

A METHOD OF ASSEMBLING WAFERS BY MOLECULAR BONDING

Technical field and prior art

The present invention relates to the field of
5 producing multilayer semiconductor wafers or substrates
produced by transfer of at least one layer formed from an
initial substrate onto a final substrate, the transferred
layer corresponding to a portion of the initial
substrate. The transferred layer may further comprise
10 all or part of a component or a plurality of
microcomponents.

More precisely, the present invention relates to the
problem of heterogeneous deformations that appear during
transfer of a layer from a substrate termed the "donor
15 substrate" onto a final substrate termed the "receiving
substrate". Such deformations have in particular been
observed with the three-dimensional component integration
technique (3-D integration) that requires transfer of one
or more layers of microcomponents onto a final support
20 substrate, but also when transferring circuits or
fabricating back-lit imagers. The transferred layer or
layers include microcomponents (electronic,
optoelectronic, etc) produced at least partially on an
initial substrate, said layers then being stacked on a
25 final substrate that may optionally itself include
components. Primarily because of the much reduced size
and large number of microcomponents present on a single
layer, each transferred layer must be positioned on the
final substrate with high precision in order to come into
30 very strict alignment with the subjacent layer. Further,
it may be necessary to carry out treatments on the layer
after it has been transferred, for example to form other
microcomponents, to uncover the surface of the
microcomponents, to produce interconnections, etc.

35 However, the Applicant has observed that after
transfer, there are cases when it is very difficult, if
not impossible, to form additional microcomponents that

are aligned with the microcomponents formed before transfer.

This misalignment phenomenon is described with reference to Figures 1A to 1E that illustrate an example of making a three-dimensional structure comprising transfer, onto a final substrate, of a layer of microcomponents formed on an initial substrate, and formation of an additional layer of microcomponents on the exposed face of the initial substrate after bonding. Figures 1A and 1B illustrate an initial substrate 10 on which a first series of microcomponents 11 is formed. The microcomponents 11 are formed by photolithography using a mask that can define pattern formation zones corresponding to the microcomponents 11 to be produced. As can be seen in Figure 1C, the face of the initial substrate 10 with the microcomponents 11 is then brought into intimate contact with a face of a final substrate 20. Bonding between the initial substrate 10 and the final substrate 20 is generally carried out by molecular bonding. Thus, a buried layer of microcomponents 11 is formed at the bonding interface between substrates 10 and 20. After bonding, and as can be seen in Figure 1D, the initial substrate 10 is thinned in order to remove a portion of the material present above the layer of microcomponents 11. A composite structure 30 is thus formed from the final substrate 20 and a layer 10a corresponding to the remaining portion of the initial substrate 10.

As can be seen in Figure 1E, the next step in producing the three-dimensional structure consists in forming a second layer of microcomponents 12 at the exposed surface of the thinned initial substrate 10, or in carrying out additional technical steps on that exposed surface in alignment with the components included in the layer 10a (making contact, interconnections, etc). For the purposes of simplification, the term "microcomponents" is used in the remainder of this text

to define devices resulting from technical steps carried out on or in the layers that must be positioned with precision. Thus, they may be active or passive components, a simple point of contact, or
5 interconnections.

In order to form the microcomponents 12 in alignment with the buried microcomponents 11, a photolithography mask is used that is similar to that used to form the microcomponents 11. The transferred layers, like the
10 layer 10a, typically include marks, both amongst the microcomponents and on the wafer forming the layer, that are in particular used by the positioning and alignment tools during the technical treatment steps, such as those carried out during photolithography.

However, even using positioning tools, offsets occur between some of the microcomponents 11 and 12, such as the offsets Δ_{11} , Δ_{22} , Δ_{33} , Δ_{44} shown in Figure 1E (respectively corresponding to the offsets observed between the pairs of microcomponents 11₁/12₁, 11₂/12₂,
20 11₃/12₃ and 11₄/12₄).

Such offsets result from heterogeneous deformations that appear in the layer deriving from the initial substrate during its assembly with the final substrate. The deformations cause displacements of certain
25 microcomponents 11. In addition, certain of the microcomponents 12 formed on the exposed surface of the substrate after transfer exhibit positional variations with those microcomponents 11 that may be of the order of several hundred nanometers, or even a micrometer.

This phenomenon of misalignment (also termed "overlay") between the two layers of microcomponents 11 and 12 may be a source of short circuits, distortions in the stack or connection defects between the microcomponents of the two layers. This phenomenon of
35 overlay thus results in a reduction in the quality and value of multilayer semiconductor wafers as fabricated. The impact of that phenomenon is growing because of the

ceaseless increase in demand for miniaturization of microcomponents and their increased integration density per layer.

Problems with alignment during fabrication of three-dimensional structures are well known. The document by Burns et al, "A Wafer-Scale 3-D Circuit Integration Technology", IEEE Transactions On Electron Devices, vol 53, No 10, Oct 2006, describes a method of detecting variations in alignment between bonded substrates. The document by Haisma et al , "Silicon-Wafer Fabrication and (Potential) Applications of Direct-Bonded Silicon", Philips Journal of Research, vol 49, No 1/2, 1995, emphasize the importance of flatness of wafers in particular during polishing steps in order to obtain good quality final wafers, i.e. with as few offsets as possible between the microcomponents.

More generally, it is not desirable to introduce heterogeneous deformations into a substrate during transfer thereof onto another substrate.

Summary of the invention

Embodiments of the invention aim to provide a solution that can limit non-homogenous deformations that appear in a substrate during transfer onto another substrate.

According to a first aspect of the present invention, there is provided a method of bonding two wafers or substrates by molecular bonding, the method comprising :

- a) bringing the surfaces of the wafers to be assembled into at least partial contact;
- b) a first propagation of a bonding wave from a point of pressure applied to at least one of the two wafers; and
- c) a second propagation of the bonding wave over a

zone covering the point of pressure, wherein said second propagation advances in a direction different from the direction of the first propagation and over a zone covering the initiation point from which the first propagation of the bonding wave is triggered by application of the point of pressure.

As explained below in more detail, after a first propagation of the bonding wave that is normally carried out to allow molecular bonding, initiating a second

propagation of the bonding wave over a zone including the point of pressure causes the heterogeneous deformations that are produced in the wafer by initiating propagation of the first bonding wave to be reduced, while carrying out molecular bonding over all of the surfaces of the two wafers in contact.

Thus, by minimizing the deformations caused by applying a point of pressure during molecular bonding, the risk of overlay occurring during subsequent formation of additional layers of microcomponents may be substantially reduced.

The point of pressure is preferably applied close to the edge of one of the two wafers in order to allow a first bonding wave propagation over a large distance and to form a zone that is almost without deformation in the portion remote from the point of pressure.

In one embodiment of the invention, during step a), a separating element is interposed between the surfaces of the wafers to be assembled, said element being removed in step c) to initiate the second bonding wave propagation. In a variant implementation, after step b) and before step c), the separating element may also be displaced towards the interior of the wafers in order to partially open the bonding interface formed during the first bonding wave propagation.

In another embodiment of the invention, the wafers are brought completely into contact during step a). Then, before step c), the assembled wafer surfaces are partially unbonded over a zone that is located at least in the vicinity of the point of pressure, and then said surfaces are brought into contact again to initiate the second bonding wave propagation. The assembled wafer surfaces are preferably unbonded in a zone including the point of pressure, which further encourages the release of stresses in said zone.

According to a second aspect of the present invention, there is provided a method of producing a composite three-dimensional structure, the

method comprising a step of producing a first layer of microcomponents on one face of a first substrate and a step of bonding the face of the first substrate comprising the layer of microcomponents onto a second substrate, wherein the first and second substrates are assembled in accordance with the assembly method as defined in the first aspect.

Using the assembly method according to embodiments of the present invention means that during transfer of a layer of microcomponents, the phenomenon of overlay can be eliminated and very high quality multilayer semiconductor wafers can be produced. The layer of microcomponents may in particular include image sensors.

In this case, the material of the second substrate is a transparent material such as silica or quartz.

Brief description of the figures

- Figures 1A to 1E are diagrammatic views showing the production of a prior art three-dimensional structure;
- Figures 2 to 5 are diagrammatic views of a molecular bonding assembly method in accordance with one implementation of the invention;
- Figures 6 to 10 are diagrammatic views of a method of bonding by molecular bonding in accordance with one implementation of the invention;
- Figures 11A to 11D are diagrammatic views showing the production of a three-dimensional structure employing the assembly method of the present invention;
- Figure 12 is a flowchart of steps carried out during production of the three-dimensional structure illustrated in Figures 11A to 11D.

Detailed description of implementations of the invention

The present invention is generally applicable to the production of composite structures by a method including

at least bonding a first substrate or wafer onto a second substrate or wafer, by molecular bonding.

Molecular bonding is a technique that is well known per se. It should be recalled that the principle of molecular bonding is based on bringing two surfaces into direct contact, i.e. without the use of a specific bonding material (adhesive, wax, braze, etc). Such an operation requires that the surfaces to be bonded are sufficiently smooth, free of particles or of contamination, and that they are sufficiently close together for contact to be initiated, typically a distance of less than a few nanometers. Under such circumstances, the attractive forces between the two surfaces are sufficiently high to cause molecular bonding (bonding induced by the set of attractive forces (Van der Waals forces) of electronic interaction between atoms or molecules of the two surfaces to be bonded).

Molecular bonding is initiated by applying a localized pressure, for example using a Teflon® stylus, to a wafer in intimate contact with another wafer in order to trigger the propagation of a bonding wave from that initiation point. The term "bonding wave" is applied here to the bonding front or molecular bonding front that propagates from the initiation point and that corresponds to diffusion of attractive forces (van der Waals forces) from the initiation point over the whole surface in intimate contact between the two wafers (bonding interface).

The Applicant has demonstrated that the relative displacements between certain patterns or microcomponents in a single substrate appear after the step of bonding that substrate onto another by molecular bonding. More precisely, experiments carried out by the Applicant have demonstrated that stresses (tensile and/or compressive) are produced at the initiation point of bonding by molecular bonding, i.e. the region where the point of pressure is applied. These stresses lie at the source of

heterogeneous deformations appearing in the substrate and, as a result, of relative and unequal displacements of certain patterns or microcomponents relative to each other.

5 The Applicant has observed that the deformations are principally localized at and around the initiation point or triggering of bonding and that these deformations are elastic. These deformations may extend over a radius of up to 15 cm [centimeter] around the point of application
10 of pressure.

In contrast, in the portion of the substrate that is remote from the initiation point, i.e. in the portion where the bonding wave has propagated, the deformations observed are minimal. In particular, this localization
15 of deformations at the initiation point is explained by the fact that this zone corresponds to the region where the pressure is applied in order to initiate the bonding wave. Localized application of a pressure creates stresses that reduce with distance from the point of
20 application of the pressure stress.

As a result, the present invention proposes controlling the molecular bonding process during bonding of substrates in order to produce, after the first bonding wave propagation normally carried out to allow
25 molecular bonding, a second bonding wave propagation over a zone located at least in the vicinity of the point of pressure, i.e. over a zone located less than 15 cm from the point of application of pressure to reach at least a portion of the deformations. The second wave propagation
30 is preferably carried out over a zone that covers or includes the point of application of pressure.

Thus, when this second bonding wave propagation reaches the zone of application of the point of pressure corresponding to the initiation point of the first
35 bonding wave propagation, because of a different direction of propagation it can in particular release the stresses caused by initiation of the first propagation,

and as a consequence it can reduce the deformations in the wafer in this region, while producing molecular bonding over the whole of the surfaces of the two wafers in contact.

5 Further, in contrast to the first bonding wave propagation, initiation of the second bonding wave propagation in accordance with the invention does not cause new stresses, nor does it cause new deformations in the wafers. In fact, the second bonding wave propagation
10 is initiated while the partial bonding by molecular bonding produced during the first bonding wave propagation subsists between the two wafers, where the portions of the wafers that have thus already been bonded have minimal deformations beyond the vicinity of the
15 point of pressure, as explained above. As a consequence, the second bonding wave propagation may be initiated from a stress-free zone without having to apply a new point of application of pressure since molecular bonding is taken up from the subsisting partial bonding zone. In other
20 words, the second bonding wave propagation is initiated by closing the bonding interface again at a non-bonded portion or re-opened portion between the two wafers after the first bonding wave propagation, this portion being located close to a stress-free bonding zone between the
25 two wafers.

A first implementation of an assembly method of the invention is described with reference to Figures 2 to 5. In Figure 2, a first wafer or substrate 20 is placed in a bonding machine comprising a substrate carrier device 40.
30 The substrate carrier device 40 comprises a support platen 40a that holds the first wafer 20, for example by means of an electrostatic or suction system associated with the support platen 40a, with a view to assembling it with a second wafer or substrate 30 by molecular bonding.
35 As explained above and in known manner, the surfaces 21 and 31 respectively of wafers 20 and 30 intended to be bonded are previously prepared (by polishing, cleaning,

hydrophobic/hydrophilic treatment etc) to allow molecular bonding.

Surfaces 21, 31 of wafers 20, 30 are then brought into intimate contact one with the other, with the exception of a zone 42 where a separating element in the form of a pin 41 is interposed between the two wafers, as illustrated in Figure 3.

As can be seen in Figure 4, a first bonding wave propagation 44 is initiated from an initiation point 43 that corresponds to the region of the wafer 30 on which a point of pressure is exerted, for example using a Teflon® stylus. Application of a bearing pressure at the point 43 gives rise to stresses around this point as represented by stress lines 45a to 45e, with the intensity of the stress reducing as a function of distance from the initiation point 43.

The initiation point of the first bonding wave propagation 44 may be localized at any point on the wafer 30. However, in order to provide a zone with as little deformation as possible, the initiation point is preferably localized at the periphery of the wafer in order to allow the first bonding wave to propagate over a large distance and to form, in the portion remote from the initiation point, a zone that is substantially free from deformations compared with the zone located in the vicinity of the initiation point 43. In Figure 4, it can be seen that the shape of the first bonding wave propagation 44 becomes smoother as it advances in the direction A from the initiation point 43 to the opposite extremity of the wafer 30, which indicates that the stresses responsible for heterogeneous offsets in the wafer 21 reduce significantly with increasing distance from the initiation point 43.

Once the first bonding wave propagation has reached the opposite extremity of the initiation point 43, the pin 41 is withdrawn in order to close the zone 42 once more and then initiate a second bonding wave propagation

46 that advances in the direction B out from the bonding zone having no deformation, or substantially no deformation, as shown in Figure 5. The bonding wave that propagates during the second propagation has a smooth
5 shape up to the region or zone of the initiation point 43. This second bonding wave propagation can completely re-close the bonding interface between the two wafers, while correcting deformations created in the vicinity of the initiation point 43 during the first bonding wave
10 propagation 44. As can be seen in Figure 5, this second bonding wave propagation extends over a zone including or covering the initiation point or pressure 43.

The region of the initiation point 43 is preferably selected to be relatively close to the pin 41 in order to
15 ensure that separation of the two wafers is in a zone near to the zone where the point of pressure has been applied. This provides better release of the stresses caused at the point of pressure. If the initiation point is located towards the center of the wafers rather than
20 close to their edge, the pin is disposed in a position that is advanced further towards the center of the wafers.

In a variation, the separating element, for example the pin 41, initially positioned at the edge of the
25 wafer, may be displaced towards the interior of the wafers after initiation of the first bonding wave propagation in order to partially unbond the bonding interface. This means that the bonding interface can be opened close to or at the initiation point, in particular
30 when the separating element has initially been placed in a zone distant from the initiation point, such as a zone situated in the vicinity of the center of the wafer, for example.

Figures 6 to 10 show another implementation of an
35 assembly method of the invention that differs from the implementation described above in that the second bonding

wave is generated by re-opening the bonding interface between the two wafers.

More precisely, as can be seen in Figures 6 and 7, the surfaces 51 and 61 respectively of first and second wafers or substrates 50, 60 are brought into intimate contact under the same conditions as described above, the first wafer 50 being held on a support platen 70a of a substrate carrier device 70. A first bonding wave propagation 64 is initiated from a initiation point 63 by applying a point of pressure and it advances in a direction A to the opposite extremity of the wafer 50 as shown in Figure 8. Applying a bearing pressure at the point 63 gives rise to stresses around this point as represented by stress lines 65a to 65e, the intensity of the stress reducing as a function of distance from the initiation point 63.

In this implementation, no obstacle is disposed between the two wafers, with the result that molecular bonding takes place over the whole of the bonding interface during the first bonding wave propagation 64. In order to initiate the second bonding wave propagation, partial unbonding is carried out between the two wafers by opening the bonding interface over a zone 62 (Figure 9). Partial unbonding of the wafers may, for example, be achieved by inserting a blade, for example formed from Teflon®, or by applying a jet of fluid (water, air, gas, etc) at the bonding interface. Partial unbonding may also be carried out by inserting a pin such as the pin 41 described above.

The bonding interface may be re-opened from any region at the periphery of the two wafers. However, partial unbonding between the two wafers is preferably carried out at the initiation point 63. By re-opening the bonding interface at the initiation point 63, the stresses caused around this point can be released since the portion of wafer 60 comprised in the zone 62 is no longer bonded to the wafer 50. The insertion length for

the separating object (for example a blade or pin) or the power of penetration of the jet of fluid is a function of the position of the initiation point on the wafers (proximity to edge or center of the wafers).

5 The unbonded zone 62 is then closed again in order to initiate a second bonding wave propagation 66 which displaces in the direction B indicated in Figure 10 and can completely re-close the bonding interface between the two wafers without deformation. As can be seen in
10 Figure 10, this second bonding wave propagation extends over a zone including or covering the initiation point or pressure 63.

 The unbonding/rebonding steps carried out to initiate the second bonding wave propagation may be
15 repeated a number of times, changing or not changing the unbonding zone, in order to further minimize the stresses and deformations to which the wafer 60 or the two wafers 50 and 60 are subjected.

 The method of the invention is applicable to
20 assembling any type of material that is compatible with molecular bonding, in particular semiconductor materials such as silicon, germanium, glass, quartz, etc. The wafers to be assembled may have microcomponents only over a portion thereof.

25 One particular but non-exclusive field for the assembly method of the present invention is that of producing three-dimensional structures.

 One method of producing a three-dimensional structure by transfer of a layer of microcomponents
30 formed on an initial substrate onto a final substrate in accordance with an implementation of the invention is described with reference to Figures 11A to 11D and 12.

 Production of the three-dimensional structure commences by forming a first series of microcomponents
35 110 on the surface of a wafer or initial substrate 100 (Figure 11A, step S1). The initial substrate 100 may be a monolayer structure, for example a layer of silicon, or

a multilayer structure such as a SOI type structure. The microcomponents 110 are formed by photolithography using a mask that can define pattern formation zones corresponding to the microcomponents 110 to be produced.

5 During formation of the microcomponents 110 by photolithography, the initial substrate 100 is held on a substrate support device 120. The substrate support device comprises a support platen 120a with which the initial substrate 100 lies flush, for example by means of
10 an electrostatic or suction system associated with the support platen 120a.

The face of the initial substrate 100 comprising the microcomponents 110 is then brought into intimate contact with one face of a final wafer or substrate 200 (step S2)
15 with a view to bonding by molecular bonding. A layer of oxide, for example of SiO_2 , may also be formed on the face of the initial substrate 100 comprising the microcomponents 110 and/or on the face of the final substrate 200 intended to be brought into intimate
20 contact.

A first bonding wave propagation allowing molecular bonding between the two substrates is then initiated by applying localized pressure at the initiation point as explained above (step S3).

25 A second bonding wave propagation is then initiated over a zone located at least in the vicinity of the initiation point of the first bonding wave propagation (step S4). This second bonding wave propagation preferably passes through the initiation point of the
30 first bonding wave propagation.

As explained above in relation to Figures 2 to 5, the second bonding wave propagation may be initiated by withdrawing a separating element interposed between the two substrates 100, 200 during initiation of the first
35 bonding wave propagation in order to preserve a non-bonded zone that allows initiation of the second bonding wave propagation. In accordance with another variation

described above with reference to Figures 6 to 10, the second bonding wave propagation may be initiated by partially re-opening and closing the bonding interface obtained during initiation of the first bonding wave propagation.

After the second bonding wave propagation, the initial substrate 100 and the final substrate 200 are bonded together by molecular bonding over the whole of their surface in contact, with no deformation, or almost no deformation in the initial substrate 100 comprising the microcomponents 110 (Figure 11B). This thus produces a buried layer of microcomponents 110 at the bonding interface between the substrates 100 and 200.

After bonding, and as can be seen in Figure 11C, the initial substrate 100 is thinned-down in order to remove a portion of the material present above the layer of microcomponents 110 (step S5). When the substrate 100 is a SOI type substrate, it is advantageously possible to use the buried insulating layer to define the thickness of the remaining layer 100a. Thus, a composite structure 300 is produced, formed from the final substrate 200 and a layer 100a corresponding to the remaining portion of the initial substrate 100. The initial substrate 100 may in particular be thinned-down by chemical-mechanical polishing (CMP), by chemical etching, or by splitting, or fracture along a plane of weakness that has been formed in the substrate by atomic implantation.

As can be seen in Figure 11D, the next step in producing the three-dimensional structure consists in forming a second layer of microcomponents 140 at the exposed surface of the thinned-down initial substrate 100 (Figure 11D, step S6). In order to form the microcomponents 140 in alignment with the buried microcomponents 110, a photolithography mask is used that is similar to that employed to form the microcomponents 110. As during formation of the microcomponents 110, the composite structure 300 formed by the final substrate 200

and the layer 100a is held on a support platen 130a of a substrate carrier device 130 that is identical to the device 120. The photolithography mask is then applied to the free surface of the layer 100a.

5 In a variation, the three-dimensional structure is formed by a stack of layers, each layer having been transferred by the assembly method of the present invention, and each layer being in alignment with the directly adjacent layers.

10 Because of the molecular bonding initiation method of the invention, the initial substrate 100 can be bonded onto the final substrate with no deformation, or at least with reduced deformation, in such a manner that significant offsets of the microcomponents 110 before and
15 after transfer of the initial substrate 100 onto the final substrate 200 are no longer observed. Thus, these residual offsets can be limited to values of less than 200 nm [nanometer], or even 100 nm in a homogeneous manner over the whole surface of the wafer. The
20 microcomponents 140, even those of very small dimensions (for example $< 1 \mu\text{m}$ [micrometer]), may thus easily be formed in alignment with the microcomponents 110, even after transfer of the initial substrate.

25 As a result, the assembly method of the present invention can eliminate the phenomenon of overlay during transfer of one circuit layer onto another layer or onto a support substrate and produce very high quality multilayer semiconductor wafers.

CLAIMS

1. A method of bonding two wafers or substrates by molecular bonding, the method comprising:
 - a) bringing the surfaces of the wafers to be assembled into at least partial contact;
 - b) a first propagation of a bonding wave from a point of pressure applied to at least one of the two wafers; and
 - c) a second propagation of the bonding wave, wherein said second propagation advances in a direction different from the direction of the first propagation and over a zone covering the initiation point from which the first propagation of the bonding wave is triggered by application of the point of pressure.
2. A method according to claim 1, wherein the point of pressure is applied close to the edge of one of the two wafers.
3. A method according to claim 1 or claim 2, wherein during step a), a separating element is interposed between the surfaces of the wafers to be assembled, and wherein in step c) the separating element is withdrawn in order to initiate the second propagation of the bonding wave.
4. A method according to claim 3, wherein after step b) and before step c), the separating element is displaced towards the interior of the wafers.
5. A method according to claim 1 or claim 2, wherein in step b), molecular bonding takes place over the whole of the bonding interface and wherein before step c) and after step b), the surfaces of the assembled wafers are partially unbonded over a zone that is located at least in the vicinity of the point of pressure.
6. A method according to claim 5, wherein the surfaces of the assembled wafers are partially unbonded over a zone including the point of local pressure.

7. A method of producing a three-dimensional composite structure comprising a step of producing a first layer of microcomponents on one face of a first substrate and a step of bonding the face of the first substrate comprising the layer of microcomponents onto a second substrate, wherein the first and second substrates are assembled in accordance with an assembly method according to any one of claims 1 to 6.
8. A method according to claim 7, wherein it comprises, after the bonding step, a step of thinning the first substrate.
9. A method according to claim 7 or claim 8, wherein it further comprises a step of producing a second layer of microcomponents on the face of the first substrate opposite to the face comprising the first layer of microcomponents.
10. A method according to any one of claims 7 to 9, wherein it comprises, before the bonding step, a step of forming a layer of oxide on the face of the first substrate comprising the first layer of microcomponents.
11. A method according to any one of claims 7 to 10, wherein the first substrate is a SOI type structure.
12. A method according to any one of claims 7 to 11, wherein at least the first layer of microcomponents includes image sensors.

13. A method according to any one of claims 7 to 12, wherein the material of the second substrate is a transparent material.