first and second bonding surfaces,
3 wherein said edge dispensed fluid enables contact of said volatile fluid with said center of said
4 first bonding surface or said second bonding surface.

1 13. The method as recited in claim 1 further comprising:
2 initiating said contact between said first and second bonding surfaces at said center of said
3 first and second bonding surfaces and subsequently expanding said contact to a full extent of said
4 first and second bonding surfaces.

1 14. The method as recited in claim 1 further comprising:
2 performing an etch on one or more of said first and second bonding surfaces to create
3 recesses in said one or more of said first and second bonding surfaces, wherein said recesses enable
4 faster removal of said volatile fluid from a bonding interface during and after bonding.

- 1 15. The method as recited in claim 14, wherein said recesses are present within one or more of
2 the following distances from said edge of one or more of said first bonding surface and said second
3 bonding surface: sub-5 μm , sub-10 μm , sub-20 μm , sub-50 μm , sub-100 μm , sub-200 μm , sub-500
4 μm , and sub-1 mm.
- 1 16. The method as recited in claim 14, wherein metal pads or vias present on one or more of
2 said first and second bonding surfaces are interspersed with said recesses.
- 1 17. The method as recited in claim 14, wherein said recesses have sufficient depth that said
2 volatile fluid does not completely fill said recesses during said bonding.
- 1 18. The method as recited in claim 1, wherein said bonding is performed in one of the following
2 manners: a face-to-face, a face-to-back, a back-to-face, and a back-to-back manner.
- 1 19. A method for bonding with precision alignment, the method comprising:
2 dispensing droplets of a volatile fluid at pre-specified locations on a first bonding surface
3 or a second bonding surface, wherein said precision alignment is enabled by lubricated relative
4 motion due to said volatile fluid being deployed between said first bonding surface and said second
5 bonding surface, wherein said volatile droplets are maintained in a first environment during said
6 dispensing of said droplets, wherein said volatile droplets are maintained in a second environment
7 during performance of said lubricated relative motion, wherein said volatile droplets are
8 maintained in a third environment during contact initiation with one or more of said first and
9 second bonding surfaces and subsequent bonding.
- 1 20. The method as recited in claim 19, wherein one or more of said first, second and third
2 environments comprise one of the following pre-specified environmental variables: humidity and
3 temperature.
- 1 21. The method as recited in claim 19, wherein said first environment or said second
2 environment comprises a humidity value that is over one of the following: 40%, 50%, 60%, 70%,
3 80%, 90%, and 95% relative humidity.

1 22. The method as recited in claim 19, wherein said third environment comprises a humidity
2 value that is below one of the following: 50%, 40%, 30%, 20%, 10%, 5%, and 1% relative
3 humidity.

1 23. The method as recited in claim 19, wherein said first and said second environments are
2 substantially the same.