

DESCRIPTION

TITLE: Method for manufacturing a tiled donor substrate, involving an additive manufacturing technique

FIELD OF THE INVENTION

The present invention targets the field of microelectronics and semiconductors. In particular, the invention relates to a method for manufacturing a donor substrate having a working layer in the form of tiles, a surface layer of said tiles being intended to be transferred onto a receiver substrate. The method according to the invention involves an additive manufacturing technique.

TECHNOLOGICAL BACKGROUND OF THE INVENTION

In the field of microelectronics, optics or optoelectronics, it may be advantageous to transfer thin layers (less than $1.5\mu\text{m}$), in the form of disjunct tiles (for example made of III-V material), onto a receiver substrate of large dimensions (for example made of silicon). Specific components (on the tiled thin layers) can thus be produced, and potentially co-integrated with silicon components, while at the same time benefiting from the equipment and sizes of substrates in the conventional microelectronics industry.

The Smart Cut™ process, which is a well-known technique for transferring thin layers, can in particular produce a composite structure comprising tiled thin layers on a receiver substrate, starting from a donor substrate that has a working layer in the form of tiles. It will be recalled that the Smart Cut process is based on the formation of a buried weakened plane in the tiled working layer of the donor substrate, by implantation of light species: this buried weakened plane defines, with the free surface of the tiled working layer, the tiled surface layer that will be transferred. This process then involves assembly between the tiled working layer and the receiver substrate. Finally, separation occurs along the buried weakened plane in order to transfer the tiled surface layer onto the receiver substrate; the remainder of the donor substrate can be recovered, conditioned and used for the transfer of a new tiled surface layer.

The donor substrate, in such a scenario, therefore has a carrier substrate on which are disposed disjunct tiles, distributed on the surface of said carrier substrate according to the needs of the target application for the final composite structure.

The manufacturing of such a donor substrate (also called pseudo-donor substrate) is usually based on the assembly of the tiles of the working layer on the carrier substrate by direct or adhesive bonding. Each tile typically has a thickness of between a few tens of micrometres and a few hundreds of micrometres, and lateral dimensions conferring thereon a surface area of between 1mm² and 400mm². Given their thickness, these tiles may be handled using "pick and place" techniques and assembled on the carrier substrate.

Since the tiles of the donor substrate may have non-uniform thicknesses with respect to each other, and since excellent surface flatness is required in order to obtain an assembly and then a tiled thin layer transfer of high quality, the step of preparing the surface of the tiled working layer is particularly critical. Given the discontinuity of this layer, the steps of mechanical or chemical-mechanical thinning tend to modify, collapse or damage the edges of the tiles, and this inevitably reduces the quality of the subsequent assembly.

SUBJECT MATTER OF THE INVENTION

The present invention addresses this problem and proposes a method for manufacturing a donor substrate, comprising a tiled working layer that is particularly suitable for assembly on a receiver substrate with a view to the transfer of a tiled surface thin layer. The method according to the invention implements a step of additive manufacturing in order to form a layer complementary to the tiled working layer on the donor substrate, and ensure continuity of material between the tiles, thus allowing quality surface preparation.

BRIEF DESCRIPTION OF THE INVENTION

The present invention relates to a method for manufacturing a tiled donor substrate, comprising the following steps:

a) providing an initial structure comprising a carrier substrate having a front face and a rear face, and a plurality of tiles made of a first, single-crystal material, which are disposed on the front face and spaced apart from one another,

b) forming a complementary layer via an additive manufacturing technique, the complementary layer:

- being disposed between the tiles, in contact with the front face of the carrier substrate,
- being composed of a material, referred to as second material, having a thermal expansion coefficient that is matched to that of the first material,

c) applying a mechanical and/or chemical-mechanical surface treatment to the complementary layer and to the tiles, in order to obtain the tiled donor substrate of which a front face has a flat and continuous surface, at which the plurality of tiles and the complementary layer are flush.

According to advantageous features of the invention, taken alone or in any feasible combination:

- in step b), the complementary layer is also formed on all or part of the tiles;
- the complementary layer has a thickness greater than or equal to an average thickness of the tiles;
- the additive manufacturing technique implemented in step b) is based on:
 - the at least partial melting of a powder of the second material, in a nozzle heated by a laser beam or an electron beam,
 - the movement of the nozzle so as to deposit the melted powder on the carrier substrate, between the tiles, and optionally on all or part of the tiles, until the complementary layer is formed;
- step b) is based on:
 - a sub-step of additive manufacturing of a stencil on a plate, the stencil having a surface area identical to that of the carrier substrate and having localized openings at the locations of the tiles of the initial structure,
 - a sub-step of assembly between the stencil and the initial structure, the stencil forming the complementary layer;
- the carrier substrate is made of silicon;
- the first, single-crystal material forming the tiles is chosen from semiconductor materials, piezoelectric materials and electrically insulating materials;
- the first, single-crystal material forming the tiles is indium phosphide;
- the tiles of the initial structure are spaced apart by a distance of between 100µm and 10mm, or even 10cm;

- the second material is of the same nature as the first material;
- the second material is composite and comprises a binder, the proportion of binder being less than 30%.

The invention also relates to the use of a tiled donor substrate resulting from an above-mentioned manufacturing method, in order to transfer a surface layer of each tile onto a receiver substrate.

Advantageously, this use implements a thin layer transfer technique involving the following steps:

- forming a buried weakened plane, substantially parallel to a front face of the tiled donor substrate, in the tiles and in the complementary layer,
- assembling the front face of the tiled donor substrate on the receiver substrate,
- separation along the buried weakened plane, in order to form a composite structure comprising the receiver substrate and at least one thin layer originating from each tile transferred onto said receiver substrate.

Preferentially, after the separation, a remainder of the tiled donor substrate is conditioned and then reused for a new thin layer transfer onto a new receiver substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

Other features and advantages of the invention will become apparent from the detailed description that will follow, with reference to the appended figures, in which:

[Fig. 1a]

[Fig. 1b] Figures 1a and 1b show a tiled donor substrate obtained via a manufacturing method in accordance with the present invention;

[Fig. 2a]

[Fig. 2b] Figures 2a and 2b show an initial structure provided in step a) of a manufacturing method in accordance with the invention;

[Fig. 3a]

[Fig. 3b] Figures 3a and 3b show examples of an intermediate donor substrate obtained at the end of step b) of a manufacturing method in accordance with the invention;

[Fig. 4] Figure 4 shows a first embodiment of step b) of a method in accordance with the invention;

[Fig.5a]

[Fig.5b]

[Fig.5c]

[Fig. 5d] Figures 5a, 5b, 5c and 5d show sub-steps of a second embodiment of step b) of a manufacturing method in accordance with the present invention;

[Fig.6a]

[Fig.6b]

[Fig.6c]

[Fig. 6d] Figures 6a, 6b, 6c and 6d show step c) of a manufacturing method in accordance with the invention;

[Fig.7a]

[Fig.7b]

[Fig.7c]

[Fig.7d] Figures 7a, 7b, 7c and 7d show steps of the use of a tiled donor substrate resulting from a manufacturing method, in accordance with the invention.

The figures are schematic depictions that, for the sake of legibility, are not to scale. In particular, the thicknesses of the layers along the z axis are not to scale in relation to the lateral dimensions along the x and y axes.

In the figures or in the description, the same references may be used for elements of the same nature.

DETAILED DESCRIPTION OF THE INVENTION

The invention relates to a method for manufacturing a tiled donor substrate 100 as illustrated in figures 1a and 1b.

The manufacturing method comprises a first step a) of providing an initial structure 10 comprising a carrier substrate 1 and a plurality of tiles 2 (figures 2a and 2b). The carrier substrate 1 has a front face 1a and a rear face 1b and is preferentially in the form of a wafer with a diameter of 200mm, 300mm or even more. Its thickness is typically between 100µm and 900µm. Advantageously, the carrier substrate 1 is made of silicon, or another semiconductor material available in the form of a wafer of large diameter.

The tiles 2 are formed from a first, single-crystal material, and are disposed on the front face 1a and spaced apart from one another. Typically, the tiles 2 are spaced apart by a distance of between 100µm and 10mm, or even up to 10cm. Each tile may have a thickness greater than or equal to 100µm, for example between 300µm and 600µm, and dimensions of between 1mm² and 20x20mm².

The first material is advantageously chosen from:

- semiconductor materials (such as a III-V compound, in particular indium nitride (InN), gallium nitride (GaN), aluminium nitride (AlN), indium arsenide (InAs), gallium arsenide (GaAs), aluminium arsenide (AlAs), indium phosphide (InP), gallium phosphide (GaP) or aluminium phosphide (AlP), or such as a IV or IV-IV material, in particular germanium or silicon carbide (SiC)),
- piezoelectric materials (such as lithium tantalate (LiTaO₃), lithium niobate (LiNbO₃), potassium-sodium niobate (K_xNa_{1-x}NbO₃ or KNN), barium titanate (BaTiO₃), quartz, lead titanate-zirconate (PZT), a compound of lead-magnesium niobate and lead titanate (PMN-PT), zinc oxide (ZnO), aluminium nitride (AlN) or aluminium-scandium nitride (AlScN)), and
- electrically insulating materials (such as diamond, strontium titanate, yttriated zirconia or sapphire).

This initial structure 10 can be produced using any technique known to those skilled in the art. In general, the tiles 2 originate from an initial substrate constituted by the first material, which has been cut by sawing, laser cutting or the like. The variation in thickness (TTV), at the scale of the initial substrate, may be several micrometres. The tiles 2 may therefore have these same variations in thickness with respect to each other.

The tiles 2 are then assembled on the carrier substrate 1. They may be placed on said carrier substrate 1 using an item of "pick and place" equipment, which is

widely used for handling dies or chips. The assembly is preferentially based on direct bonding by molecular adhesion, not requiring the addition of intermediate adhesive layers. Surface treatments (cleaning, plasma activation, etc.) prior to the assembly are recommended in order to obtain a bonding interface of good quality and affording significant mechanical strength.

Next, the manufacturing method comprises a step b) corresponding to the formation of a complementary layer 20, on the side of the front face 1a of the initial structure 10, via an additive manufacturing technique (figures 3a, 3b). The complementary layer 20 is at least disposed between the tiles 2, in contact with the front face 1a of the carrier substrate 1. It can also be formed on all or part of the tiles 2.

The complementary layer 20 is composed of a material, referred to as second material, having a thermal expansion coefficient that is matched to that of the first material. "Matched" is understood to mean that the difference between the thermal expansion coefficient of the second material and that of the first material is less than or equal to $\pm 10\%$.

At the end of step b), an intermediate donor substrate 100' is obtained.

Advantageously, the first material and the second material are of the same nature; by way of example, for a first material made of single-crystal InP, the second material may be made of polycrystalline or amorphous InP.

Advantageously, the carrier substrate 1 may also be chosen so as to have an expansion coefficient close to the material of the tiles. For example, the carrier substrate 1 may also be formed by the same additive manufacturing technique and with the same material (second material) of the complementary layer 20.

According to a variant, the second material is composite and comprises a material of which the thermal expansion coefficient is close to that of the first material, and a binder. The proportion of binder is less than 30%, less than 20%, or even less than 10%, so that the thermal expansion coefficient of the second, composite material differs as little as possible from that of the first material.

Preferentially, the complementary layer 20 also has a thickness greater than or equal to an average thickness of the tiles 2, in order to make it possible to limit, as

much as possible, the discontinuities of material between the tiles 2 and the complementary layer 20, during the following step c) of the method.

According to a first embodiment, the additive manufacturing technique implemented in step b) is based on the at least partial melting of a powder of the second material, in a nozzle B heated by a laser beam or an electron beam (figure 4). The movement of the nozzle B makes it possible to deposit the melted powder 20' on the carrier substrate 1, between the tiles 2, and optionally on all or part of the tiles 2, until the complementary layer 20 is formed. A plurality of passes of the nozzle B at the same location may be required in order to reach the desired thickness of the complementary layer 20.

A technique of the CLAD ("Direct Additive Laser Construction") type can in particular be implemented.

By way of example, if the second material constituting the powder is InP, a local temperature, generated by the laser beam or the electron beam, between 650°C and 800°C, allows the melting, at least at the surface, of the grains of the powder and consequently the agglomeration thereof in the form of a complementary layer 20 when they cool. The temperature perceived by the initial structure 10 is much lower than this temperature, typically less than or equal to 100°C: this prevents any degradation of the adjacent tiles 2, of which the first material is for example single-crystal InP.

According to another example, the second material is composite and comprises InP and a binder (polymer compatible with the temperatures of use): a local temperature, generated by the laser beam or the electron beam, typically between 100°C and 800°C, can allow the melting of the binder, which ensures the agglomeration of the powder in the form of a complementary layer 20. Here again, the temperature perceived by the initial structure 10 remains low (typically less than 100°C), and this prevents the degradation thereof. It should be noted that the use of a binder, even if the proportion thereof is limited to 30%, 20% or even 10%, involves shrinking of the complementary layer 20, to be taken into account in the definition of the initial deposited thickness of complementary layer.

Irrespective of the examples of this first embodiment, it is important to ensure that the complementary layer 20 adheres well to the front face 1a of the carrier

substrate 1. The presence of a binder in the second material is favourable to this adherence. It is also possible to choose an initial structure 10 comprising a surface layer on the carrier substrate 1, of which surface layer the nature is favourable to the adhesion of the complementary layer 20.

Furthermore, in order to promote the adherence between the complementary layer 20 and the carrier substrate 1, texturing of the front face 1a may be advantageous; this could be for example a level of roughness of the front face 1a that is greater than 1nm RMS (on a scan of $20 \times 20 \mu\text{m}^2$ with atomic force microscopy).

According to a second embodiment, step b) comprises a first sub-step of additive manufacturing of a stencil 20" on a plate. A 3D printing technique of the DMLS ("direct metal laser sintering") type may in particular be implemented.

The stencil 20" has a surface area identical to that of the carrier substrate 1 and has localized openings 3 at the locations of the tiles 2 of the initial structure 10 (figures 5a, 5b). Next, step b) comprises a second sub-step of assembly between the stencil 20" and the initial structure 10 (figure 5c), the stencil 20" then forming the complementary layer 20 (figure 5d).

Good flatness of the stencil 20" is important in order to obtain a quality assembly, in particular when assembly by molecular adhesion is envisaged (typically, a deformation of less than $100 \mu\text{m}$ and a maximum variation in flatness of a few micrometres are expected). It will be noted that any known type of assembly may be carried out, on the condition that the mechanical and thermal strength of the bonding is compatible with the rest of the method and the intended use of the tiled donor substrate 100.

Finally, the method comprises a step c) corresponding to the application of a surface treatment that is mechanical (for example grinding) and/or chemical-mechanical (for example polishing), to the complementary layer 20 and to the tiles 2 (figures 6a, 6b, 6c).

Whether the complementary layer 20 is of a thickness less than, substantially equal to or greater than the average thickness of the tiles 2, step c) aims to planarize the front face 100'a of the intermediate donor substrate 100', in order to obtain the tiled donor substrate 100 of which the front face 100a has a flat and continuous surface, at which the plurality of tiles 2 and the complementary layer 20 are flush (figure 6d). Flat and continuous is understood to mean a surface devoid of reliefs

(i.e. typically with reliefs of less than 5nm, less than 1nm, or even less than 0.5nm, in particular at the junctions between tiles 2 and complementary layer 20). The complementary layer 20 may optionally have a thickness substantially less than that of the tiles 2 after planarization, so as not to impede the complete transfer of the tiled surface layer originating from the tiles 2.

The removal of material carried out in step c) can vary according to the configuration of the intermediate donor substrate 100', and according to the thickness of the complementary layer 20. Typically between 1µm and 200µm, preferentially between 20µm and 60µm, is removed.

As mentioned above, the tiles 2 may have variations in thickness with respect to each other, which are linked to the TTV of the initial substrate from which they originate. Step c) makes it possible to rectify these variations in thickness and to obtain a flat surface compatible with a thin layer transfer. Furthermore, the presence of the complementary layer 20 makes the planarization easier since it ensures the continuity of the surface 100'a treated and consequently prevents the phenomena of collapsing of the edges of the tiles ("corner rounding") during chemical-mechanical treatments.

Finally, since the complementary layer 20 is preferentially predominantly composed of a material of the same nature as the first material of the tiles 2, the surface treatments are made easier and do not come up against problems of polishing with two materials with, in particular, different abrasion rates.

According to the present invention, the tiled donor substrate 100 can be used to transfer a surface layer of each tile 2 onto a receiver substrate 50. Preferentially, a thin layer transfer technique involving the following steps is implemented. First, a buried weakened plane 4, substantially parallel to a front face 100a of the tiled donor substrate 100, is formed in the tiles 2 and in the complementary layer 20 (figure 7a). For this, an implantation of light species such as hydrogen, helium or combination of these two species may be implemented. The following step consists of assembling the front face 100a of the tiled donor substrate 100 on the receiver substrate 50 (figure 7b). Preferably, this assembly is based on bonding by molecular adhesion, not requiring the presence of adhesive layers. As is well known per se, cleaning and other surface activations can be implemented in order to improve the

quality and the mechanical strength of the bonding interface 5. Finally, separation along the buried weakened plane 4 occurs, in order to form a composite structure comprising the receiver substrate 50 and at least one thin layer 2i originating from each tile 2 and transferred onto said receiver substrate 50 (figure 7c). As a function of the nature of the second material of the complementary layer 20, a complementary thin layer 20i, originating from the complementary layer 20, can also be transferred onto the receiver substrate 50. In this case, a subsequent step consists in locally etching this complementary thin layer 20i, so as to conserve only the tiled thin layer 2i on the receiver substrate 50 (figure 7d).

Sequences of polishing and cleaning can be applied in order to restore a good surface finish to the tiled thin layer 2i, before or after the removal of the complementary thin layer 20i (when this is present).

After the separation step, the remainder 100i of the tiled donor substrate 100 may be conditioned (mechanical grinding and/or chemical-mechanical polishing and cleaning) and then reused for a new thin layer transfer onto a new receiver substrate.

Of course, the invention is not limited to the embodiments described, and variant embodiments can be added thereto without departing from the scope of the invention.

CLAIMS

1. **Method for manufacturing a tiled donor substrate** (100), comprising the following steps:
 - a) providing an initial structure (10) comprising a carrier substrate (1) having a front face (1a) and a rear face (1b), and a plurality of tiles (2) made of a first, single-crystal material, which are disposed on the front face (1a) and spaced apart from one another,
 - b) forming a complementary layer (20) via an additive manufacturing technique, the complementary layer (20):
 - being disposed between the tiles (2), in contact with the front face (1a) of the carrier substrate (1),
 - being composed of a material, referred to as second material, having a thermal expansion coefficient that is matched to that of the first material,
 - c) applying a mechanical and/or chemical-mechanical surface treatment to the complementary layer (20) and to the tiles (2), in order to obtain the tiled donor substrate (100) of which a front face (100a) has a flat and continuous surface, at which the plurality of tiles (2) and the complementary layer (20) are flush.
2. Manufacturing method according to Claim 1, wherein, in step b), the complementary layer (20) is also formed on all or part of the tiles (2).
3. Manufacturing method according to either of the preceding claims, wherein the complementary layer (20) has a thickness greater than or equal to an average thickness of the tiles (2).
4. Manufacturing method according to one of the preceding claims, wherein the additive manufacturing technique implemented in step b) is based on:
 - the at least partial melting of a powder of the second material, in a nozzle (B) heated by a laser beam or an electron beam,
 - the movement of the nozzle (B) so as to deposit the melted powder (20') on the carrier substrate, between the tiles (2), and optionally on all or part of the tiles (2), until the complementary layer (20) is formed.

5. Manufacturing method according to one of Claims 1 to 3, wherein step b) is based on:
 - a sub-step of additive manufacturing of a stencil (20") on a plate, the stencil (20") having a surface area identical to that of the carrier substrate (1) and having localized openings at the locations of the tiles (2) of the initial structure (10),
 - a sub-step of assembly between the stencil (20") and the initial structure (10), the stencil (20") forming the complementary layer (20).
6. Manufacturing method according to one of the preceding claims, wherein the carrier substrate (1) is made of silicon.
7. Manufacturing method according to one of the preceding claims, wherein the first, single-crystal material forming the tiles (2) is chosen from semiconductor materials, piezoelectric materials and electrically insulating materials.
8. Manufacturing method according to one of the preceding claims, wherein the first, single-crystal material forming the tiles (2) is indium phosphide (InP).
9. Manufacturing method according to one of the preceding claims, wherein the tiles (2) of the initial structure (10) are spaced apart by a distance of between 100µm and 10mm, or even 10cm.
10. Manufacturing method according to one of the preceding claims, wherein the second material is of the same nature as the first material.
11. Manufacturing method according to one of the preceding claims, wherein the second material is composite and comprises a binder, the proportion of binder being less than 30%.
12. **Use of a tiled donor substrate (100)** resulting from a manufacturing method in accordance with Claims 1 to 11, in order to transfer a surface layer of each tile (2) onto a receiver substrate (50).

13. Use of a tiled donor substrate (100) according to the preceding claim, implementing a thin layer transfer technique involving the following steps:

- forming a buried weakened plane (4), substantially parallel to a front face (100a) of the tiled donor substrate (100), in the tiles (2) and in the complementary layer (20),
- assembling the front face (100a) of the tiled donor substrate (100) on the receiver substrate (50),
- separation along the buried weakened plane (4), in order to form a composite structure comprising the receiver substrate (50) and at least one thin layer (2i) originating from each tile (2) transferred onto said receiver substrate (50).

14. Use of a tiled donor substrate (100) according to the preceding claim, wherein, after the separation, a remainder (100i) of the tiled donor substrate (100) is conditioned and then reused for a new thin layer transfer onto a new receiver substrate.