

DESCRIPTION

TITLE: Method for manufacturing a composite structure including a grading step

FIELD OF THE INVENTION

The present invention relates to the field of semiconductor materials, notably the composite structures comprising a thin film (derived from a donor substrate made of single-crystal silicon carbide) transferred onto a carrier substrate made of polycrystalline silicon carbide. It particularly relates to a method for manufacturing such a composite structure, including a grading step based on the map for checking the donor substrate and on the map for checking the thin film of the composite structure.

TECHNOLOGICAL BACKGROUND OF THE INVENTION

Silicon carbide is a particularly interesting material for manufacturing power and radio frequency devices or even devices operating at very high temperatures.

The quality of substrates made of single-crystal silicon carbide (c-SiC) has significantly improved over the last ten years, and this has been accompanied by increasingly precise knowledge and detection of the various types of crystalline defects likely to be present in this material. The JEITA ("Japan Electronics and Information Technology Industries Association") standard includes four documents relating to the zoology of defects on/in a film produced by homoepitaxy on a 4H-SiC substrate (EDR 4712/100) and to non-destructive procedures for optically inspecting these defects (EDR 4712/200, /300, /400). In particular, a procedure is provided for evaluating and referencing the defects by combining optical inspection and photoluminescence imaging.

Commercially available equipment, notably such as Lasertec's SICA88, can be used to combine visible light Nomarski prism confocal microscopy and photoluminescence techniques (as described in document [1] by T. Kimoto et al., "Fundamentals of Silicon Carbide Technology Growth Characterization Devices and Applications", pg. 126, or in document [2] by D. Baierhofer et al., "Materials Science in Semiconductor processing 140", (2022) 106414) and are commonly used to inspect c-SiC substrates before or after epitaxy.

By way of an example, document [3] by Das et al., ("Statistical analysis of killer and non-killer defects in SiC and the impact of device performance", Material Science Forum, ISSN 1662-9752, Vol. 1004, pp.

458-463 (2020), Trans Tech Publications Ltd), proposes a statistical analysis of “killer” defects in devices produced on a homoepitaxial film made of c-SiC, and shows optical and photoluminescence images of typical c-SiC defects.

Even though they are developing rapidly, high-quality c-SiC substrates remain expensive and difficult to supply in large quantities. It is therefore advantageous for film transfer solutions to be used in order to produce composite structures comprising a thin film made of single-crystal SiC (derived from a high-quality c-SiC donor substrate) on a lower-cost carrier substrate, for example, made of polycrystalline SiC (p-SiC), which can also offer advantages in terms of electrical conductivity. A well-known thin-film transfer solution is the Smart Cut™ method, which is based on light ion implantation and on direct bonding assembly between a donor substrate made of c-SiC and a carrier substrate on a bonding interface. The implantation creates a buried weak plane, along which separation will occur, resulting in the transfer of a thin film made of c-SiC onto the carrier substrate in order to form the composite structure, and allowing the remainder of the donor substrate to be recovered and recycled in order to potentially carry out one or more other transfers of films. Epitaxy then can be carried out on the thin film of the composite structure, followed by the production of electronic devices.

In order for the implementation of a film transfer method to be economically viable, it is important to be able to know how to check the quality of the donor substrates, so as to avoid transferring a film that would inevitably result in the declassification of the composite structure, or that would result in an epitaxial film that is out-of-specification, in terms of “killer” defects. The zoology of defects of c-SiC is relatively well known, and numerous studies (some of which are referenced above) tend to define the type and the size of the defects, present in an epitaxial film made of c-SiC, that would be killer defects for the components; nevertheless, the Applicant has observed that the criteria for classifying defects in a donor substrate are not necessarily the same when epitaxy is carried out on said substrate and when thin-film transfer is carried out from said substrate.

It is therefore essential to detect but also to accurately classify the crystalline defects (called primary defects) that are present on the donor substrates, in order to declassify those donor substrates from among these donor substrates that will not allow a thin film to be manufactured with the required quality.

Furthermore, the detection and recognition of defects (called secondary defects) on and/or in the thin film (derived from a donor substrate) of a composite structure whose carrier substrate is made of polycrystalline SiC (p-SiC) are complex because the p-SiC grains are visible under said thin film, in

particular with equipment combining visible light Nomarski prism confocal microscopy and photoluminescence imaging. However, reliable and efficient (not requiring too much inspection time per structure) checking of the quality of the thin film is required in order to avoid continuing with the epitaxy steps if secondary defects in the thin film are likely to generate an out-of-specification density of killer defects in the homoepitaxial film.

In view of the increasing use of film transfer techniques in the manufacturing chain for electronic devices on c-SiC, a major requirement therefore exists for defining checking steps that allow reliable and rapid inspection of both the donor substrates, at the start of the chain, and the composite structures, in the middle of the chain, so as to assign a grade, as early as possible in the overall manufacturing chain, to the donor substrates or composite structures and to allow the specifications and yields expected for the devices to be achieved.

SUBJECT MATTER OF THE INVENTION

The present invention addresses the stated problem. The invention relates to a method for manufacturing a composite structure comprising a thin film made of single-crystal silicon carbide transferred onto a carrier substrate made of polycrystalline silicon carbide. The manufacturing method comprises an original, reliable and rapid step of grading the composite structure, combining an initial check of the donor substrate and a final check of said structure.

BRIEF DESCRIPTION OF THE INVENTION

The invention relates to a method for manufacturing a composite structure comprising a thin film made of single-crystal silicon carbide disposed on a carrier substrate made of polycrystalline silicon carbide, the method comprising the following steps of:

- 1) providing at least one donor substrate made of single-crystal silicon carbide, having a front face and a rear face, with the front face potentially having defects, called primary defects;
- 2) checking the quality of the at least one donor substrate using a photoluminescence imaging technique so as to extract a map of the front face, called first map, listing the primary defects identified as being of the micro-pipe type, of the complex star-shaped stacking defect type or of the point defect type;

- 3) transferring a thin film, derived from a surface film of the at least one donor substrate, onto a carrier substrate made of polycrystalline silicon carbide, in order to obtain a composite structure and a residual donor substrate;
- 4) inspecting a free surface of the thin film of the composite structure using a defect inspection technique using ultraviolet laser beam scattering, so as to extract a map of the free surface, called second map, listing defects, called secondary defects;
- 5) grading the composite structure, including comparing the first map and the second map.

According to other advantageous and non-limiting features of the invention, taken individually or according to any technically feasible combination:

- step 2) comprises the following sub-steps of:
 - i) inspecting a front face of the donor substrate in order to detect the primary defects, due to local variations in intensity of a photoluminescence signal emitted by the front face following excitation by an incident beam, and in order to form a photoluminescence image for each primary defect;
 - ii) assigning a tagged type of defect with a certain level of similarity to each detected primary defect, by virtue of an image recognition algorithm trained on various types of defect likely to be present on the front face of a donor substrate made of single-crystal silicon carbide, such as micro-pipes, complex star-shaped stacking defects and point defects notably linked to inclusions, with a level of contrast being associated with the photoluminescence image of each detected primary defect;
 - iii) classifying each primary defect by applying the following conditions:
 - if the tagged type of defect is a micro-pipe and if the level of similarity is greater than a first level, the primary defect is classified as a critical micro-pipe type defect;
 - if the tagged type of defect is a complex star-shaped stacking defect and if the level of similarity is greater than a second level, the primary defect is classified as a critical defect of the complex star-shaped stacking defect type;
 - if the tagged type of defect is a point defect, if the level of similarity is greater than a third level, and if the level of contrast is greater than a predetermined threshold, the primary defect is classified as a critical defect of the point defect type;
 - otherwise, the primary defect is classified as a non-critical defect.

- the inspection step i) is carried out with an incident beam with a wavelength of 313 nm and the emitted photoluminescence signal is collected in a wavelength range ranging from 700 nm to 1,000 nm;
- the predetermined threshold is established empirically for a type of donor substrate, based on a study of a correlation between the contrast value of primary defects detected on a front face of a test donor substrate and the presence of secondary defects on a thin film, derived from the test donor substrate, transferred onto a carrier substrate;
- a donor substrate having a density of primary defects, classified as critical defects irrespective of the type, that is greater than 1 defect/cm², or even preferably greater than 0.25 defect/cm², is declassified on completion of step 2) and is not used for step 3);
- step 5) comprises a reconciliation between the primary defects classified as critical defects and the secondary defects, with each primary defect classified as a critical defect and not associated with a secondary defect being added to the defects of the second map in order to be taken into account in a grading decision;
- the grading decision corresponds to a declassification of the composite structure if said composite structure comprises:
 - a density of secondary defects associated with critical primary defects and of primary defects classified as critical defects added to the second map, that is greater than 0.25 defects/cm²; and/or
 - a density of secondary defects only detected on the second map, not associated with critical primary defects, that is greater than 0.2 defects/cm²;
- step 5) comprises a reconciliation between the primary defects classified as critical defects and the secondary defects, and step 5) comprises an additional check using a technique combining visible light optical microscopy and photoluminescence imaging, for checking whether defects are present in the thin film, at the sites of said primary defects classified as critical defects;
- step 3) comprises the following sub-steps of:
 - 3a)** implanting light species in a donor substrate in order to form a buried weak plane delimiting, with a front face of the donor substrate, the surface film to be transferred;
 - 3b)** assembling a carrier substrate made of polycrystalline silicon carbide with the donor substrate implanted in step 3a);
 - 3c)** separating along the buried weak plane in order to form an intermediate composite structure comprising the surface film post-transfer and the carrier substrate, on the one hand, and the remainder of the donor substrate, called residual donor substrate, on the other hand;

- 3d)** applying one or more heat, mechanical and/or chemical treatments to a free surface of the surface film in order to form the composite structure provided with the thin film made of single-crystal silicon carbide;
- in the composite structure, the thin film comprises a buried face disposed opposite the carrier substrate, corresponding to the front face of the donor substrate, and another face, opposite the front face, corresponding to a free surface of said film; and a mirror inversion is applied to the first map or to the second map in order to compare them;
 - step 3) comprises the following sub-steps of:
 - 3i)** implanting light species in a donor substrate in order to form a buried weak plane delimiting, with a front face of the donor substrate, the surface film to be transferred;
 - 3ii)** assembling a temporary substrate with the donor substrate implanted in step 3i), via a first bonding interface;
 - 3iii)** separating along the buried weak plane in order to form an intermediate assembly comprising the surface film post-transfer and the temporary substrate, on the one hand, and the remainder of the donor substrate, called residual donor substrate, on the other hand;
 - 3iv)** applying one or more heat, mechanical and/or chemical treatments to a free surface of the surface film in order to form a temporary structure provided with the thin film made of single-crystal silicon carbide disposed on the temporary substrate;
 - 3v)** assembling a carrier substrate made of polycrystalline silicon carbide with the thin film of the temporary structure, via a second bonding interface;
 - 3vi)** dismantling along the first bonding interface in order to separate the temporary substrate from the composite structure provided with the thin film made of single-crystal silicon carbide;
 - the manufacturing method comprises a step 6) of recycling the residual donor substrate in order to produce a recycled donor substrate, and wherein:
 - the recycled donor substrate is directly introduced in step 3) as a donor substrate; and
 - in the following step 4), grading the resulting composite structure uses the first map established for the initial donor substrate from which the recycled donor substrate is derived.

The invention also relates to a method comprising the following steps of:

- 1)** providing at least one donor substrate made of single-crystal silicon carbide, having a front face and a rear face, with the front face potentially having defects, called primary defects, that pass through and also exist on the rear face;

- 2) checking the quality of the at least one donor substrate using a photoluminescence imaging technique so as to extract a map of the rear face, called first map, listing the primary defects identified as being of the micro-pipe type, of the complex star-shaped stacking defect type or of the point defect type;
- 3) transferring a thin film, derived from a surface film of the at least one donor substrate on the side of the front face thereof, onto a carrier substrate made of polycrystalline silicon carbide, in order to obtain a composite structure and a residual donor substrate;
- 4) inspecting a free surface of the thin film of the composite structure using a defect inspection technique using ultraviolet laser beam scattering, so as to extract a map of the free surface, called second map, listing defects, called secondary defects;
- 5) grading the composite structure, including comparing the first map and the second map.

BRIEF DESCRIPTION OF THE FIGURES

Further features and advantages of the invention will become apparent from the following detailed description of the invention, which is provided with reference to the appended figures, in which:

[Fig. 1] Figure 1 shows a donor substrate, a composite structure without and with an epitaxial film;

[Fig. 2a]

[Fig. 2b]

[Fig. 2c]

[Fig. 2d] Figure 2a, figure 2b, figure 2c and figure 2d show examples of a study, carried out on SICA88 type equipment, of a correlation between primary defects present on a front face of a donor substrate and associated secondary defects present on the free face of a thin film in a composite structure; the primary defects are imaged by photoluminescence microscopy; they result in secondary defects when they have a contrast value that is above a predetermined threshold; the secondary defects are imaged by Nomarski prism confocal optical microscopy;

[Fig. 3a]

[Fig. 3b]

[Fig. 3c]

[Fig. 3d]

[Fig. 3e]

[Fig. 3f] Figures 3a, 3b, 3c, 3d, 3e and 3f show steps of a method for manufacturing a composite structure according to the present invention;

[Fig. 4] Figure 4 shows a map (first map) listing the primary defects of a donor substrate, in step 2) of the method according to the invention;

[Fig. 5a]

[Fig. 5b] Figure 5a and figure 5b show two examples of a map (second map) listing the secondary defects of a composite structure (with the thin film being derived from the donor substrate whose first map is also illustrated in the figures), in step 4) of the method according to the invention;

[Fig. 6a]

[Fig. 6b]

[Fig. 6c]

[Fig. 6d]

[Fig. 6e]

[Fig. 6e']

[Fig. 6e''] Figures 6a, 6b, 6c, 6d, 6e, 6e' and 6e'' show steps of an alternative embodiment of the method for manufacturing a composite structure according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The invention relates to a method for manufacturing a composite structure 100 comprising a thin film 10 made of single-crystal silicon carbide disposed on a carrier substrate 20 made of polycrystalline silicon carbide. Of course, it will be understood that, although the description only refers to manufacturing a composite structure 100 for the sake of readability, the method applies to the manufacture of a plurality of composite structures 100.

In the following description, "primary defects" will conventionally refer to defects present on and/or in a donor substrate 1 that the thin film 10 is derived from, "secondary defects" will conventionally refer to defects present on and/or in the thin film of a composite structure 100, and "tertiary defects" will conventionally refer to defects present on and/or in the epitaxial film grown on the thin film 10.

In a principal plane (x, y), the donor substrate 1 and the composite structure 100 are preferably in the form of circular wafers with a diameter of 100 mm, 150 mm, 200 mm or even more. They could, however, assume any other form allowing them to be subsequently processed for manufacturing components. The thickness of the substrates and structures extends along the z axis in figure 1. It is the front faces 1a, 10a, 150a of the substrate 1 and of the structure 100 that are inspected and are likely to have the aforementioned defects.

The manufacturing method comprises a **first step 1)** of providing a donor substrate 1 made of single-crystal silicon carbide. The single-crystal SiC can be of the 4H, 6H or 3C polytype. The donor substrate 1 is preferably in the form of a wafer with a diameter that is identical or very similar to that of the carrier substrate 20 with which it will be subsequently assembled, and with a thickness typically ranging between 300 μm and 800 μm . It has a front face 1a and a rear face 1b (figure 3a). The surface roughness of the front face 1a is advantageously selected so as to be lower than 1 nm RMS, or even lower than 0.5 nm RMS, as measured by Atomic Force Microscopy (AFM) on a 20 μm $\times$ 20 μm scan. The type of doping and the resistivity of the donor substrate 1 are defined according to the application and the targeted devices. Preferably, the front face 1a is a “carbon” face [000-1], for providing, after the transfer, a thin film 10 with a “silicon” type front face 10a [0001] in the composite structure 100.

Although step 1) states that a donor substrate 1 is provided, a plurality of donor substrates 1 clearly can be provided in this step in an industrial context.

The **second step 2)** of the method comprises checking the quality of the at least one donor substrate 1 using a photoluminescence imaging technique so as to extract a map of the front face 1a, called first map, listing the primary defects identified as being of the micro-pipe type, of the complex star-shaped stacking defect type and of the point defect type (for example, a defect linked to an inclusion of species). Indeed, the Applicant has identified that these types of defects could form critical defects that generate problematic secondary defects in the thin film 10 of the composite structure 100.

The primary defects of a donor substrate 1 are revealed by photoluminescence imaging due to local variations in the intensity of a photoluminescence (PL) signal emitted by the front face 1a, following excitation using an incident beam. Local variations in the PL signal intensity reflect altered properties of the material (stresses, roughness, flatness, etc.), corresponding to the primary defect. The latter may appear on the generated PL image in the form of white or black spot(s) depending on its characteristics.

This checking step can be carried out on known equipment, for example, SICA88 (by Lasertec) or “Photoluminescence scanner” (by Intego) or “MiPlato SiC” (by EtaMax). This equipment conventionally uses a combination of a visible light optical microscopy image and the photoluminescence image of the same defect in order to assign dimensional (size, surface) and intensity (contrast) criteria based on the measured optical microscope and photoluminescence signals; it can also assign a typology criterion (predefined defect classes) to each of the primary defects, based on a learning algorithm, for example. The predefined classes typically correspond to defects of the micro-pipe type, complex star-shaped stacking defects, point defects (notably linked to inclusions), scratches, particles, etc.

Advantageously, step 2) comprises the three sub-steps described below:

i) Inspecting the front face 1a of the donor substrate 1:

The purpose of this step is to detect primary defects, due to local variations in the intensity of a photoluminescence signal emitted by the front face 1a following excitation by an incident beam, and to form a photoluminescence image for each primary defect. In SICA88 equipment, which will be preferred throughout the remainder of this description, the incident excitation beam has a wavelength of 313 nm and the emitted photoluminescence signal is collected in a wavelength range ranging from 700 nm to 1,000 nm.

ii) Assigning a tagged type of defect to each detected primary defect:

An image recognition algorithm, based, for example, on an SSD (Single Shot Detector) type model for detecting objects, is supplied with and trained on various types of defects likely to be present on the front face 1a of a donor substrate 1 made of single-crystal silicon carbide, such as micro-pipes, complex star-shaped stacking defects and point defects notably linked to inclusions (tagged type of defect). Therefore, the equipment can assign a tagged type of defect to each detected primary defect, with a certain level of similarity. A level of contrast is also associated with the photoluminescence image of each detected primary defect.

iii) Classifying each primary defect by applying the following conditions:

- if the tagged type of defect is a micro-pipe and if the level of similarity is greater than a first level, the primary defect is classified as a critical micro-pipe type defect;

- if the tagged type of defect is a complex star-shaped stacking defect and if the level of similarity is greater than a second level, the primary defect is classified as a critical defect of the complex star-shaped stacking defect type;
- if the tagged type of defect is a point defect, if the level of similarity is greater than a third level, and if the level of contrast is greater than a predetermined threshold, the primary defect is classified as a critical defect of the point defect type;
- otherwise, the primary defect is classified as a non-critical defect.

The first, second and third levels of similarity can differ from each other, since they are dependent on the type of defect and on the number of defects of each type used to train the image recognition algorithm.

The predetermined contrast threshold can be established empirically for a given type of donor substrate 1 (supplier, crystalline structure, roughness of the front face, manufacturing technique, etc.), based on a study of the correlation between the contrast value of primary defects detected on a front face 1a of a (or preferably a plurality of) test donor substrate(s) and the presence of secondary defects on a (or preferably a plurality of) thin film(s) 10, derived from the one or more test donor substrates, transferred onto a carrier substrate 20.

The table in figure 2a shows the correlation that can be observed between a critical primary defect (figure 2a (a)) on a donor substrate 1 and a secondary defect (figure 2a (b)) induced in the thin film 10 derived from this substrate 1.

The tables in figures 2b, 2c and 2d show that not all the primary defects detected on a donor substrate 1 result in secondary defects in the transferred thin film 10, and that criteria therefore need to be defined for correctly classifying these primary defects as critical or non-critical defects. In addition to the level of similarity applied to each primary defect associated with a tagged type of defect, the level of contrast of the photoluminescence image is an important criterion, particularly for judging the criticality of point defects, since these defects can exhibit a wide range of contrasts, from low to high. For this reason, a predetermined contrast threshold is used to separate critical defects from non-critical defects. In the example shown in figure 2b, the predetermined contrast threshold is set to 600 a.u. This threshold obviously depends on the parameters of the recipe and the features of the carrier substrate 1 (roughness, doping, residual stress, manufacturing method, etc.) and a universal value never can be proposed.

For defects of the micro-pipe or of the complex star-shaped stacking defect type, the level of similarity is often sufficient because these defects have a very specific signature and a high associated contrast. The

photoluminescence image also can be associated with the optical microscopy image of these defects in order to further improve their classification.

By way of a reminder, the contrast in a photoluminescence image can be defined as the normalised difference between a photoluminescence signal intensity on the primary defect and a surrounding intensity in a field that is less than or equal to the field size of the microscope. Other computations of the contrast value would yield different numerical results and a different predetermined contrast threshold, but with similar meaning.

The example of a first map is provided in figure 4: it lists the primary defects that are detected on a donor substrate 1 and are classified as critical defects (notably of the following type: complex star-shaped stacking defects, micro-pipes or point defects of the species inclusion type); another defect, classified as non-critical, is illustrated in the top left of figure 4.

According to one advantageous embodiment, in step 2) of the method according to the invention, a donor substrate 1 having a density of primary defects, classified as critical defects irrespective of the type, that is greater than 1 defect/cm², or even greater than 0.25 defect/cm², is declassified on completion of step 2) and is not used for the subsequent step, step 3).

The manufacturing method then comprises a **third step 3)** of transferring a thin film 10, derived from a surface film 10' of the donor substrate 1, onto a carrier substrate 20 made of polycrystalline silicon carbide, in order to obtain the composite structure 100 and a residual donor substrate 1' devoid of the surface film 10'. In the composite structure 100, the front face 1a of the donor substrate 1 is thus disposed opposite a front face 20a of the carrier substrate 20, and corresponds to a buried face of the thin film 10, which is not accessible for surface inspection; the other face 10a of the thin film 10, opposite the buried face (front face 1a), is free and will be inspected during the next step.

Advantageously, the surface film 10' is transferred using a thin film transfer technique such as Smart Cut. A first sub-step 3a) comprises implanting light species in a donor substrate 1 in order to form a buried weak plane 11 delimiting, with a front face 1a of the donor substrate 1, the surface film to be transferred 10' (figure 3b). The light species are preferably hydrogen and/or helium, and are implanted in the donor substrate 1 at a depth that is consistent with the thickness of the targeted thin film 10. These light species will form, around the determined depth, microcavities distributed in a fine film parallel to the free surface

1a of the donor substrate 1, that is parallel to the plane (x, y) in the figures. This thin film is called buried weak plane 11, for the sake of simplicity. The implantation energy of the light species is selected so as to reach the given depth. For example, hydrogen ions will be implanted with an energy level ranging between 10 keV and 250 keV, and at a dose ranging between $5 \times 10^{16}/\text{cm}^2$ and $1 \times 10^{17}/\text{cm}^2$, in order to delimit a thin film 10 with a thickness of the order of 100 nm to 1,500 nm. It should be noted that a protective film can be deposited onto the front face 1a of the donor substrate 1, prior to the ion implantation step. This protective film can be made up of a material such as silicon oxide or silicon nitride, for example. It can be removed before the following sub-step 3b). This sub-step corresponds to the assembly of a carrier substrate 20 made of polycrystalline silicon carbide, on the side of the front face 20a thereof, with the implanted donor substrate 1, also on the side of the front face 1a thereof (figure 3c). The carrier substrate 20 corresponds to the mechanical support of the future composite structure 100. The lateral dimensions in the principal plane (x, y) of the carrier substrate 20 (its diameter in particular) are the same as those of the composite structure 100. The thickness of the carrier substrate 20 typically ranges between approximately 50 μm and several hundred micrometres, for example, between 50 μm and 650 μm , or between 100 μm and 450 μm , or even between 200 μm and 350 μm .

The assembly is carried out by direct bonding, by molecular adhesion, along a bonding interface 40. Optionally, an intermediate film can be formed on the front face 1a of the donor substrate 1, before or after the introduction of the light species, and in any case, before the assembly phase. This intermediate film can be made of a dielectric, semiconductor or metal material (such as, for example, silicon oxide, silicon, silicon carbide, tungsten, titanium, etc.). Optionally, an intermediate film also can be deposited onto the face 20a of the carrier substrate 20 that is to be assembled, prior to the assembly phase; it can be selected so as to be the same nature as or a different nature from the intermediate film mentioned for the donor substrate 1. An intermediate film optionally can be deposited onto either one of the two substrates 1, 20 to be assembled. The purpose of the one or more intermediate films is essentially to promote the bonding energy (notably in the temperature range below 1,100 °C), due to the formation of covalent bonds at lower temperatures than in the case of two directly assembled SiC surfaces; another advantage of the one or more intermediate films can be to improve the vertical electrical conduction of the bonding interface 40. The one or more intermediate films is/are intended to be buried in the bonded assembly 50 after assembly, and ultimately in the composite structure 100.

Direct bonding by molecular adhesion does not require an adhesive material, as bonds are established on the atomic scale between the assembled surfaces. Several types of molecular adhesion bonding exist, which notably differ in terms of their temperature, pressure or atmosphere conditions or treatments before the surfaces are brought into contact. Room temperature bonding with or without prior plasma activation

of the surfaces to be assembled, atomic diffusion bonding (ADB), surface-activated bonding (SAB), etc., can be cited.

By way of a reminder, the assembly step 3b) can include, before bringing the faces 1a, 20a to be assembled into contact, conventional sequences of chemical cleaning (for example, RCA cleaning), of surface activation (for example, by oxygen or nitrogen plasma) or other surface preparations (such as cleaning by brushing (scrubbing)), which are liable to promote the quality of the bonding interface 40 (low defectiveness, high adhesion energy).

The following sub-step 3c) corresponds to a separation along the buried weak plane 11, in order to form an intermediate composite structure 100' comprising the thin film 10 post-transfer and the carrier substrate 20, on the one hand, and the remainder 1' of the donor substrate, on the other hand (figure 3d). The separation along the buried weak plane 11 is usually carried out by applying a heat treatment at a temperature ranging between 800 °C and 1,200 °C. Such a heat treatment causes cavities and microcracks to develop in the buried weak plane 11, and causes them to be pressurized by the light species present in gaseous form, until a fracture propagates along said weak plane 11. Alternatively, or conjointly, a mechanical stress can be applied to the bonded assembly 50, and in particular to the buried weak plane 11, so as to propagate or assist the mechanical propagation of the fracture leading to the separation. On completion of this separation, the intermediate composite structure 100' is obtained, on the one hand, and the remainder 1' of the donor substrate is obtained, on the other hand. The free surface 10'a of the surface film 10' is usually rough after separation: for example, it exhibits roughness ranging between 5 nm and 100 nm RMS.

The following sub-step 3d) comprises applying heat, mechanical and/or chemical treatments to a free surface 10'a of the surface film 10' in order to form the composite structure 100 provided with the thin film 10 made of single-crystal silicon carbide having surface roughness that is less than or equal to 0.5 nm RMS, or even less than or equal to 0.1 nm RMS (10 x 10 μm^2 or 20 x 20 μm^2 AFM scan) (figure 3e). In particular, this sub-step 3d) can comprise a chemical-mechanical smoothing treatment of the free surface 10'a of the surface film 10'. Removal ranging between 50 nm and 300 nm allows the surface finish of said film to be effectively restored. It can also include at least one heat treatment at a temperature ranging between 1,200 °C and 1,800 °C. Such a heat treatment is applied to remove the residual light species from the thin film 10' and to promote the rearrangement of the crystal lattice thereof, thus forming the thin film 10. It also allows the bonding interface 40 to be reinforced.

At this stage of the method, the thickness of the thin film 10 of the composite structure 100 typically ranges between a few tens of nm and a few hundred nm, for example, between 50 nm and 800 nm. The types and levels of doping of the thin film 10 and of the carrier substrate 20 are defined as a function of the intended applications and devices.

With further reference to the general description of the manufacturing method according to the invention, step 3) of transferring the thin film 10 onto the carrier substrate 20 is followed by a **fourth step 4)** of inspecting the free surface 10a of said thin film 10 using a defect inspection technique based on dark-field and bright-field imaging combined with scanning the surface 10a with a DUV ("Deep UV", typically with a wavelength of the order of 200-280 nm) laser beam; the laser beam is scattered by the defects in proportion to their size, which allows said defects to be located on the surface 10a and their size to be estimated. For example, equipment such as KLA SPA2 can be used. The DUV laser beam hardly penetrates the thickness of the thin film 10, so it is not polluted by the presence of the p-SiC grains of the carrier substrate 20. This technique allows secondary defects present on the surface of the thin film 10 to be detected and to be associated with known defects in the equipment database, such as voids, bubbles, scratches, particles, other point or agglomerated defects, etc.

This inspection step is widely used in the semiconductor industry (particularly silicon), which makes it a step that is compatible with industrial standards and production rate requirements.

The secondary defects can be induced by primary defects (crystalline defects present on the donor substrate 1 that resulted in the thin film 10), by particles or other surface contaminations that have not been completely eliminated before assembling the donor substrate 1 and the carrier substrate 20, or even by a specific problem during a step of the manufacturing method (scratches, deposited particles, flaking, etc.). Therefore, these can be defects of crystalline origin or defects linked to the transfer such as voids (local absence of thin film 10), bubbles (defect on the bonding interface 40, where the thin film 10 is not bonded and forms a blister), particles, scratches, etc.

On completion of step 4), a map of the free surface 10a, called second map, can be extracted, listing the identified secondary defects. An example of a second map listing the secondary defects detected on a composite structure 100 whose thin film 10 is derived from the donor substrate 1 (first map) is shown in figure 5a. It should be noted that, in order to compare the first and second maps, a "mirror" inversion of the first map needs to be applied, since the front face 1a of the donor substrate 1 is assembled on the carrier substrate 20, and is therefore inverted. In this example, several primary defects that are classified

as critical (visible on the first map) are also visible on the second map. Another example is shown in figure 5b: in this case, several primary defects that are classified as critical and are visible on the first map are not visible on the second map.

The advantage of this inspection step 4) is that it is fast and therefore allows a complete check of composite structures in a production line. However, it is likely to miss defects of crystalline origin that are present in the thin film, as some of these defects do not cause the UV laser beam to scatter and remain hidden from this inspection.

By contrast, a checking technique combining visible light optical microscopy and photoluminescence imaging can allow these defects of crystalline origin to be detected, but the inspection can be made more difficult by the presence of the underlying p-SiC grains and especially requires a much longer processing time per structure, which affects a high-volume production line.

Thus, the Applicant has defined a reliable and efficient **fifth step 5)** of grading the composite structure 100, based on the use of the first map of the donor substrate 1 (step 2) from which the thin film 10 of the composite structure 100 in question is derived, and of the second map of said structure 100 (step 4). The purpose of this grading is to separate the structures that meet the target specifications from the declassified structures.

The second map is compared with the first map, obviously while ensuring that a mirror inversion is applied to the first map since the donor substrate 1, bonded to the carrier substrate 20, has an inverted front face 1a (buried face of the thin film 10). The grading of the composite structure 100 is decided based on this comparison.

Advantageously, step 5) comprises a reconciliation between the primary defects classified as critical defects in the first map and the secondary defects in the second map. This reconciliation is possible because the first and second maps are established in the same orthonormal reference frame, and each point of either one of the maps is identified by a Cartesian or polar coordinate system, for example. When a primary defect that is classified as a critical defect cannot be associated with a secondary defect, because no defect is detected on the second map, at the site of said primary defect, an additional defect is added to the defects on the second map in order to be taken into account in the grading decision. The primary defects identified as critical (i.e., generating defects in the transferred thin film), are thus

considered for assessing the quality of the composite structures 100, yet without requiring an inspection, which is complex and ultimately time-consuming, on the composite structures 100.

According to one variant, step 5) comprises a reconciliation between the primary defects classified as critical defects and the secondary defects, and if a large number of primary defects classified as critical defects are not each associated with a secondary defect, step 5) comprises an additional check of the composite structure 100 in question, using a technique combining visible light confocal microscopy and photoluminescence imaging, making it possible to check whether defects are actually present in the thin film 10 at the sites of said critical primary defects.

The grading step 5) of the manufacturing method according to the invention allows reliable and efficient decisions to be made concerning the grade to be assigned to the composite structures 100, by benefiting from a precise check of the donor substrates 1 adapted to the film transfer field, by carrying out a rapid and ultimately standardised quality check on all the composite structures 100, and by combining the teaching of these two checks.

In particular, a composite structure 100 can be declassified if it has:

- a density of secondary defects associated with critical primary defects and of primary defects classified as critical defects added to the second map that is greater than 0.25 defects/cm²; and/or
- a density of secondary defects only detected on the second map (i.e., not associated with critical primary defects) that is greater than 0.2 defects/cm².

In a subsequent step, epitaxial growth of SiC can be carried out on the thin film 10 of the composite structures 100 that have positively passed the grading step 5), in order to increase the thickness thereof and to form the epitaxial film 150 on and in which the devices will be produced (figure 3f). The epitaxial growth step can be carried out using the known techniques of the prior art.

The manufacturing method can also comprise a sixth step 6) of recycling the residual donor substrate 1' in order to produce a recycled donor substrate. Step 6) can include mechanical and/or chemical treatments, similar to those applied to the composite structure 100, implemented on the front face 1'a of the residual donor substrate 1'.

The recycled donor substrate is then directly introduced in step 3) as a new donor substrate 1. In step 5), the grading of the resulting composite structure 100 uses the first map (step 2) established for the initial donor substrate 1 from which the recycled donor substrate is derived.

The first map reflecting the quality of the initial donor substrate 1 is therefore used to grade each composite structure 100 derived from this substrate 1, in its initial state and after a plurality of recycling steps. Although this check is time-consuming, it is industrially viable because it is amortised over a very large number of composite structures 100 manufactured from the donor substrate 1.

The manufacturing method has been described with a step 3) of transferring the thin film 10 onto the carrier substrate 20, without intermediate handling, which can be called a single transfer.

According to an alternative embodiment, step 3) can involve a double transfer, illustrated in figures 6a to 6f, during which the thin film 10 is initially transferred from the donor substrate 1 onto a temporary substrate 30, via a first bonding interface 60 (figures 6a, 6b, 6c, 6d, 6e), then transferred a second time from the temporary substrate 30 onto the carrier substrate 20 (figures 6e', 6e''), via a second bonding interface 40.

Step 3) thus can comprise the following sub-steps of:

- 3i)** implanting light species in a donor substrate 1 in order to form a buried weak plane 11 delimiting, with a front face 1a of the donor substrate 1, the surface film 10' to be transferred;
- 3ii)** assembling a temporary substrate 30 with the donor substrate 1 implanted in step 3i), via a first bonding interface 60;
- 3iii)** separating along the buried weak plane 11 in order to form an intermediate assembly comprising the surface film 10' post-transfer and the carrier substrate 30, on the one hand, and the remainder 1' of the donor substrate, called residual donor substrate 1', on the other hand;
- 3iv)** applying one or more heat, mechanical and/or chemical treatments to a free surface 10'a of the surface film 10' in order to form a temporary structure provided with the thin film 10 made of single-crystal silicon carbide disposed on the temporary substrate 30;
- 3v)** assembling a carrier substrate 20 made of polycrystalline silicon carbide with the thin film 10 of the temporary structure, via a second bonding interface 40;
- 3vi)** dismantling along the first bonding interface 60 in order to separate the temporary substrate 30 from the composite structure 100 provided with the thin film 10 made of single-crystal silicon carbide.

The first bonding interface 60 can be based on molecular adhesion bonding, as can the second interface 40. The temporary substrate 30 can be selected from any material compatible with direct bonding, notably silicon, silicon carbide, etc. The temporary substrate 30 can be removed by mechanical dismantling, for example.

The composite structure 100 obtained in this alternative embodiment comprises a thin film 10 whose free surface 10b corresponds to the front face 1a of the donor substrate 1, taking into account the double transfer.

Thus, in step 5) of grading the composite structure 100, the comparison of the first map and the second map can be carried out without mirror inversion.

According to another particular embodiment, involving a single transfer in step 3), the method can comprise the following steps:

- 1) providing at least one donor substrate 1 made of single-crystal silicon carbide, having a front face 1a and a rear face 1b, with the front face 1a potentially having defects, called primary defects, that pass through and also exist on the rear face 1b;
- 2) checking the quality of the at least one donor substrate 1 using a photoluminescence imaging technique so as to extract a map of the rear face 1b, called first map, listing the primary defects identified as being of the micro-pipe type, of the complex star-shaped stacking defect type or of the point defect type;
- 3) transferring a thin film 10, derived from a surface film 10' of the at least one donor substrate 1 on the side of the front face 1a thereof, onto a carrier substrate 20 made of polycrystalline silicon carbide, in order to obtain a composite structure 100 and a residual donor substrate 1';
- 4) inspecting a free surface 10a of the thin film 10 of the composite structure 100 using a defect inspection technique using ultraviolet laser beam scattering, so as to extract a map of the free surface 10a, called second map, listing defects, called secondary defects;
- 5) grading the composite structure 100, including comparing the first map and the second map.

According to this particular embodiment, the quality of the donor substrate 1 is checked on its rear face 1b, considering that the critical primary defects are mostly through defects and will therefore be detectable on the rear face 1b, as on the front face 1a. In step 5), the first and second maps can be compared without mirror inversion.

It should be noted that the generic details of steps 1) to 5) set forth in this description in the case of a single transfer can be applied to this particular embodiment, as well as to the alternative embodiment based on a double transfer.

Of course, the invention is not limited to the described embodiments and examples, and alternative embodiments can be used without departing from the scope of the invention as defined by the claims.

CLAIMS

1. **Method for manufacturing a composite structure (100)** comprising a thin film (10) made of single-crystal silicon carbide disposed on a carrier substrate (20) made of polycrystalline silicon carbide, the method comprising the following steps of:

1) providing at least one donor substrate (1) made of single-crystal silicon carbide, having a front face (1a) and a rear face (1b), with the front face (1a) potentially having defects, called primary defects;

2) checking the quality of the at least one donor substrate (1) using a photoluminescence imaging technique so as to extract a map of the front face (1a), called first map, listing the primary defects identified as being of the micro-pipe type, of the complex star-shaped stacking defect type or of the point defect type;

3) transferring a thin film (10), derived from a surface film (10') of the at least one donor substrate (1), onto a carrier substrate (20) made of polycrystalline silicon carbide, in order to obtain a composite structure (100) and a residual donor substrate (1');

4) inspecting a free surface (10a, 10b) of the thin film (10) of the composite structure (100) using a defect inspection technique using ultraviolet laser beam scattering, so as to extract a map of the free surface (10a, 10b), called second map, listing defects, called secondary defects;

5) grading the composite structure (100), including comparing the first map and the second map.

2. Method for manufacturing a composite structure (100) according to Claim 1, wherein step 2) comprises the following sub-steps of:

i) inspecting a front face (1a) of the donor substrate (1) in order to detect the primary defects, due to local variations in intensity of a photoluminescence signal emitted by the front face (1a) following excitation by an incident beam, and in order to form a photoluminescence image for each primary defect;

ii) assigning a tagged type of defect with a certain level of similarity to each detected primary defect, by virtue of an image recognition algorithm trained on various types of defect likely to be present on the front face (1a) of a donor substrate (1) made of single-crystal silicon carbide, such as micro-pipes, complex star-shaped stacking defects and point defects notably linked to inclusions, with a level of contrast being associated with the photoluminescence image of each detected primary defect;

ii) classifying each primary defect by applying the following conditions:

- if the tagged type of defect is a micro-pipe and if the level of similarity is greater than a first level, the primary defect is classified as a critical micro-pipe type defect;

- if the tagged type of defect is a complex star-shaped stacking defect and if the level of similarity is greater than a second level, the primary defect is classified as a critical defect of the complex star-shaped stacking defect type;

- if the tagged type of defect is a point defect, if the level of similarity is greater than a third level, and if the level of contrast is greater than a predetermined threshold, the primary defect is classified as a critical defect of the point defect type;

- otherwise, the primary defect is classified as a non-critical defect.

3. Method for manufacturing a composite structure (100) according to Claim 2, wherein the inspection step i) is carried out with an incident beam with a wavelength of 313 nm and the emitted photoluminescence signal is collected in a wavelength range ranging from 700 nm to 1,000 nm.

4. Method for manufacturing a composite structure (100) according to any of Claims 2 and 3, wherein the predetermined threshold is established empirically for a type of donor substrate (1), based on a study of a correlation between the contrast value of primary defects detected on a front face (1a) of a test donor substrate (1) and the presence of secondary defects on a thin film (10), derived from the test donor substrate, transferred onto a carrier substrate (20).

5. Method for manufacturing a composite structure (100) according to any of Claims 2 to 4, wherein a donor substrate (1) having a density of primary defects, classified as critical defects irrespective of the type, that is greater than 1 defect/cm², or even preferably greater than 0.25 defect/cm², is declassified on completion of step 2) and is not used for step 3).

6. Method for manufacturing a composite structure (100) according to any of Claims 2 to 5, wherein step 5) comprises a reconciliation between the primary defects classified as critical defects and the secondary defects, with each primary defect classified as a critical defect and not associated with a secondary defect being added to the defects of the second map in order to be taken into account in a grading decision.

7. Method for manufacturing a composite structure (100) according to Claim 6, wherein the grading decision corresponds to a declassification of the composite structure if said composite structure comprises:

- a density of secondary defects associated with critical primary defects and of primary defects classified as critical defects added to the second map, that is greater than 0.25 defects/cm²; and/or
- a density of secondary defects only detected on the second map, not associated with critical primary defects, that is greater than 0.2 defects/cm².

8. Method for manufacturing a composite structure (100) according to any of Claims 2 to 5, wherein step 5) comprises a reconciliation between the primary defects classified as critical defects and the secondary defects, and step 5) comprises an additional check using a technique combining visible light optical microscopy and photoluminescence imaging, for checking whether defects are present in the thin film (10), at the sites of said primary defects classified as critical defects.

9. Method for manufacturing a composite structure (100) according to any of the preceding claims, wherein step 3) comprises the following sub-steps of:

3a) implanting light species in a donor substrate (1) in order to form a buried weak plane (11) delimiting, with a front face (1a) of the donor substrate (1), the surface film (10) to be transferred;

3b) assembling a carrier substrate (20) made of polycrystalline silicon carbide with the donor substrate (1) implanted in step 3a);

3c) separating along the buried weak plane (11) in order to form an intermediate composite structure (100') comprising the surface film (10') post-transfer and the carrier substrate (20), on the one hand, and the remainder (1') of the donor substrate, called residual donor substrate (1'), on the other hand;

3d) applying one or more heat, mechanical and/or chemical treatments to a free surface (10'a) of the surface film (10') in order to form the composite structure (100) provided with the thin film (10) made of single-crystal silicon carbide.

10. Method for manufacturing a composite structure (100) according to any of the preceding claims, wherein, in the composite structure (100):

- the thin film (10) comprises a buried face disposed opposite the carrier substrate (20), corresponding to the front face (1a) of the donor substrate (1), and another face, opposite the front face (1a), corresponding to a free surface (10a) of said film (10);

- in step 5), a mirror inversion is applied to the first or to the second map in order to compare them.

11. Method for manufacturing a composite structure (100) according to any of Claims 1 to 8, wherein step 3) comprises the following sub-steps of:

3i) implanting light species in a donor substrate (1) in order to form a buried weak plane (11) delimiting, with a front face (1a) of the donor substrate (1), the surface film (10) to be transferred;

3ii) assembling a temporary substrate (30) with the donor substrate (1) implanted in step 3i), via a first bonding interface (60);

3iii) separating along the buried weak plane (11) in order to form an intermediate assembly comprising the surface film (10') post-transfer and the temporary substrate (30), on the one hand, and the remainder (1') of the donor substrate, called residual donor substrate (1'), on the other hand;

3iv) applying one or more heat, mechanical and/or chemical treatments to a free surface (10'a) of the surface film (10') in order to form a temporary structure provided with the thin film (10) made of single-crystal silicon carbide disposed on the temporary substrate (30);

3v) assembling a carrier substrate (20) made of polycrystalline silicon carbide with the thin film (10) of the temporary structure, via a second bonding interface (40);

3vi) dismantling along the first bonding interface (60) in order to separate the temporary substrate (30) from the composite structure (100) provided with the thin film (10) made of single-crystal silicon carbide.

12. Method for manufacturing a composite structure according to any of the preceding claims, comprising a step 6) of recycling the residual donor substrate (1') in order to produce a recycled donor substrate (1''), and wherein:

- the recycled donor substrate (1'') is directly introduced in step 3) as a donor substrate (1); and
- in the following step 4), grading the resulting composite structure (100) uses the first map established for the initial donor substrate (10) from which the recycled donor substrate (1'') is derived.

13. **Method for manufacturing a composite structure** (100) comprising a thin film (10) made of single-crystal silicon carbide disposed on a carrier substrate (20) made of polycrystalline silicon carbide, the method comprising the following steps of:

1) providing at least one donor substrate (1) made of single-crystal silicon carbide, having a front face (1a) and a rear face (1b), with the front face (1a) potentially having defects, called primary defects, that pass through and also exist on the rear face (1b);

2) checking the quality of the at least one donor substrate (1) using a photoluminescence imaging technique so as to extract a map of the rear face (1b), called first map, listing the primary defects identified as being of the micro-pipe type, of the complex star-shaped stacking defect type or of the point defect type;

3) transferring a thin film (10), derived from a surface film (10') of the at least one donor substrate (1) on the side of the front face (1a) thereof, onto a carrier substrate (20) made of polycrystalline silicon carbide, in order to obtain a composite structure (100) and a residual donor substrate (1');

4) inspecting a free surface (10a) of the thin film (10) of the composite structure (100) using a defect inspection technique using ultraviolet laser beam scattering, so as to extract a map of the free surface (10a), called second map, listing defects, called secondary defects;

5) grading the composite structure (100), including comparing the first map and the second map.