Apparatus for Manufacturing Semiconductor Devices

Field of Invention

The present invention relates to an apparatus for the manufacture of semiconductor devices wherein the apparatus comprises a bonding module for the molecular bonding of wafers.

Background of the invention

Three-dimensional (3-D) integrated circuit technology where circuit structures formed on substrates, like for instance silicon-on-insulator (SOI) substrates, are bonded together and integrated into a 3-D circuit with dense-vertical connections becomes of increasing importance in modern semiconductor technology (see, for example, paper by Burns et al., entitled A Wafer-Scale 3-D Circuit Integration Technology, IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 53, NO. 10, OCTOBER 2006, pages 2507 - 2516). The building blocks of the 3-D circuit integration technology are, precision wafer–wafer alignment, low-temperature wafer–wafer bonding (molecular bonding or oxide fusion bonding), and electrical connection of the circuit structures with dense vertical interconnections. When compared to conventional bump bond technology, the wafer-scale 3-D technology offers higher density vertical interconnections and reduced system power.

Molecular bonding of wafers requires that the surfaces of the same are sufficiently smooth, free of particles or contamination, and that they are sufficiently close to each another to allow contact to be initiated, typically at a distance of less than a few nanometres at a point of initiation. In this case, the forces of attraction between the two surfaces are sufficiently high to cause propagation from this location of a "bonding wave" and molecular adhesion (bonding induced by all of the forces of attraction - Van

Der Waals forces - of the electronic interaction between the atoms or the molecules of the two surfaces of the wafers that are to be bonded). By the term "bonding wave" it is referred to the front of the bond or the molecular adhesion spreading from the point of initiation and corresponding to the dissemination of the forces of attraction (Van Der Waals forces) from the point of initiation over the entire surface of close contact between the two wafers (bonding interface).

However, molecular bonding faces the severe problems of bonding interface defects, like edge voids, wafer misalignment and wafer distortion defects which appear in the transfer layer during its assembly with the receiving substrate.

Such distortions are not the result of elementary transformations (translation, rotation or combinations thereof) that could originate in inaccurate assembly of the substrates (misalignment). These distortions result from non-homogeneous deformations that appear in the layer while it is being assembled with the final substrate. In fact, such distortions can lead to variations in position of micro components formed on or in the layer which may be in the order of several hundred nanometres or even microns. Since these distortions are not homogenous, it is not possible to correct completely these local misalignment errors during subsequently performed photolithography steps. Thereby dysfunctional semiconductor devices may result.

In view of the above and in spite of the recent technological progress there is a need for an apparatus for the manufacture of semiconductor devices that provides molecular bonding of wafers for 3D integrated circuit technology with sufficient accuracy, in particular, alignment, reduced layer distortion and suppression of bonding interface defects, as well as a high through-put.

Description of the Invention

The present invention addresses the above-mentioned need and, accordingly, provides an apparatus for the manufacture of semiconductor devices according to claim 1, comprising

a bonding module comprising a vacuum chamber to provide bonding of wafers under pressure below atmospheric pressure; and

a load lock module connected to the bonding module and configured for wafer transfer to the bonding module and connected to a first vacuum pumping device configured to reduce the pressure in the load lock module below atmospheric pressure.

According to the invention molecular bonding of wafers is performed in an evacuated vacuum chamber of a bonding module. Since the bonding is performed under (partial) vacuum, it has been observed that bonding interface defects such as edge voids can significantly be suppressed without affecting the bonding strength. In addition, wafers are transferred from the evacuated load lock module to the vacuum chamber of the bonding module thereby significantly increasing the throughput as compared to the prior art vacuum bonding module. Since the load lock module provides the wafers to the bonding module at vacuum pressure close to the low-pressure of the evacuated vacuum chamber of the bonding module, switching from vacuum pressure to atmospheric pressure and vice versa of the bonding module between two bonding steps (bonding step and step of transfer of at least one wafer from the load lock module to the bonding module) is avoided.

The load lock module is evacuated by a first pumping device, for example, to a pressure of about 1 mbars to below atmospheric pressure (below 1 bar), in particular, to a pressure in the range of 1 mbars to 10 mbars or 100 mbars. The vacuum chamber of the bonding module is, for example, evacuated by a second pumping device to a pressure in the range of 0.01 mbars to 10 mbars or 100 mbars, in particular, 0.1 mbars to 5 mbars. It is also noted that the temperature in the vacuum chamber is kept at room temperature in order to avoid deformation of the wafers due to thermal expansion of the wafer semiconductor material. The first and/or the second pumping devices can be connected to the load lock module and the vacuum chamber of the bonding module, respectively, by respective control valves provided to control the desired degree of vacuum. For both the first and the second pumping device a multi-stage rotary vane pump can be provided, for example.

It is noted that the bonding module encloses all means necessary for the aligned wafer bonding process under vacuum and is, thus, hermetically closed from the environment. The load lock module may be configured to receive and transfer to the bonding module one wafer at the same time or it may be configured to receive multiple wafers that can be stored in a multi wafer storing system provided in the load lock module. In the former case, the size of the load lock module can be minimized such that the vacuum of the vacuum chamber of the bonding module is not heavily affected by opening a gate separating the bonding module from the load lock module during wafer transfer. In the latter case, the throughput can be increased.

In particular, the load lock module may comprise a first gate that can be opened and closed for receipt of a wafer and a second gate that can be opened and closed for transfer of a wafer from the load lock module to the bonding module. After the wafer is received in the load lock module via the opened first gate and the first gate is closed again the first pumping device can start evacuating the load lock module.

According to an embodiment of the inventive apparatus at least one additional load lock module connected to the bonding module and configured to receive one or more wafers (wafer stacks) that were already bonded in the bonding module is provided in order to even further increase the throughput.

The bonding module may comprise at least a first moveable bonding chuck configured to hold a first wafer and a second moveable bonding chuck different from the first bonding chuck and configured to hold a second wafer different from the first wafer. A robot means can be provided inside the bonding module that is configured to grip the wafers from the load lock system and position them on the bonding chuck. Gripping can be achieved by mechanical means, electrostatic means or vacuum (if the clamping vacuum is well below the operating vacuum level of the vacuum chamber of the bonding module).

Two movable bonding chucks, positioned face to face, to support and clamp the wafers may be provided inside the vacuum chamber of the bonding module. The chucks are movable in translation and rotation in order to be able to position and align the two

wafers in front to each other. Each bonding chuck shall be provided with a planarity as good as possible, because it has been determined that chuck bow is one of the contributors for distortion defects. According to an embodiment the chucks are made of metal or ceramics, which cannot be easily deformed and maintain the planarity of the wafer. Bow of the chucks (maximum deviation from a median plane) should preferably be below 1 micron or even below 0.1 micron.

The first and second bonding chucks can be configured/orientated to hold or clamp the first and the second wafer, respectively, in a vertical position within less than 10° with respect to a vertical plane, more particularly, with an angle of at most about 1°. Each wafer has two main surfaces. According to an example, the main surfaces of the wafers are orientated (almost) vertically with respect to a horizontal plane whereupon the bonding module is located. In particular, the main surfaces of the wafers are orientated inclined to the vertical plane with an angle of less than about 10°, more particularly, with an angle of less than about 10°, and ev en more particularly, with an angle of at most about 1°. By this orientation, deformation (leading to distortion defects) of the wafers due to their own weight can be avoided and even large wafers of more than 300 mm in diameter can reliably be processed. In particular, the first and the second bonding chucks positioned vertically within less than 10° with respect to a vertical plane.

The apparatus may also include a control unit for controlling operation of different modules of the apparatus as well as the transfer of wafers from one module to another by means of robot means.

If required by the application, an optical positioning system can be provided in the bonding module that is operated to identify the exact position of alignment marks on the wafers, and the two chucks are then moved in translation and rotation to align the wafers in accordance with the identified alignment marks.

The actual molecular bonding process can be controlled by the above-mentioned control unit according to different alternatives, as for example disclosed in US20100122762. According to a first approach, the clamping is released to free the

two wafers from their chuck, and an additional force is applied locally to cause intimate contact (in terms of the acting molecular forces) of the wafers and initiate the bonding wave propagation. This additional force should be minimized (for instance below 5 N or even 1 N) so that no deformation of the wafer results. Thus, the inventive apparatus may further comprise a control unit configured to control the first and the second bonding chucks to move to each other to locate the first and the second wafers at a predetermined distance to each other, release the first and the second wafers at the predetermined distance and to initiate local application of a force by an appropriate local force application means to at least one of the first and the second wafers such that they locally become that close to each other that bonding is initiated. Here and in the following it is understood that bonding is initiated by molecular forces acting between the main surfaces of the wafers that have been approached closely to each other and are to be bonded.

According to a second approach, the intimate contact is first created, and then the un-clamping of the wafer is performed gradually. Intimate contact (in terms of the acting molecular forces) can be created by slightly deforming locally at least one of the wafers while bringing the two wafers in contact to each other. Deformation can be realized by locally decreasing the clamping force that retain the wafer onto the chuck. Once intimate contact has been created, the un-clamping is performed gradually to control the propagation speed of the bonding wave. According to a third approach un-clamping is performed non-gradually rather than gradually without any control of the bonding wave propagation. The latter approach is easier to implement.

Accordingly, the apparatus according to the present invention may further comprise a control unit configured to control the first and the second bonding chucks to move to each other to locate the first and the second wafers at a predetermined distance to each other and, subsequently, locally decreasing the clamping force applied by the first and/or second bonding chucks in order to hold the first and second wafer, respectively, such that the first and the second wafers locally become that close to each other that bonding is initiated.

The control unit may be configured to control gradual or non-gradual release of the first and/or second wafer upon the first and the second wafer locally became that close to each other that bonding is initiated.

The present invention, moreover, provides a manufacturing system (see also detailed discussion below) comprising the apparatus of one of the above-described examples and further comprising

a load port module configured to introduce a wafer (from an external environment) in the manufacturing system;

a plasma module configured to perform a plasma treatment of a surface of the wafer introduced in the manufacturing system;

a cleaning module configured to clean the surface of the wafer; and

a moveable robot means configured to transport the wafer from one of the load port module, plasma module, cleaning module, and load lock module to another one of these modules.

One or more plasma modules can be provided for activating one or both of the main surfaces of wafers. The cleaning module cleans and/or brushes the surfaces of the wafers that are to be bonded to each other in the bonding module. The robot means is configured to manipulate and transfer the wafers from the load port to any individual module, and also from one module to the other. The robot is particularly moving along a robot moving area, to enable the transfer of the wafer from one place to another. The system may also include a control unit controlling operation of the individual modules and transfer of the wafers by the robot means.

The above-mentioned need is also addressed by the herein provided method for the bonding of semiconductor wafers, comprising the steps of

evacuating a vacuum chamber of a bonding module;

transferring at least a first wafer to a load lock module that is connected to the bonding module;

evacuating the load lock module after transfer of at least the first wafer to the same;

transferring at least the first wafer from the evacuated load lock module to the evacuated vacuum chamber of the bonding module;

optionally adjusting the vacuum of the vacuum chamber after transfer of at least the first wafer (if this is desired due to quality reasons of the bonded wafers);

positioning the first wafer and a second wafer on a first and a second bonding chuck, respectively; and

moving the first and the second wafer to each other by movement of the first and/or second bonding chuck such that a main surface of the first wafer and a main surface of the second wafer locally come that close to each other that bonding is initiated.

In particular, the first and the second wafers can be positioned on the first and the second bonding chuck, respectively, in a vertical position within less than 10° with respect to a vertical plane and moved in that vertical position that close to each other that bonding is initiated.

The present invention furthermore provides a bonding module comprising

at least a first moveable bonding chuck configured to hold a first wafer; and

a second moveable bonding chuck different from the first bonding chuck and configured to hold a second wafer different from the first wafer;

wherein the first and the second bonding chucks are configured to hold the first and second wafers, respectively, in a vertical position within less than 10°with respect to a

vertical plane. The bonding chucks can be configured to hold the first and second wafers by mechanical means, electrostatic means or vacuum

The first and the second bonding chucks of this bonding module are positioned vertically within less than 10° with respect to a vertic al plane.

Further, the bonding module may comprise a vacuum chamber and the first and second bonding chucks are provided in the vacuum chamber. This bonding module can be combined with the load lock module described above in the context of the apparatus for the manufacture of semiconductor devices.

Eventually there is provided a bonding chuck configured to hold a semiconductor wafer that is to be bonded with another semiconductor wafer such that the semiconductor wafer is held in a vertical position within less than 10° with respect to a vertical plane. In particular the main surfaces of the wafer are orientated inclined to the vertical plane with an angle of less than about 10°, mor e particularly, with an angle of less than about 10°, and even more particularly, with an angle of at most about 1°. In particular, a main surface of the chuck that contacts a main surface of a wafer can be orientated vertically within 10° with respect to a vertical plane. The bonding chuck may hold the wafer by mechanical means, electrostatic means or vacuum.

Additional features and advantages of the present invention will be described with reference to the drawings. In the description, reference is made to the accompanying figures that are meant to illustrate preferred embodiments of the invention. It is understood that such embodiments do not represent the full scope of the invention.

Figure 1 illustrates an example of the inventive apparatus for the manufacture of a semiconductor device comprising a bonding module and a load lock module connected to the bonding module.

Figure 2 illustrates an example of a bonding module according to the present invention.

Figure 3 illustrates an example of a manufacturing system comprising the apparatus illustrated in Figure 1.

As shown in Figure 1 the apparatus of the present invention according to a particular example comprises a bonding module 1 and a load lock module 2. Bonding is performed in a vacuum chamber of the bonding module 1. The vacuum in the vacuum chamber of the bonding module 1 is established by a vacuum pumping means 3 that is connected to the vacuum chamber of the bonding module 1 via a control valve 4. Similarly a vacuum can be provided in the load lock module 2 by another vacuum pumping means 5 that is connected by another control valve 6 to the load lock module 2. In an alternative embodiment, a single vacuum pumping means is connected by separate control valves to both the load lock module and the bonding module. Moreover, the load lock module 2 comprises a first gate 7 that is opened when a wafer is transferred from the load lock module 2 to the bonding module 1 and a second gate 8 that is opened when a wafer is transferred by a robot to the load lock module 2.

The load lock module 2 may be configured as a one-wafer transfer module providing one single wafer at the same time to the bonding module 1 or may include a multi wafer storing systems for receiving multiple wafers via the second gate 8 and storing the same and, then, providing these multiple wafers to the bonding module 1 at the same time.

According to the present invention after one or more wafers have been loaded into the load lock module 2 and the second gate 8 has been closed (the first gate 7 is kept closed during the loading procedure), the load lock module 2 is evacuated to some predetermined pressure. Evacuation may be provided by the pumping device 5 at a rate of between 2.5 and 1,000 m^3/h, in particular, more than 500 m^3/h. The load lock module 2 is evacuated for example, to a pressure of about 1 mbars to some hundred mbar or to below atmospheric pressure. The vacuum chamber of the bonding module 1 is, for example, evacuated to a pressure in the range of 0.01 mbars to 10 mbars or 100mbars, in particular, 0.1 mbars to 5 mbars.

After evacuation the one or more wafers are transferred upon opening of the first gate 7 to the vacuum chamber of the bonding module 1 that was already evacuated by the first pumping means 3. Since during this transfer of the one or more wafers from the load lock module 2 to the bonding module 1 the latter is not exposed to atmospheric pressure only relatively slight adjustment of the pressure of the vacuum chamber of the bonding module 1 is necessary (if at all) after completion of the wafer transfer and closing the first gate 7. Thus, the throughput can significantly be increased.

It is noted that the throughput can be even further increased when another load lock module is provided, for example, on the left-hand-side of the bonding module 1 of Figure 1 and connected to the bonding module 1 to receive the already bonded wafers. In this case, the other load lock module shall also be evacuated before transfer of the bonded wafers from the bonding module 1. Alternatively, the load lock module 1 can be used to output the bonded wafers from the bonding module 1 to the external environment.

In Figure 2 an example of the bonding module 1 according to the present invention is illustrated. The bonding module comprises a vacuum chamber and is connected to a pumping device as described with reference to Figure 1. In addition, the bonding module comprises an optical system 9 that allows determining the exact position of alignment marks on the surfaces of the wafers to be bonded in the bonding module 1.

The optical system 9 is only necessary if the two wafers need to be perfectly aligned with micrometer precision. This is the case when the two wafers present micro components. By micro components elements are designated that result from technical steps carried out on or in the layers that must be positioned with precision. Thus, the micro components may be active or passive components, a mere contact point, or interconnections, like surface copper contact and interconnects. In the case of the process consist only of bonding one wafer with micro components onto a virgin support wafer the alignment step may and thus provision of the optical system 9 are not necessary.

Furthermore, the bonding module 1 is provided with a first bonding chuck 10 and a second bonding chuck 11 that clamp a first wafer 12 and a second wafer 13, respectively. The bonding chucks 10 and 11 may be made of metal or ceramics to maintain planarity of the wafers 12 and 13. Whereas in Figure 2 the bonding chucks 11 and 12 are shown to hold the wafers 12 and 13 horizontally, the bonding chucks 11 and 12 may advantageously be arranged to hold the wafers 12 and 13 vertically. In this case, deformation of the wafers due to their own weight can be avoided.

In the shown example, the optical system 9 is electrically coupled to a control unit 14 that is computing the displacement of the bonding chucks 11 and 12 (in the plane and in rotation) in order to perfectly align the two wafers 12 and 13. Moreover, the control unit 14 controls movement of the of the bonding chucks 11 and 12 to each other until the wafers 12 and 13 come into contact for molecular bonding.

Figure 3 illustrates an example of a manufacturing system 20 comprising the apparatus illustrated in Figure 1. In particular, the manufacturing system 20 comprises a bonding module 1, for example, the bonding module 1 shown in Figure 2, and two load lock modules 2 and 2'. The manufacturing system 20 includes at least a load port 21 for introducing wafers into the manufacturing system 20. A robot 22 is configured to manipulate and transfer the wafers from the load port 21 to any individual module of the manufacturing system 20, and also from one module to the other. The robot is moving along a robot moving area (indicated by dashed lines), to enable the transfer of the wafer from one place to another.

In addition, the manufacturing system 20 comprises a plasma station 23 for activating one or two main surfaces of the wafers introduced into the manufacturing system 20. In order to minimize the surface preparation time, a second plasma station could be added, if the wafer processing requires that the main surface of both wafers to be bonded need to be activated. Alternatively, the same plasma station 23 can be used to treat surfaces to be bonded of each respective wafer. A first cleaning station 24 is provided to clean a bonding main surface of a first wafer and a second cleaning station 25 is provided to clean a bonding main surface of a second wafer.

The manufacturing system 20, further comprises a control unit (not shown in Figure 3) for controlling the robot means 22 for transporting wafers in the manufacturing system 20. For example, the control unit may control the robot means 22 to:

pick a first wafer from load port 21 and transport it to plasma station 23;

pick a second wafer from load port 21 and transport it to cleaning station 25;

pick the first wafer from plasma station 23 and transport it to cleaning station 24;

pick the second wafer from cleaning station 25 and transport it to load lock module 2';

pick the first wafer from cleaning station 24 and transport it to load lock module 2; and

pick bonded first and second wafers after they have been processed in the bonding module 1 from the load lock module 2 and transport it to the load port 21.

All previously discussed embodiments are not intended as limitations but serve as examples illustrating features and advantages of the invention. In particular, and although the invention as been described in the context of wafers for use in the semiconductor industry, it is applicable to different sorts of wafers or substrates, that may present characteristics (for instance in term of nature, size or shaped) different from the characteristics typical from a wafer used in the semiconductor industry. It is also to be understood that some or all of the above described features can also be combined in different ways.

Claims

1. Apparatus for the manufacture of semiconductor devices; comprising

a bonding module comprising a vacuum chamber to provide bonding of wafers under pressure below atmospheric pressure; and

a load lock module connected to the bonding module and configured for wafer transfer to the bonding module and connected to a first vacuum pumping device configured to reduce the pressure in the load lock module below atmospheric pressure;

and further comprising a second vacuum pumping device connected via a control valve to the vacuum chamber of the bonding module and configured to reduce the pressure in the vacuum chamber of the bonding module below atmospheric pressure;

and wherein the load lock module comprises a first gate that can be opened and closed for receipt of a wafer and a second gate that can be opened and closed for transfer of a wafer from the load lock module to the bonding module.

2. The apparatus according to claim 1 wherein the load lock module comprises a multi wafer storage system for storing multiple wafers to be transferred to the bonding module.

3. The apparatus according to claim 1 or 2, further comprising at least one additional load lock module connected to the bonding module and configured to receive one or more wafers bonded in the bonding module.

4. The apparatus according to claim 1 or 2, wherein the bonding module comprises at least a first moveable bonding chuck configured to hold a first wafer and a second moveable bonding chuck different from the first bonding chuck and configured to hold a second wafer different from the first wafer.

5. The apparatus according to claim 4, wherein the first and second bonding chucks are configured to hold the first and the second wafer, respectively, in a vertical position within less than 10° with respect to a vertical plane.

6. The apparatus according to claim 4, wherein at least one of the first bonding chuck and the second bonding chuck have a bow below 1 micron or below 0.1 micron, wherein the bow is a maximum deviation from a median plane.

7. The apparatus according to claim 4, wherein at least one of the first bonding chuck and the second bonding chuck is made of metal or ceramics.

8. The apparatus according to claim 4, further comprising a control unit configured to control the first and the second bonding chucks to move to each other to locate the first and the second wafers at a predetermined distance to each other, release the first and the second wafers at the predetermined distance and to

initiate local application of a force to at least one of the first and the second wafers such that the main surfaces of the first and the second wafers become close to each other so that bonding is initiated by molecular forces acting between the main surfaces of the first and the second wafers.

9. The apparatus according to claim 4, further comprising a control unit configured to control the first and the second bonding chucks to move to each other to locate the first and the second wafers at a predetermined distance to each other and, subsequently, locally decreasing the clamping force applied by at least one of the first and second bonding chucks in order to deform locally at least one of the first and second wafers, respectively, such that the main surfaces of the first and the second wafers become close to each other so that bonding is initiated by molecular forces acting between the main surfaces of the first and the second wafers.

10. The apparatus according to claim 9, wherein the control unit is configured to control gradual release of at least one of the first and second wafers upon the first and the second wafers became close to each other so that bonding is initiated by molecular forces acting between the main surfaces of the first and the second wafers.

11. Manufacturing system comprising the apparatus of claim 1 or 2, further comprising

a load port module configured to introduce a wafer in the manufacturing system;

a plasma module configured to perform a plasma treatment of a surface of the wafer introduced in the manufacturing system;

a cleaning module configured to clean the surface of the wafer; and

a moveable robot means configured to transport the wafer from one of the load port module, plasma module, cleaning module, and load lock module to another one of these modules.

12. Method for bonding semiconductor wafers, comprising the steps of

evacuating a vacuum chamber of a bonding module;

transferring at least a first wafer to a load lock module that is connected to the bonding module;

evacuating the load lock module after transfer of at least the first wafer;

transferring at least the first wafer from the evacuated load lock module to the evacuated vacuum chamber of the bonding module;

optionally adjusting the vacuum of the vacuum chamber after transfer of at least the first wafer;

positioning the first wafer and a second wafer on a first and a second bonding chuck, respectively; and

moving the first and the second wafers to each other by movement of at least one of the first and second bonding chucks such that a main surface of the first wafer and a main surface of the second wafer come close to each other so that bonding is initiated by molecular forces acting between the main surfaces of the first and the second wafers.

13. The method according to claim 12, wherein the first and the second wafers are positioned in a vertical position within less than 10° with respect to a vertical plane on the first and the second bonding chucks, respectively, and moved in the vertical position close to each other such that bonding is initiated by molecular forces acting between the main surfaces of the first and the second wafers.

14. The apparatus according to claim 9, wherein the control unit is configured to control non-gradual release of at least one of the first and second wafers upon the first and the second wafers became close to each other so that bonding is initiated by molecular forces acting between the main surfaces of the first and the second wafers.