Method of fabricating a hybrid substrate

Background of the invention

The present invention relates to a method of fabricating a hybrid substrate comprising at least two layers of crystalline material that are bonded together by direct bonding.

Description of the prior art

This type of substrate can be used in the fields of optics, electronics or optoelectronics, these terms also including in general microelectronics, nanoelectronics, optomicroelectronics, optonanoelectronics and component technology.

The aforementioned two layers of materials may be of the same or different nature, the term "nature" covering both the chemical nature of the materials and their physicochemical properties and/or their crystalline orientation.

The term "direct bonding" of two layers or two substrates denotes molecular bonding without an intermediate layer, such as an adhesive layer.

Among these hybrid substrates are those known to a person skilled in the art by the acronym DSB (direct silicon bonding). Such substrates comprise an active silicon layer directly bonded to a receiver substrate made of silicon of a different crystalline orientation, without the formation of an intermediate layer, especially without the formation of a buried oxide layer. Thus, it is possible to produce a substrate comprising a layer of silicon with a (110) crystalline orientation directly bonded to a support of silicon with a (100) crystalline orientation, or vice versa.

When the receiver substrate is made of silicon carbide (SiC), it is possible to fabricate hybrid substrates known to a person skilled in the art by the acronym SopSiC (silicon-on-polycrystalline-SiC).

Such hybrid substrates are useful for the production of high-performance microelectronic circuits.

The article by C.Y. Sung, "*Direct Silicon Bonded (DSB) Mixed Orientation Substrate for High Performance Bulk CMOS Technology*", *Extended Abstracts of the 2006 International Conference on Solid-State Devices and*

Materials, Yokohama, 2006, pp. 160-161, cites an example of the fabrication of such a substrate, which consists in transferring a layer of a (110) silicon donor substrate onto a (100) silicon receiver substrate by bonding followed by thinning. This article records that the fabrication of such a substrate does not require any insulating layer between the two layers bonded together.

The above article also mentions that the absence of SiO_2 insulating layer in the final structure means that a hydrophobic-type prebonding preparation is preferred to a hydrophilic-type preparation.

This is because hydrophilic bonding includes the formation of a thin silicon oxide layer during surface preparation of the layers to be brought into contact with each other, and this oxide, which is buried in the final structure, must be subsequently removed, for example by a final annealing step at very high temperature, thereby complicating the method of fabrication in the present case.

However, hydrophobic bonding, which involves hydrogen-terminated bonds, is much more difficult to implement since these H-terminated bonds attract particles that have a negative impact on the bonding.

Also known, from the document US 6 020 252, is a method of obtaining a thin layer of a semiconductor material from a donor substrate. This method consists in implanting rare-gas or hydrogen ions into a donor substrate, at a predetermined temperature and with a predetermined implantation dose, so as to create a weakened zone therein, and then carrying out a heat treatment at a temperature high enough to cause said substrate to separate into two parts on either side of the plane of weakness.

In accordance with what is described in the above document, the temperature and implantation dose are chosen so as to create microcavities within the substrate in sufficient quantities to obtain the weakened zone but in insufficient quantities to obtain detachment by the subsequent heat treatment alone. Detachment requires the additional application of a mechanical force.

However, this document does not relate specifically to a surface preparation allowing good direct bonding.

Embodiments of the invention seek to solve the aforementioned drawbacks of the prior art, and in particular to provide a method of fabricating a hybrid substrate obtained by layer transfer and which does not require bonding using an intermediate layer and in which the bonding between the donor substrate and the receiver substrate is carried out via high-quality hydrophobic bonding.

Summary of the invention

According to an aspect of the invention, there is provided a method of fabricating a hybrid substrate, which comprises at least two layers of crystalline material that are bonded directly to each other, including a layer of material called the "active" layer, coming from a crystalline substrate called a "donor" substrate, the method comprises the following successive steps consisting in:

- carrying out a step of implanting at least one category of atomic and/or ionic species into said donor substrate so as to form therein a weakened zone forming the boundary between said active layer and the remainder of the donor substrate;

- subjecting one of the faces called the "front" face of the donor substrate and one of the faces called the "front'" face of a crystalline substrate, called a "receiver" substrate, to a heat treatment, called "prebonding preparation" heat treatment, at a temperature between 800°C and 1200°C, in a gaseous atmosphere comprising hydrogen and/or argon for a time of at least 30 seconds, so as to make said front faces hydrophobic;

- directly bonding said front faces to each other;

- carrying out a heat treatment of the two substrates under conditions for obtaining strong bonding between them; and

- detaching said remainder along the weakened zone by a purely mechanical action,

the nature, implantation dose and implantation energy of said atomic and/or ionic species being chosen so that the defects induced by these species within the donor substrate allow the remainder of the donor substrate to be subsequently detached but do not develop sufficiently during the prebonding preparation heat treatment to prevent the subsequent bonding or to deform the front face of the donor substrate.

According to other advantageous and non limiting embodiments of the invention, taken individually or in combination:

- said prebonding preparation treatment is carried out in a gaseous atmosphere containing exclusively argon;

- said prebonding preparation treatment is carried out in a gaseous atmosphere containing exclusively hydrogen:

- said prebonding preparation treatment is carried out in a rapid thermal annealing (RTP) furnace;

- the heat treatment to strengthen the bonding of the two substrates is carried out by a long heat treatment for at least 2 hours at a temperature of 1100°C or higher;

- the species implanted to form the weakened zone are chosen from hydrogen, helium, fluorine, neon, argon, krypton and xenon;

- the active layer of the donor substrate consists of a material chosen from silicon (Si), (110) silicon, (100) silicon, silicon-germanium (SiGe), germanium (Ge), silicon carbide (SiC) and gallium nitride (GaN); and

- the receiver substrate consists at least partly of a material chosen from silicon (Si), (110) silicon, (100) silicon and silicon carbide (SiC).

Other features and advantages of the invention will become apparent from the description thereof which will now be given with reference to the appended drawings, which represent, by way of indication but implying no limitation, one possible embodiment thereof.

Brief description of the drawings

In these drawings:

- figures 1 to 6 illustrate the successive steps in the method of fabrication according to the invention.

Description of the preferred embodiment

The sequence of the various steps of the method will now be briefly described.

As may be seen in figure 1, a "donor" substrate 1 comprises two opposed faces 10 and 11, called "front" and "rear" faces respectively.

As shown in figure 2, the donor substrate 1 then can undergo an implantation of atomic/or ionic species so as to form therein a weakened zone 12, which forms the boundary between a layer 13 called an "active" layer 13 and the remainder 14 of this substrate.

Advantageously, this implantation is carried out through a sacrificial insulation layer 3, for example a layer of silicon dioxide (SiO_2), deposited on the front face 10 of the substrate 1.

This insulation layer 3 is then removed, as shown in figure 3.

The donor substrate 1 and a "receiver" substrate 2 then undergo a "prebonding preparation" treatment, which will be explained in detail later (see figure 4).

The receiver substrate 2 comprises two opposed faces 20 and 21, called "front" and "rear" faces respectively.

Next, the front face 20 of the receiver substrate 2 is applied by direct bonding to the front face 10 of the donor substrate 1 (see figure 5).

The bonding interface has the numerical reference 4.

After a treatment to strengthen the bonding, the remainder 14 of the donor substrate 1 is detached, as shown in figure 6, so as to transfer the active layer 13 onto the receiver substrate 2 and obtain a hybrid substrate, with the reference 5.

The various steps will now be described in greater detail.

The donor substrate 1 and receiver substrate 2 may or may not consist of semiconductor materials.

In general, the material constituting the donor substrate 1 will be chosen from crystalline materials in which it is possible to create a dense distribution of cavities, by implanting atomic and/or ion species, followed by a thermal annealing step.

As an example, the material constituting the donor substrate 1 may be chosen from silicon (Si), (110) silicon, (100) silicon, silicon-germanium (SiGe), germanium (Ge), silicon carbide (SiC) and gallium nitride (GaN).

The receiver substrate 2 consists of any crystalline or noncrystalline material, for example silicon (Si), (110) silicon, (100) silicon or silicon carbide (SiC), preferably single-crystal silicon or polycrystalline silicon carbide, but also polycrystalline silicon. It may be a semiconductor or an insulator material.

Two particular applications of the invention consist in forming a DSB-type substrate in which the donor substrate 1 and the receiver substrate 2 are both made of silicon, preferably single-crystal silicon and of different crystalline orientations (for example (100), (110) or (111)), or in forming an SopSiC-type substrate in which the donor substrate 1 is made of silicon (preferably single-crystal silicon) and the receiver substrate 2 is made of polycrystalline silicon carbide.

It should be noted that the donor and receiver substrates may also be multilayer substrates. However, in this case it is necessary for the layer of material constituting the front faces 10 and 20 of the substrates 1 and 2 to meet the aforementioned specifications.

The step of implanting atomic and/or ionic species is carried out by selecting the implanted species, their dose and their implantation energy so that the defects induced by these species within the donor substrate 1 allow the remainder 14 to be subsequently detached (see figure 6) but do not develop sufficiently, during the prebonding preparation heat treatment shown in figure 4, to deform the front face 10 to be bonded or prevent the subsequent bonding shown in figure 5.

As examples of species that can be implanted, mention may be made of hydrogen (H), helium (He), fluorine (F), neon (Ne), argon (Ar), krypton (Kr) and xenon (Xe).

These species are particularly appropriate for implantation in a silicon substrate 1.

The choice of these species, their dose and their implantation energy will be made so as to avoid the phenomenon of surface bubbling that is typically obtained when a material, implanted in standard fashion, is annealed.

In general, it is also possible to carry out a co-implantation operation, the surface of the substrate being bombarded in succession with different species. It is advantageous to use, for example, a first implantation of helium followed by an implantation of H^+ ions.

Likewise, the nature of the species, their dose and their implantation energy are chosen in such a way that the bubbling of the implanted species is limited.

Thus, whether this be simple implantation or co-implantation, the implantation energies and doses of the aforementioned species will be chosen between 20 and 500 keV and between 1×10^{14} at/cm^2 and 1×10^{17} at/cm^2.

As an example, helium atoms are implanted into the substrate with an energy of around 30 to 200 keV and with a dose being within the 5×10^{16} to 1×10^{17} at/cm^2 range. In the case of argon atoms, the applied energy is around 200 to 500 keV and the implantation dose around 1×10^{16} to 5×10^{16} at/cm^2.

In the case of co-implantation, it is possible for example to use hydrogen co-implanted with fluorine or hydrogen co-implanted with helium.

In the case of hydrogen/fluorine co-implantation, the hydrogen is implanted with an energy between 20 and 50 keV and a dose between 1×10^{15} and 5×10^{16} H^+/cm^2, whereas the fluorine is implanted with an energy between 150 and 200 keV and for implantation doses of 1×10^{14} to 1×10^{16} F^+/cm^2.

In the case of hydrogen/helium co-implantation, the helium is implanted with an energy between 70 and 90 keV and a dose between 1×10^{16} and

6×10^{16} He^+/cm^2, whereas the hydrogen is implanted with an energy between 70 and 90 keV for implantation doses of 1×10^{15} to 6×10^{15} H^+/cm^2.

As regards the implantation, the reader may refer to the literature on the Smart Cut ™ process.

Preferably, and as shown in figure 2, the implantation takes place through the front face 10.

Also preferably, all the implantations are carried out through a sacrificial oxide layer 3. This oxide layer 3 may be formed thermally (for example from SiO_2 in the case of a silicon substrate) or deposited by deposition techniques well known to those skilled in the art, such as chemical vapor deposition (CVD) at atmospheric pressure or low-pressure chemical vapor deposition (LPCVD). These techniques will not described here in detail.

The oxide 3 may also be native oxide.

The sacrificial oxide 3 is then removed after the implantation, for example by immersing the substrate 1 in a dilute hydrofluoric acid (HF) solution or by placing it in an atmosphere of hydrofluoric acid vapor.

The removal of the sacrificial oxide is preferably followed by an RCA-type cleaning operation in order to protect the front face 10 from contaminating particles.

The treatment using a chemical bath called RCA-clean consists in treating the front face 10 in succession with:

- a first bath of a solution known as SC1 (Standard Clean 1) which comprises a mixture of ammonium hydroxide (NH_4OH), hydrogen peroxide (H_2O_2) and deionized water; and

- a second bath of a solution known as SC2 (Standard Clean 2), which comprises a mixture of hydrochloric acid (HCl), hydrogen peroxide (H_2O_2) and deionized water.

The prebonding preparation treatment shown in figure 4 consists in subjecting at least one of the faces to be bonded, 10 or 20, to a heat treatment at a temperature between 800°C and 1200°C in a gaseous atmosphere comprising hydrogen and/or argon, but not oxygen.

The gaseous atmosphere may therefore be chosen to comprise: exclusively hydrogen, or exclusively argon, or a mixture of these two gases, or even one or other or both of them combined with another gas, excluding oxygen.

The duration of the treatment is at least 30 seconds, but preferably does not exceed a few minutes.

The effect of the hydrogen and/or argon is to remove the native oxide possibly present on the face(s) thus treated, to passivate these surfaces by means of hydrogen atoms, and also to obtain very low surface roughness.

This prebonding preparation treatment also has the effect of making the treated surfaces hydrophobic. This effect was demonstrated by measuring the contact angle of a drop of water, giving a value of 80°. This value is much higher than the value obtained after a treatment of the "HF-last" type, which is typically 70° (see the article by Y. Bäcklünd, Karin Hermasson and L. Smith, "*Bond-strength measurements related to silicon surface hydrophilicity*", J. Electrochem. Soc., Vol. 1398, No. 8, 1992).

The advantage of this treatment is that no species is adsorbed on the treated surface. Since the hydrogen atom is very small, when it desorbs, to allow the creation of covalent bonds between the facing front faces 10 and 20, it does not remain trapped at the interface but defuses into the material, without generating outgasing defects.

In addition, this treatment is of the dry type, unlike for example the aforementioned HF-last treatment. It is therefore simpler to implement it as it requires no drying.

Finally, this prebonding preparation treatment has the effect that the implanted ions, for example the He^+ ions, are trapped and stabilized in the microcavities that form and expand. This results in the coalescence of the microcavities and in the embrittlement of the implanted material in the zone containing the microcavities. However, the implantation conditions are chosen in such a way that the aforementioned coalescence phenomenon does not lead to the detachment of the layer 13 from the remainder 14.

The prebonding preparation treatment can be carried out in a chamber for high-temperature annealing in a controlled atmosphere, for example a single-wafer RTP (rapid thermal process) furnace or else an epitaxial growth furnace.

The use of a conventional furnace, in which the substrates are treated in batches, may also be envisioned.

After the aforementioned treatment, the front faces 10 and 20 must be bonded together very rapidly, so as to minimize the risks of contamination by the ambient atmosphere. This bonding step is shown in figure 5.

Advantageously, it is also possible to store the treated substrates in a chamber having a controlled atmosphere containing only an inert gas, typically

argon or nitrogen. Such a treatment makes it possible to extend the hold time, i.e. the time before the donor substrate 1 and receiver substrate 2 are bonded to each other.

It has also been noticed that the surfaces that have undergone the prebonding preparation treatment were much less reactive than surfaces prepared by the aforementioned HF-last process. This reduces the contamination of these surfaces with particles. Industrialization is thereby simplified.

The direct bonding step shown in figure 5 corresponds to bringing the respective front faces 10 and 20 of the donor 1 and receiver 2 substrates into intimate contact with each other, that is to say bonding by molecular adhesion.

This bonding step is followed by a treatment for strengthening the bonding, carried out in the form of a long heat treatment, that is to say for a time of at least two hours, at a temperature of 1100°C or higher.

As shown in figure 6, detachment of the donor substrate 1 from the remainder 14 then takes place.

This detachment is purely mechanical.

A "purely" mechanical detachment is initiated by a mechanical action, for example by running a tool, such as a blade, along the weakened zone 12 from one side of the substrate, or by applying an air jet or water jet at this point.

While this type of purely mechanical detachment is being carried out, the structure may also be rotated so as to facilitate the detachment.

Two examples of how to implement the invention will be given below.

Example 1:

A (110) Si silicon substrate covered with a silicon oxide (SiO_2) layer underwent an implantation with helium ions (He^+) with a dose of slightly less than 1×10^{17} He^+/cm^2 and an implantation energy of 50 keV.

The silicon oxide SiO_2 formed was then removed by treatment in a hydrofluoric acid (HF) solution followed by cleaning of the aforementioned RCA-clean type.

This silicon donor substrate and a receiver substrate, also made of silicon but of (100) crystalline orientation, then underwent the prebonding preparation treatment in a gaseous atmosphere comprising hydrogen and argon for a time of about 4 minutes at a temperature of 1050°C.

The two substrates 1 and 2 were then bonded together via their respective front faces and underwent a heat treatment for 2 hours at 1100°C in order to strengthen the bonding.

Finally, the donor substrate was detached from the remainder, purely mechanically by inserting a blade.

A substrate of the silicon/silicon DSB type was thus able to be obtained.

This product thus had a very high-quality bonding interface necessary for the production of future components.

Example 2:

A (100) Si silicon substrate covered with a silicon oxide (SiO_2) layer underwent a hydrogen/fluorine co-implantation. The fluorine was implanted with a dose of about 1×10^{15} F^+/cm^2 and an implantation energy of 180 keV, whereas the hydrogen was implanted with a dose of about 4×10^{16} H^+/cm^2 and an implantation energy of 30 keV.

The silicon oxide SiO_2 formed was then removed by treatment in a hydrofluoric acid (HF) solution followed by cleaning of the aforementioned RCA-clean type.

This silicon donor substrate and a receiver substrate, made of polycrystalline silicon carbide (pSiC), then underwent the prebonding preparation treatment in a gaseous atmosphere comprising hydrogen for a time of about 5 minutes at a temperature 800°C.

The two substrates 1 and 2 were bonded together via their respective front faces and underwent a heat treatment for 3 hours at 1000°C in order to strengthen the bonding.

Finally, the donor substrate was detached from the remainder purely mechanically, by injecting a fluid jet.

A substrate of the SopSiC (silicon-on-polycrystalline silicon carbide) type was thus able to be obtained with a very high-quality bonding interface.

CLAIMS

1. A method of fabricating a hybrid substrate, which comprises at least two layers of crystalline material that are bonded directly to each other, including a layer of material called the "active" layer, coming from a crystalline substrate called a "donor" substrate, which method comprises the following successive steps consisting in:

- carrying out a step of implanting at least one category of atomic and/or ionic species into said donor substrate so as to form therein a weakened zone forming the boundary between said active layer and the remainder of the donor substrate;

- subjecting one of the faces called the "front" face of the donor substrate and one of the faces called the "front" face of a crystalline substrate, called a "receiver" substrate, to a heat treatment, called "prebonding preparation" heat treatment, at a temperature between 800°C and 1200°C, in a gaseous atmosphere comprising hydrogen and/or argon for a time of at least 30 seconds, so as to make said front faces hydrophobic;

- directly bonding said front faces to each other;

- carrying out a heat treatment of the two substrates under conditions for obtaining strong bonding between them; and

- detaching said remainder along the weakened zone by a purely mechanical action,

the nature, implantation dose and implantation energy of said atomic and/or ionic species being chosen so that the defects induced by these species within the donor substrate allow the remainder of the donor substrate to be subsequently detached but do not develop sufficiently during the prebonding preparation heat treatment to prevent the subsequent bonding or to deform the front face of the donor substrate.

2. The method as claimed in claim 1, wherein said prebonding preparation treatment is carried out in a gaseous atmosphere containing exclusively argon.

3. The method as claimed in claim 1, wherein said prebonding preparation treatment is carried out in a gaseous atmosphere containing exclusively hydrogen.

4. The method as claimed in one of the preceding claims, wherein said prebonding preparation treatment is carried out in a rapid thermal annealing (RTP) furnace.

5. The method as claimed in one of the preceding claims, wherein the heat treatment to strengthen the bonding of the two substrates is carried out by a long heat treatment for at least 2 hours at a temperature of 1100°C or higher.

6. The method as claimed in one of the preceding claims, wherein the species implanted to form the weakened zone are chosen from hydrogen, helium, fluorine, neon, argon, krypton and xenon.

7. The method as claimed in one of the preceding claims, wherein the active layer of the donor substrate consists of a material chosen from silicon, (110) silicon, (100) silicon, silicon-germanium, germanium, silicon carbide and gallium nitride.

8. The method as claimed in one of the preceding claims, wherein the receiver substrate consists at least partly of a material chosen from silicon, (110) silicon, (100) silicon and silicon carbide.