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### Compression system calibration

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#### Abstract

A method to aid in a calibration of a compression system includes mounting a first substrate in a press. The press has calibration parameters, and the first substrate has a test film on a first surface. The method includes mounting a second substrate in the press. The second substrate has spikes arranged in a spike pattern on a second surface. The method includes compressing the first substrate and the second substrate together with a force that causes the spikes to form indentations in the test film, separating the first substrate from the second substrate, determining local pressures applied by the spikes against the test film, and adjusting one or more calibration parameters of the press in response to the local pressures.

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## Background/Summary

## TECHNICAL FIELD

(1) The disclosure relates generally to flip-chip bonding, and in particular, to a compression system calibration.

## BACKGROUND

(2) Current computing systems involve dense integrations of a range of different elements, including processors, application specific integrated circuit accelerators, memory devices, high speed input/output devices, network processing devices, and power delivery/power management devices. Three-dimensional integration of the devices provides a performance advancement due to an increase in interconnectivity between constituent elements. The three-dimensional integration involves inter-chip bonding. The inter-chip bonding is dependent on even pressure distributions across arrays of bumps and bonding pads on the chips. Issues arise where the bonding pressure that each bump experiences is non-uniform. Bumps at the edges and corners tend to be over compressed during the bonding. If the pitch between bumps is large, for example 50 microns or greater, the compression forces have a varying function with an oscillatory behavior.

(3) Accordingly, those skilled in the art continue with research and development efforts in the field of flip-chip bonding to provide uniform compression forces.

## SUMMARY

(4) A method to aid in a calibration of a compression system is provided herein. The method includes mounting a first substrate with a first surface facing outward in a press. The press has a plurality of calibration parameters, and the first substrate has a test film on the first surface. The method includes mounting a second substrate in the press with a second surface of the second substrate facing the first surface of the first substrate. The second substrate has a plurality of spikes arranged in a spike pattern on the second surface. The method further includes compressing the first substrate and the second substrate together with a force that causes the plurality of spikes to form a plurality of indentations in the test film, separating the first substrate from the second substrate, determining a plurality of local pressures applied by the plurality of spikes against the test film during the compressing, and adjusting one or more of the plurality of calibration parameters of the press in response to the plurality of local pressures.

(5) In one or more embodiments of the method, the determining of the plurality of local pressures includes generating an image of the plurality of indentations in the test film, wherein a plurality of light intensities in the image are representative of the plurality of local pressures applied by the plurality of spikes against the test film during the compressing.

(6) In one or more embodiments, the method further includes determining a plurality of dimensions of the plurality of indentations in response to the plurality of light intensities in the image, and calculating a plurality of absolute values of the plurality of local pressures applied to the test film in response to the plurality of dimensions of the plurality of indentations and the force applied between the first substrate and the second substrate.

(7) In one or more embodiments, the method further includes forming an over-coat layer on each of the plurality of spikes that prevents a formation of a metallurgical bond between the plurality of spikes and the test film during the compressing.

(8) In one or more embodiments of the method, the adjusting of the one or more of the plurality of calibration parameters of the press is adjusting a tilt that the press establishes between the first substrate and the second substrate.

(9) In one or more embodiments of the method, the adjusting of the one or more of the plurality of calibration parameters of the press is adjusting the force that the press applies during the compressing.

(10) In one or more embodiments, the method further includes generating a pressure map in two-dimensions based on the plurality of local pressures, wherein the adjusting of the one or more of the plurality of calibration parameters of the press is in further response to the pressure map.

(11) In one or more embodiments, the method further includes replacing the first substrate with an additional first substrate after the adjusting of the one or more of the plurality of calibration parameters of the press, and compressing the additional first substrate and the second substrate together with the force.

(12) In one or more embodiments, the method further includes replacing the first substrate with a first working part after the adjusting of the one or more of the plurality of calibration parameters, replacing the second substrate with a second working part, and bonding the first working part to the second working part with the press.

(13) A compression system is provided herein. The compression system includes a first substrate, a second substrate, a press, and a sensor. The first substrate has a test film on a first surface. The second substrate has a plurality of spikes arranged in a spike pattern on a second surface. The press has a plurality of calibration parameters. The press is configured to mount the first substrate with the first surface facing outward, mount the second substrate with the second surface of the second substrate facing the first surface of the first substrate, compress the first substrate and the second substrate together with a force that causes the plurality of spikes to form a plurality of indentations in the test film, and separate the first substrate from the second substrate. The sensor is configured to determine a plurality of local pressures applied by the plurality of spikes against the test film during the compression. One or more of the plurality of calibration parameters of the press is adjustable in response to the plurality of local pressures.

(14) In one or more embodiments of the compression system, the sensor is a camera configured to generate an image of the plurality of indentations in the test film. A plurality of light intensities in the image are representative of the plurality of local pressures applied by the plurality of spikes against the test film during the compression.

(15) In one or more embodiments, the compression system further includes a computer configured to determine a plurality of dimensions of the plurality of indentations in response to the plurality of light intensities in the image, and calculate a plurality of absolute values of the plurality of local pressures applied to the test film in response to the plurality of dimensions of the plurality of indentations and the force applied between the first substrate and the second substrate.

(16) In one or more embodiments of the compression system, each of the plurality of indentations has a shape that retroreflects light, and the camera presents the image as off-axis light reflecting from the plurality of indentations.

(17) In one or more embodiments of the compression system, each of the plurality of spikes is formed with an over-coat layer that prevents a formation of a metallurgical bond between the plurality of spikes and the test film during the compression.

(18) In one or more embodiments of the compression system, the plurality of spikes have a cone shape, and the spike pattern comprises at least 1,000 of the plurality of spikes.

(19) A calibration kit is provided herein. The calibration kit includes a first substrate and a second substrate. The first substrate has a test film on a first surface. The test film has a first hardness. The second substrate has a plurality of spikes arranged in a spike pattern on a second surface. A second hardness of the plurality of spikes is greater than the first hardness of the test film such that the plurality of spikes create a plurality of indentations in the test film in response to the first substrate and the second substrate being compressed together.

(20) In one or more embodiments of the calibration kit, the plurality of spikes includes an over-coat layer that prevents a formation of a metallurgical bond between the plurality of spikes and the test film while being compressed together.

(21) In one or more embodiments of the calibration kit, each of the first substrate and the second substrate comprises a semiconductor.

(22) In one or more embodiments of the calibration kit, the first substrate is one of a semiconductor die, a semiconductor tile, or a semiconductor wafer, and the second substrate is one of the semiconductor die, the semiconductor tile, or the semiconductor wafer.

(23) In one or more embodiments of the calibration kit, the test film is formed from gold, aluminum, indium, copper, platinum, palladium, or a first alloy thereof, and the plurality of spikes is formed from beryllium, titanium, palladium, vanadium, copper, manganese, nickel, cobalt, iron, rhodium, chromium, molybdenum, ruthenium, platinum, tantalum, tungsten, rhenium, iridium, aluminum oxide, silicon carbide, or a second alloy thereof.

(24) The above features and advantages, and other features and advantages of the present disclosure are readily apparent from the following detailed description of the best modes for carrying out the disclosure when taken in connection with the accompanying drawings.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

- (1) FIG. 1 is a schematic diagram of a compression system in accordance with one or more exemplary embodiments.
- (2) FIG. 2 is a schematic plan diagram of various substrates in accordance with one or more exemplary embodiments.
- (3) FIG. 3 is a schematic side diagram of a calibration kit in accordance with one or more exemplary embodiments.
- (4) FIG. 4 is a schematic perspective diagram of a test film in accordance with one or more exemplary embodiments.
- (5) FIG. 5 is a schematic diagram of a method for fabrication of spikes in accordance with one or more exemplary embodiments.
- (6) FIG. 6 is a schematic perspective diagram of a structure of a spike in accordance with one or more exemplary embodiments.
- (7) FIG. 7 is an image of a set of spikes in accordance with one or more exemplary embodiments.
- (8) FIG. 8 is an image of an array of spikes in accordance with one or more exemplary embodiments.
- (9) FIG. 9 is an image of a local indentation pattern in accordance with one or more exemplary embodiments.
- (10) FIG. 10 is an image of a wide indentation pattern in accordance with one or more exemplary embodiments.
- (11) FIG. 11 is an image of a non-uniform indentation pattern in accordance with one or more exemplary embodiments.
- (12) FIG. 12 is a flow diagram of a method to aid in a calibration of the compression system in accordance with one or more exemplary embodiments.
- (13) FIG. 13 is a flow diagram of a method to determine local pressures in accordance with one or more exemplary embodiments.
- (14) FIG. 14 is a flow diagram of a method to adjust calibration parameters in accordance with one or more exemplary embodiments.

### DETAILED DESCRIPTION

- (15) Embodiments of the present disclosure generally include a system, method and/or kit that addresses calibration of a press used in inter-substrate bonding. The designs disclosed herein enable high resolution measurements and/or visualizations of local (e.g., nanometer scale to micrometer scale) bonding pressures and global (e.g., millimeter scale to decimeter scale) pressure distributions in fine-pitch area arrays. The bonding pressures occur during substrate-to-substrate bonding for fine-pitch integration applications. Pitch in reference to distance generally means a period of the array pattern. The period indicates how close two spikes may be placed next to each other.
- (16) Maps of local pressure distributions and global pressure distributions are created by employing arrays of nanometer-sharp spike structures to imprint (e.g., plastically deform) a surface of a

patterned or an un-patterned metallized substrate (e.g., wafer, tile, die). The metal on the substrate has known, or measurable, material properties (e.g., hardness, thickness, and Young's modulus). An applied pressure distribution is determined from an indentation dimension distribution. Since an overall force applied to the substrate is known or measured by a sensor of the compression system, accurate quantitative local pressures and global pressure distributions may be derived. The arrays of spike indenters are configured in either arbitrary patterns or uniform arrayed patterns to mimic a particular bond pad layout. The arrays allow direct measurement of stress and displacement distributions suitable to predict bond yields of a given applied force for a particular array configuration. In various embodiments, the dimensions of the indented imprints are detected using dark field microscopy where reflected light intensities are directly related to the dimensions of the imprints. Measuring the reflected light intensities allows efficient assessment and direct conversion of the light intensity distributions into pressure maps.

(17) Referring to FIG. 1, a schematic diagram of an example implementation of a compression system **100** is shown in accordance with one or more exemplary embodiments. The compression system **100** generally includes a press **102**, a sensor **110**, and a computer **120**. The press **102** includes a top chuck **104**, a bottom chuck **106**, and a load cell **108**. The sensor **110** may implement a camera **110a** or a dark field camera **110b**. The computer **120** includes one or more processors **122** (one shown) and one or more memory devices **124** (one shown).

(18) The press **102** implements a precision die bonder. In various embodiments, the press **102** implements a substrate-to-substrate thermocompression press. The press **102** is operational to align and press two substrates together to form inter-substrate connections. The alignment may be provided by movement of the top chuck **104** relative to the bottom chuck **106** in multiple dimensions. By way of example, the top chuck **104** may tilt **130** relative to the bottom chuck **106**. The tilt **130** may include movement in a pitch direction **130a** and a roll direction **130b**. In some embodiments, the bottom chuck **106** may be rotatable relative to the top chuck **104** in a yaw direction **132**. In other embodiments, the top chuck **104** may be rotatable relative to the bottom chuck **106** in the yaw direction **132**. The top chuck **104** is also moveable relative to the bottom chuck **106** in a vertical direction **134**.

(19) Movement of the top chuck **104** downward along the vertical direction **134** presses a first substrate **140** being held by the bottom chuck **106** against a second substrate **160** being held by the top chuck **104** with a force **136**. The force **136** compresses spikes formed on the second substrate **160** into a test film on the first substrate **140**. In some embodiments, the first substrate **140** may be held by the top chuck **104** and the second substrate **160** may be held by the bottom chuck **106**. The load cell **108** measures the force **136** being applied between the first substrate **140** and the second substrate **160**.

(20) The top chuck **104** and the bottom chuck **106** each implement a vacuum chuck. The top chuck **104** and the bottom chuck **106** are operational to hold the second substrate **160** and the first substrate **140** during the bonding process.

(21) The load cell **108** implements a pressure sensor. The load cell **108** is operational to detect the force **136** applied by the second substrate **160** onto the first substrate **140** during a calibration test of the press **102**.

(22) The sensor **110** implements an optical sensor. In various embodiments, the sensor **110** is implemented as a camera **110a**. In some embodiments, the sensor **110** is implemented as a dark field camera **110b**. The sensor **110** is operational to generate a two-dimensional image of the test film of the first substrate **140** after the spikes of the second substrate **160** have been pressed into the test film.

(23) The computer **120** is coupled to the sensor **110** and the load cell **108**. The computer **120** implements one or more data processing computers. In embodiments with multiple computers **120**, the individual computers **120** are coupled together to share data, memory space, and processing resources. The computer **120** may be operational to store the configuration data of the press **102**

and execute software used to analyze the information received from the sensor **110** and the load cell **108**.

(24) The processor **122** implements one or more processors within the computer **120**. The processor **122** is in communication with the memory device **124** to exchange commands and data. The processor **122** is operational to execute the software tools used to analyze the images generated by the sensor **110** and the data generated by the load cell **108**.

(25) The memory device **124** implements one or more non-transitory computer readable storage devices (e.g., random access memory, read-only memory, magnetic hard drives, solid-state drives, etc.). The memory device **124** stores software programs (or tools) that are executed by the processor **122**.

(26) The compression system **100** implements a technique for measuring the local pressure and pressure distributions (maps) that occur during compression bonding of fine-pitch area arrays (e.g., less than 2.5 microns (um) pitch arrays). Therefore, the pressure distribution maps are high resolution pressure maps. Knowledge of the pressure distribution enables development of high yield compression bonding that is fundamental to high density interfaces used to fabricate two-and-a-half dimensional and three-dimensional integrated microelectronic systems. The multi-dimensional integration provides performance advancements due to an increase in interconnectivity between the first substrate **140** and the second substrate **160**. The performance advantages may include lower latency, lower energy per bit, faster switching speeds, and the like. In the absence of a method for reworking the high density inter-substrate interfaces, successful bonding takes place in a single pass. Therefore, after the first substrate **140** and the second substrate **160** have calibrated the press **102**, the first substrate **140** may be replaced by a first working part **141**, and the second substrate **160** may be replaced by a second working part **161**. The first working part **141** is subsequently bonded to the second working part **161** by the press **102**.

(27) The compression system **100** provides high-resolution positional (e.g., less than 3 um) measurement of local pressures and pressure distribution maps of large area substrates, including wafers, tiles, and/or die level substrates. Arrays of fine-pitch metal knife-edge-like structures (e.g., spikes) on a top substrate (e.g., the second substrate **160**) are used to indent a thin test film (e.g., a metal film, an array of metal pads, or an array of bumps) coated on a bottom substrate (e.g., the first substrate **140**). In various embodiments, the technique provides large area, fine-pitch nano-indenter arrays. Since a hardness and various material properties of the test film are known, locally applied pressures may be determined from an area and/or a depth of the indentations in the test film. The indenters may be fabricated as conically symmetric tips in a photolithographic process that enables large area spike arrays to be formed on silicon or other substrates with low variation in tip heights. The indenter material is chosen to be harder than the imprinted thin film/pad/bumps to simplify the pressure measurement. In an analysis of the pressure distributions, since the total applied force is known (e.g., determined by a load cell **108** in the stack), the local pressures and the global pressure distributions may be quantitatively determined by the computer **120**. Furthermore, the indentation depths and areas may be measured using optical microscopy and a camera **110a**. In particular, a dark field camera **110b** operates with off-axis light to generate images in dark field operations. The images capture the intensity of the scattered light from the individual imprints. The light intensity has a linear relation with the dimensions (e.g., area and depth) of the imprints. Conically shaped spike indenters generally provide radially symmetric indentation divots that acts as retroreflectors. Other shapes of the indenters may be implemented to meet a design criteria of a particular application.

(28) In nano-indentation metrology applications, a maximum load  $P_{max}$  may be obtained from knowing a hardness  $H$  of the indented material and the residual indentation area  $A_r$  from the expression  $P_{max}=H \times A_r$ . In the case of compression bonded arrays, the candidate metal contact layout may be replicated in a spike array fabrication process with the spike structures substituted for the bond pads. The replicated fine-pitch spike array is subsequently used to imprint a blanket-

coated metal substrate (typically a silicon wafer with a thin (e.g., 0.5  $\mu\text{m}$ ) gold film. The imprinted divot pattern is used to measure the pressure distribution of an original bump layout pattern. The pressure measurement may also be used to measure tool and/or bonder related effects such as tilts, tool bending, and clamping issues.

(29) Referring to FIG. 2, a schematic plan diagram of example implementations of various substrates are shown in accordance with one or more exemplary embodiments. The substrate may be formed of a semiconductor **181**. The semiconductor **181** generally includes silicon, germanium, gallium arsenide, aluminum gallium arsenide, silicon carbide, gallium nitride, indium phosphide and the like. The substrates may be in the form of a semiconductor die **183**, a semiconductor tile **185**, or a semiconductor wafer **187**.

(30) Referring to FIG. 3, a schematic side diagram of an example arrangement of a calibration kit **400** is shown in accordance with one or more exemplary embodiments. The calibration kit **400** generally includes the first substrate **140** and the second substrate **160**. The first substrate **140** is generally positioned below the second substrate **160** in the press **102** (FIG. 1). The first substrate **140** has a first surface **142** facing a second surface **162** of the second substrate **160**. The first substrate **140** includes a third surface **144** opposite the first surface **142**. Likewise, the second substrate **160** includes a fourth surface **164** opposite the second surface **162**.

(31) A test film **146** is fabricated on the first surface **142** of the first substrate **140**. In various embodiments, the test film **146** may be a uniform sheet of material (e.g., metal), an array of pads, or an array of bonding bumps. The test film **146** may be fabricated as one or more layers of a variety of test film materials **148** each having a test film hardness **150** (e.g., Young's Modulus). The test film materials **148a-148g**/test film harnesses **150a-150g** in gigapascals (GPa) may include, but are not limited to, gold/78 GPa, aluminum/70 GPa, indium/11 GPa, copper/130 GPa, platinum/168 GPa, palladium/121 GPa, and alloys thereof with a hardness less than approximately 116 GPa.

(32) An array of pads **166** is fabricated on the second surface **162** of the second substrate **160**. In various embodiments, the pads **166** may be a uniform array of pads **166** and/or a random array of pads **166**. One or more spikes **168** is fabricated on each pad **166**. The spikes **168** are fabricated as one or more layers of a spike material **170** each having a spike material hardness **172**. The spike materials **170a-170u**/spike material hardness **172a-172u** may include, but are not limited to, beryllium/287 GPa, titanium/116 GPa, palladium/121 GPa, vanadium/128 GPa, copper/130 GPa, manganese/198 GPa, nickel/200 GPa, cobalt/209 GPa, iron/211 GPa, rhodium/275 GPa, chromium/279 GPa, molybdenum/329 GPa, ruthenium/447 GPa, platinum/168 GPa, tantalum GPa/186 GPa, tungsten/411 GPa, rhenium/463 GPa, iridium/528 GPa, aluminum oxide/300 GPa, silicon carbide/137 GPa, and an alloy thereof having a hardness of at least approximately 116 GPa. The spike material hardness **172** is selected to be larger than the test film hardness **150** to avoid the tips of the spikes **168** being plastically deformed during the indentation.

(33) The force **136** that presses the second substrate **160** against the first substrate **140** applies a local pressure **154** between each spike **168** and the test film **146**. The local pressure **154** of a spike **168** creates an indentation **152** in the test film **146**, one indentation **152** per spike **168**.

(34) Referring to FIG. 4, a schematic perspective diagram of an example indentation in the test film **146** is shown in accordance with one or more exemplary embodiments. The indentation generally has a shape **180** of a spike **168**. In various embodiments, the shape **180** of the spike **168** may be conical. Other shapes **180** of other spikes **168** may be implemented to meet the design criteria of a particular application.

(35) The shape **180** includes multiple dimensions **182**. The dimensions **182** may include at least a diameter **182a** and a depth **182b**. An off-axis light **190** is illustrated to show how the test film **146** is illuminated while measuring an amount of scattered light caused by the indentation.

(36) Referring to FIG. 5, a schematic diagram of an example method **200** for fabrication of the spikes **168** is shown in accordance with one or more exemplary embodiments. The method **200** includes steps **202** to **212**, as illustrated. The sequence of steps is shown as a representative



example. Other step orders may be implemented to meet the criteria of a particular application. The method (or process) **200** may be performed using standard semiconductor fabrication techniques. A shape and dimensions of the spikes **168** are controlled by a lithographic patterning used to define a base diameter of the spikes **168**. Deposited metal is used to fabricate the spikes **168**.

(37) In the step **202**, the second surface **162** of the second substrate **160** may be cleaned and prepared for a metal deposition. A metal for the pads **166** is deposited and patterned in the step **204**. A mask is deposited on the pads **166** in the step **206**. The mask may be a reverse image or bilayer resist process so that when images, re-entrant sidewalls result. In various embodiments, the deposition and patterning for the pads **166** may be skipped and the mask deposited directly on the second substrate **160**. Gaps are imaged into the mask in the step **208**.

(38) In the step **210**, the spike material **170** is deposited onto the mask and into the gaps to form the spikes **168**. The spike material **170** may be deposited by evaporation. The deposition results in the formation of knife-edge microstructures in the gaps. An over-coat material may optionally be formed over the spikes **168** using a photoresist coating, a photoresist patterning, and an evaporation of the over-coat material. The spike material **170** remaining on the mask and the mask itself are removed in the step **212** to leave the spikes **168** exposed and protruding away from the second surface **162** of the second substrate **160**.

(39) Referring to FIG. **6**, a schematic perspective diagram of an example structure of a spike **168** is shown in accordance with one or more exemplary embodiments. The spike **168** generally has a cone shape **174**. The spike **168** comprises an inner layer **176** optionally covered by an over-coat layer **178**. The inner layer **176** may be selected from among the spike materials **170**. The over-coat layer **178** may be selected from among the spike materials **170** and/or oxides of the spike materials **170**. In various embodiments, the over-coat layer **178** is included to prevent a metallurgical bond from forming between the spike **168** and the test film **146** due to the compression.

(40) A taper angle of the spikes **168** is controlled by the metal used in the fabrication. Examples of taper angles include gold (78°), titanium (68°), and platinum (78°). Other metals may be used to achieve other taper angles. The spikes **168** may be constructed with narrow tip radii of approximately 5 nanometers (nm) and larger, and a fine pitch of 0.3  $\mu\text{m}$  and larger (e.g.,  $>0.8$ ). Other tip radii and/or pitch may be implemented to meet the design criteria of a particular application.

(41) Referring to FIG. **7**, an image **192** of an example set of spikes **168** is shown in accordance with one or more exemplary embodiments. In the example, four spikes **168** are created on a pad **166**. The image **192** illustrates a scanning electron micrograph of titanium spikes **168** used to form patterned arrays of indenter tips. Using a single evaporator source titanium, the spikes **168** exhibit a 68° taper angle. The four spikes **168** have a separation of approximately 2.75  $\mu\text{m}$  tip-to-tip. Reducing base diameter of the spike **168** results in lower tips that may be packed closer together and decrease the pitch. Titanium spike structures have been observed to be compressed against test films **146** multiple times without deformation. The conical shaped tips of the spikes **168** create simple divot indentations that simplify the analysis and correlation of the imprint area with the scattered illumination in dark field microscopy.

(42) Referring to FIG. **8**, an image **194** of an example array of spikes **168** is shown in accordance with one or more exemplary embodiments. The image **194** illustrates another scanning electron micrograph of the titanium spikes **168** and pads **166**. The pads **166** are arranged in a pad pattern **177**. On each pad **166**, the spikes **168** are arranged in a spike pattern **179**. The spike pattern **179** illustrated has a group of four spikes **168** on one side of a pad **166** and another group of four spikes **168** on an opposing side of the pad **166**. The quad groups of spikes **168** are illustrated on a 10 micron pitch. Other pitches may be implemented to meet the design criteria of a particular application.

(43) Referring to FIG. **9**, an image **240** of an example local indentation pattern is shown in accordance with one or more exemplary embodiments. The image **240** illustrates a 4 millimeter $\times$ 4

millimeter (mm) indentation pattern using a spike array with a 10 um pitch. Brightness of the image **240** is reversed for the sake of presentation and reproduction. Dark areas of the image **240** are actually bright, and light areas are actually dark. Therefore, area **246** would be seen as a dark background area, and groups of spikes **242** would be seen as bright areas that form indentation patterns of bright lights **244**.

(44) The image **240** is a dark field micrograph showing the light intensity **250** of individual bright indentations **248** (e.g., individual indented divots) seen at high magnification that collectively form the entire array. In the example, the spike array is fabricated on a 600 um thick silicon substrate and the spikes **168** are made with titanium (68° taper angle). The spike pattern forms groups of 4 spikes **168** with 2.75 um tip-to-tip separation, on a 10 um pitch. The intensity distribution is proportional to the changes in the local pressure that is dependent on pattern uniformity and discontinuities at the boundaries (edges and corners). The light intensity **250** from the imprints is related to the area and the depth of the imprints as the scattered light in the dark field image **240** is proportional to the exposed sidewalls of the conical imprint. The light intensity **250** is directly proportional to the absolute values **252** of the local pressures **154** (FIG. 3)

(45) Referring to FIG. 10, an image **260** of an example wide indentation pattern is shown in accordance with one or more exemplary embodiments. The 4 mm×4 mm array of spikes **168** in the image **260** includes 640,000 individual imprints with array patterns identical to the pattern shown in the image **240** (FIG. 9). While the spike array in the example was uniform, the effects of tooling are evident where the under-compressed edges and corners (due to footprint of the tool being undersized relative to the spike array) and the center (due to the vacuum hold pattern) show up as darker areas **262**, and the properly-compressed areas show up as bright areas **264**.

(46) The dark field microscopy optical technique was used to generate the image **240** (FIG. 9) and the image **260** to determine the area of the indentation pattern. In the dark field microscopy, an aperture is located behind a collecting lens. The aperture takes out the normal reflected light and only allows off-angled light to enter and be recorded. Therefore, the spike patterns are more intense than the relatively flat test film **146**.

(47) The light intensities in the image **260** represent a high-resolution pressure map **266**. The computer **120** (FIG. 1) may sum the individual light intensities. The total light intensity is proportional to the force that has been applied. Knowing the force **136** as measured by the load cell **108** (FIG. 1) and the total number of spikes **168**, the computer **120** may calculate the local pressure **154** (FIG. 3) that each spike **168** applied to the test film **146**. Thereafter, the computer **120** may convert the light intensity distribution into the pressure map **266** on the first surface **142** of the first substrate **140**.

(48) Referring to FIG. 11, an image **270** of an example non-uniform indentation pattern is shown in accordance with one or more exemplary embodiments. In the example, the top chuck **104** of the press **102** (e.g., an FC300 precision bonder) was intentionally tilted relative to the bottom chuck **106** to demonstrate the effect. Other tooling and array pattern effects may be assessed using a similar method (e.g., tooling sizes, vacuum hold downs for sample clamping, array pattern non-uniformities, etc.). With indentation divot depths on the order of 200 nm, silicon-based spike arrays may accommodate approximately 50 microradian (approximately 3 millidegree) of tilt over a 4 mm distance.

(49) The image **270** is a dark-field optical micrograph showing a non-uniform pressure distribution resulting from the tilted condition between the spikes **168** and the flat test film **146**. Tilts may arise from improper tooling calibration, load path non-uniformities, defects on the backside of the samples, and/or layout design errors. High pressures region **272** in a corner, and along a lower edge, are the result of the pattern discontinuities at the perimeter of the uniform array. Intermediate pressure regions **274** generally exist along the edges and beneath the vacuum hold. Proper pressure regions **276** were formed in a few areas.

(50) For thermal compression bonding, a minimum amount of pressure is specified to create the

bonds between bonding bumps on one substrate and corresponding bonding pads on another substrate. To achieve a high bond yield, a majority of the bonds may be in the proper pressure regions **276** and some bonds may be acceptable in the intermediate pressure regions **274**. No bonds are formed in null pressure areas or low pressure areas. In the high pressure regions **272**, the bump bonds are likely to expand outward and short to one another. Therefore, the image **260** (FIG. **10**) and the image **270** enable quick assessment of pressure distributions of the array patterns.

(51) Referring to FIG. **12**, a flow diagram of an example method **300** to aid in a calibration of the compression system **100** is shown in accordance with one or more exemplary embodiments. The method **300** includes steps **302** to **332**, as illustrated. The sequence of steps is shown as a representative example. Other step orders may be implemented to meet the criteria of a particular application. The method (or process) **300** is implemented with the compression system **100** with an unused first substrate **140** and a second substrate **160**.

(52) In the step **302**, the test film **146** may be fabricated on the first substrate **140**. The spikes **168** may be fabricated on the second substrate **160** in the step **304**. The optional over-coat layer **178** may be formed on each spike **168** in the step **306**. The over-coat layer **178** generally prevents a formation of a metallurgical bond between the spikes **168** and the test film **146** during the compressing.

(53) In the step **308**, the first substrate **140** may be mounted to the bottom chuck **106** in the press **102** with a first surface **142** facing outward. In the step **310**, the second substrate **160** may be mounted to the top chuck **104** in the press **102** with a second surface **162** of the second substrate **160** facing the first surface **142** of the first substrate **140**. In such a configuration, the spikes **168** are facing the test film **146**. The first substrate **140** and the second substrate **160** are compressed together in the step **312** with a sufficient force **136** to causes the spikes **168** to form the indentations **152** in the test film **146**. After the indentations **152** are created, the first substrate **140** is separated from the second substrate **160** in the step **314**.

(54) In the step **316**, the computer **120** may determine local pressures **154** applied by the spikes **168** against the test film **146** during the compression based on the images received from the sensor **110**. The computer **120** may generate a pressure map **266** in two-dimensions based on the calculated local pressures **154** in the step **318**.

(55) A check of the acceptability of the calibration acceptable is performed at the step **320**. If the calibration parameters did not produce an acceptable pressure map **266**, one or more calibration parameters (e.g., the tilt **130** and/or the force **136**) of the press **102** may be adjusted in the step **322**. Thereafter, the first substrate **140** may be replaced in the step **324** with an additional first substrate **140** with a new test film **146**. With the additional first substrate **140** in place, the spikes **168** are compressed into the new test film **146** in the step **326**.

(56) If the calibration is acceptable in the step **320**, the first substrate **140** may be replaced in the step **328** with the first working part **141**. The second substrate **160** may be replaced in the step **330** with the second working part **161**. In the step **332**, the first working part **141** and the second working part **161** may be bonded together by the force **136** applied by the press **102**.

(57) Referring to FIG. **13**, a flow diagram of an example method for step **316** to determine the local pressures is shown in accordance with one or more exemplary embodiments. The method generally includes steps **340** to **344**, as illustrated. The sequence of steps is shown as a representative example. Other step orders may be implemented to meet the criteria of a particular application.

(58) In the step **340**, the sensor **110** generates an image of the indentations **152** in the test film **146**. The light intensities **250** in the image (e.g., image **240** in FIG. **9**) are representative of the local pressures **154** applied by the spikes **168** against the test film **146** during the compression. The computer **120** determines the dimensions **182** of the indentations **152** in response to the light intensities **250** in the image in the step **342**. In the step **344**, the computer **120** calculates absolute values **252** of the local pressures **154** applied to the test film **146** in response to the dimensions **182** of the indentations **152** and the force **136** applied between the first substrate **140** and the second

substrate **160**.

(59) Referring to FIG. **14**, a flow diagram of an example method for step **322** to adjust the calibration parameters is shown in accordance with one or more exemplary embodiments. The method generally includes steps **360** to **364**, as illustrated. The sequence of steps is shown as a representative example. Other step orders may be implemented to meet the criteria of a particular application.

(60) In the step **360**, the press **102** is adjusted in the roll direction **130b** to help planarize the first substrate **140** with the second substrate **160**. The press **102** is adjusted in the pitch direction **130a** in the step **362** to help further planarize the first substrate **140** with the second substrate **160**. In the step **364**, the force **136** that the press **102** applies between the first substrate **140** and the second substrate **160** may be adjusted. Other calibration parameters of the press **102**, the top chuck **104**, the bottom chuck **106**, the load cell **108**, the first substrate **140** and/or the second substrate **160** may be changed in response to the pressure map **266**.

(61) Embodiments of the disclosure provide a fine-pitch arraying capability by employing metal indenters (e.g., the spikes **168**) with sufficient high hardness to indent many common thermocompression bond metals. The use of titanium as the indenters has benefits since titanium readily forms a surface oxide that acts as a natural release layer preventing metallurgical bonds to form between the titanium indenter tip and the indented metal materials (configured as the thin film or patterned as bumps). The hardness of the titanium indenters allow the plastically deformed indentations to remain unperturbed after the indenters are withdrawn.

(62) The fabrication of the spike arrays is useful in the pressure measurements and mapping, and generally outperforms standard methods. The fabrication process provides advantages of fine-pitch arrays (e.g., less than 10  $\mu\text{m}$ ). The fabrication process enables arrays with low tip height variation (e.g., down to <10 nm) because the spike heights are made with a self-limiting process that enables high fidelity replication. The sharp tips (e.g., approximately 10 nm dimensions) are integral to the fabrication process as the photoresist opening is closed as the titanium is deposited. The fabrication process provides an ability to fabricate a variety of different metals with high hardness (e.g., >116 GPa). The fabrication process also provides an ability to engineer the hardness by layering the spike structure (e.g., titanium and tungsten layered with softer metals such as gold, platinum, and palladium) and/or apply an over-coat to the spikes to improve its release after indentation and prevent metallurgical bonds to form (e.g., natural oxides help to prevent metallurgical bonds to indented material layers or bumps).

(63) The compression system **100** provides a method and device includes fine-pitch arrays of high hardness, conically shaped needle-like microstructures (spikes) and a flat thin metal film or a pattern flat metal film such that when the indenter array (fine-pitch spikes) is pressed onto the metal film, the local pressures and pressure distributions maps may be derived from the imprinted divot dimensions. The compression system **100** provides an optical method for converting the reflected light spatial intensity variation from conically shaped divots with nanometer dimensions into quantitative pressures and pressure distribution maps using a known applied force. The pressure distribution maps provide data useful for predicting bond yields from derived pressure thresholds from fine-pitch bond pad layout patterns using spike pressures and pressure mapping methods configured to mimic the layout pattern.

(64) Use of the first substrate **140** and the second substrate **160** to calibrate the press **102** results in an ability to prescreen candidate array layouts to access bond uniformity and yields. Since thermocompression bonds are not repairable, making a first-pass compression successful is helpful for manufacturing viability. The test kit **400** has a potential to ensure implementation of high yield designs, and allows testing of array pattern variations and tooling without the overhead of the entire process costs. Calibration of the compression system **100** has application to other semiconductor technologies where three-dimensional integration is a performance driver (e.g., radio-frequency systems, and microelectromechanical systems).

(65) In various embodiments, the compression system **100** is useful for measuring local pressures and global pressures from the nanometer to decimeter scale for wafer-to-wafer, die-to-wafer, and die-to-die thermocompression bonding applications. Numerous factors affect the pressures and pressure distributions observed during thermocompression bonding including bonder tooling, array patterns and pitches, substrate mechanical properties, and applied forces. The compression system **100** operates at high resolution to provide quantitatively accurate pressure measurements and pressure distributions across seven orders of magnitude length scales and employs materials, tooling, and layouts that closely mimic those used in semiconductor manufacturing.

(66) Embodiments of the disclosure provide measurements of pressure distributions for arbitrarily configured area arrays during bonding, where the arrays are scalable from small area arrays (e.g., 1,000 bump elements) to large area arrays (e.g., >1,000,000 bump elements). The disclosure provides light intensity to pressure conversion for efficient pressure mapping and analysis. Calibration parameters for press tilt, other bonder tooling issues (e.g., warp and tool sizing), and/or substrate parameters (e.g., thickness) that contribute to the array pressure non-uniformities may be identified before working parts are combined. The disclosure provides quick development of bond recipes by determining applied force suitable for achieving threshold local pressures for high yield bonding.

(67) This disclosure is susceptible of embodiments in many different forms. Representative embodiments of the disclosure are shown in the drawings and will herein be described in detail with the understanding that these embodiments are provided as an exemplification of the disclosed principles, not limitations of the broad aspects of the disclosure. To that extent, elements and limitations that are described, for example, in the Abstract, Background, Summary, and Detailed Description sections, but not explicitly set forth in the claims, should not be incorporated into the claims, singly or collectively, by implication, inference or otherwise.

(68) For purposes of the present detailed description, unless specifically disclaimed, the singular includes the plural and vice versa. The words “and” and “or” shall be both conjunctive and disjunctive. The words “any” and “all” shall both mean “any and all”, and the words “including,” “containing,” “comprising,” “having,” and the like shall each mean “including without limitation.” Moreover, words of approximation such as “about,” “almost,” “substantially,” “approximately,” and “generally,” may be used herein in the sense of “at, near, or nearly at,” or “within 0-5% of,” or “within acceptable manufacturing tolerances,” or other logical combinations thereof. Referring to the drawings, wherein like reference numbers refer to like components.

(69) The detailed description and the drawings or FIGS. are supportive and descriptive of the disclosure, but the scope of the disclosure is defined solely by the claims. While some of the best modes and other embodiments for carrying out the claimed disclosure have been described in detail, various alternative designs and embodiments exist for practicing the disclosure defined in the appended claims. Furthermore, the embodiments shown in the drawings or the characteristics of various embodiments mentioned in the present description are not necessarily to be understood as embodiments independent of each other. Rather, it is possible that each of the characteristics described in one of the examples of an embodiment may be combined with one or a plurality of other desired characteristics from other embodiments, resulting in other embodiments not described in words or by reference to the drawings. Accordingly, such other embodiments fall within the framework of the scope of the appended claims.

## Claims

1. A method to aid in a calibration of a compression system comprising: mounting a first substrate with a first surface facing outward in a press, wherein the press has a plurality of calibration parameters, and the first substrate has a test film on the first surface; mounting a second substrate in the press with a second surface of the second substrate facing the first surface of the first substrate,

wherein the second substrate has a plurality of spikes arranged in a spike pattern on the second surface; compressing the first substrate and the second substrate together with a force that causes the plurality of spikes to form a plurality of indentations in the test film; separating the first substrate from the second substrate; determining, with a sensor, a plurality of local pressures applied by the plurality of spikes against the test film during the compressing and generating an image of the plurality of indentations in the test film, wherein a plurality of light intensities in the image are representative of the plurality of local pressures applied by the plurality of spikes against the test film during the compressing; and adjusting one or more of the plurality of calibration parameters of the press in response to the plurality of local pressures.

2. The method according to claim 1, further comprising; determining a plurality of dimensions of the plurality of indentations in response to the plurality of light intensities in the image; and calculating a plurality of absolute values of the plurality of local pressures applied to the test film in response to the plurality of dimensions of the plurality of indentations and the force applied between the first substrate and the second substrate.

3. The method according to claim 1, further comprising: forming an over-coat layer on each of the plurality of spikes that prevents a formation of a metallurgical bond between the plurality of spikes and the test film during the compressing.

4. The method according to claim 1, wherein the adjusting of the one or more of the plurality of calibration parameters of the press is adjusting a tilt that the press establishes between the first substrate and the second substrate.

5. The method according to claim 1, wherein the adjusting of the one or more of the plurality of calibration parameters of the press is adjusting the force that the press applies during the compressing.

6. The method according to claim 1, further comprising: generating a pressure map in two-dimensions based on the plurality of local pressures, wherein the adjusting of the one or more of the plurality of calibration parameters of the press is in further response to the pressure map.

7. The method according to claim 1, further comprising: replacing the first substrate with an additional first substrate after the adjusting of the one or more of the plurality of calibration parameters of the press; and compressing the additional first substrate and the second substrate together with the force.

8. The method according to claim 1, further comprising: replacing the first substrate with a first working part after the adjusting of the one or more of the plurality of calibration parameters; replacing the second substrate with a second working part; and bonding the first working part to the second working part with the press.

9. A system to aid in a calibration of a compression system comprising: a first substrate having a test film on a first surface; a second substrate having a plurality of spikes arranged in a spike pattern on a second surface; a press having a plurality of calibration parameters, the press is configured to: mount the first substrate with the first surface facing outward; mount the second substrate with the second surface of the second substrate facing the first surface of the first substrate; compress the first substrate and the second substrate together with a force that causes the plurality of spikes to form a plurality of indentations in the test film; and separate the first substrate from the second substrate; and a sensor configured to determine a plurality of local pressures applied by the plurality of spikes against the test film during the compression, wherein one or more of the plurality of calibration parameters of the press is configured to adjust in response to the plurality of local pressures and wherein each of the plurality of spikes is formed with an over-coat layer that prevents a formation of a metallurgical bond between the plurality of spikes and the test film during the compression.

10. The system according to claim 9, wherein: the plurality of spikes have a cone shape; and the spike pattern comprises at least 1,000 of the plurality of spikes.

11. The system according to claim 9, wherein: the test film is formed from gold, aluminum, indium,

copper, platinum, palladium, or a first alloy thereof; and the plurality of spikes is formed from beryllium, titanium, palladium, vanadium, copper, manganese, nickel, cobalt, iron, rhodium, chromium, molybdenum, ruthenium, platinum, tantalum, tungsten, rhenium, iridium, aluminum oxide, silicon carbide, or a second alloy thereof.

12. The system according to claim 9, wherein each of the first substrate and the second substrate comprises a semiconductor.

13. The system according to claim 12, wherein: the first substrate is one of a semiconductor die, a semiconductor tile, or a semiconductor wafer; and the second substrate is one of a semiconductor die, a semiconductor tile, or a semiconductor wafer.

14. The system according to claim 9, wherein the sensor is a camera configured to generate an image of the plurality of indentations in the test film, wherein a plurality of light intensities in the image are representative of the plurality of local pressures applied by the plurality of spikes against the test film during the compression.

15. The system according to claim 14, further comprising a computer configured to: determine a plurality of dimensions of the plurality of indentations in response to the plurality of light intensities in the image; and calculate a plurality of absolute values of the plurality of local pressures applied to the test film in response to the plurality of dimensions of the plurality of indentations and the force applied between the first substrate and the second substrate.

16. The system according to claim 14, wherein: each of the plurality of indentations has a shape that retroreflects light; and the camera presents the image as off-axis light reflecting from the plurality of indentations.

17. A method to aid in a calibration of a compression system comprising: mounting a first substrate with a first surface facing outward in a press, wherein the press has a plurality of calibration parameters, and the first substrate has a test film on the first surface; mounting a second substrate in the press with a second surface of the second substrate facing the first surface of the first substrate, wherein the second substrate has a plurality of spikes arranged in a spike pattern on the second surface; compressing the first substrate and the second substrate together with a force that causes the plurality of spikes to form a plurality of indentations in the test film; separating the first substrate from the second substrate; determining, with a sensor, a plurality of local pressures applied by the plurality of spikes against the test film during the compressing; adjusting one or more of the plurality of calibration parameters of the press in response to the plurality of local pressures; and generating a pressure map in two-dimensions based on the plurality of local pressures, wherein the adjusting of the one or more of the plurality of calibration parameters of the press is in further response to the pressure map.

18. A method to aid in a calibration of a compression system comprising: mounting a first substrate with a first surface facing outward in a press, wherein the press has a plurality of calibration parameters, and the first substrate has a test film on the first surface; mounting a second substrate in the press with a second surface of the second substrate facing the first surface of the first substrate, wherein the second substrate has a plurality of spikes arranged in a spike pattern on the second surface; compressing the first substrate and the second substrate together with a force that causes the plurality of spikes to form a plurality of indentations in the test film; separating the first substrate from the second substrate; determining, with a sensor, a plurality of local pressures applied by the plurality of spikes against the test film during the compressing; adjusting one or more of the plurality of calibration parameters of the press in response to the plurality of local pressures; replacing the first substrate with a first working part after the adjusting of the one or more of the plurality of calibration parameters; replacing the second substrate with a second working part; and bonding the first working part to the second working part with the press.

19. The method according to claim 18, wherein the adjusting of the one or more of the plurality of calibration parameters of the press is adjusting a tilt that the press establishes between the first substrate and the second substrate.

20. The method according to claim 18, wherein the adjusting of the one or more of the plurality of calibration parameters of the press is adjusting the force that the press applies during the compressing.

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