

DESCRIPTION

TITLE: Method for checking the quality of a composite structure comprising a thin film made of c-SiC, and composite structure

FIELD OF THE INVENTION

The present invention relates to the field of semiconductor materials. It particularly relates to a method for checking the quality of a composite structure comprising a thin film made of single-crystal silicon carbide disposed on a carrier substrate made of polycrystalline silicon carbide.

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 single-crystal silicon carbide (c-SiC) substrates 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, 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 fragile buried plane, along which separation occurs, 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 check the quality of the donor substrates, so as to avoid transferring a film that is out-of-specification, or that would result in an epitaxial film that is out-of-specification, in terms of “killer” defects. 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. The zoology of defects in c-SiC is relatively well known, and numerous studies tend to define the type and the size of defects present in the c-SiC epitaxial film that would kill components; criteria for classifying primary defects, with a view to transferring a c-SiC thin film, therefore can be established.

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) is complex because the p-SiC grains are visible under said thin film. An effective method for checking the quality of the thin film is therefore required, on the one hand, to avoid continuing with the epitaxy steps if secondary defects in the thin film are likely to generate a density of killer defects, out-of-specification, in the homoepitaxial film, and, on the other hand, it is important that the

checking method is capable of distinguishing defects in the thin film from potential “false defects” (or measurement noise) associated with underlying grains in the p-SiC substrate.

In view of the increasing use of film transfer techniques in the manufacturing chain for electronic devices on c-SiC, there is therefore a major need to define checking methods that allow reliable inspection of composite structures.

SUBJECT MATTER OF THE INVENTION

The present invention addresses the stated problem. The invention relates to a method for checking the quality of a composite structure comprising a thin film (derived from a donor substrate made of single-crystal silicon carbide) disposed on a carrier substrate made of polycrystalline silicon carbide, with said checking method allowing reliable classification of any secondary defects present on and/or in the thin film.

BRIEF DESCRIPTION OF THE INVENTION

The invention relates to a method for checking the quality of 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:

- a)** inspecting a free surface of the thin film using a technique combining confocal visible light microscopy and photoluminescence imaging, allowing defects, called secondary defects, to be detected that are present on and/or in the thin film, and allowing a visible light image and a photoluminescence image to be formed for each defect;
- b)** initially identifying secondary defects, by similarity, based on their visible light image, by virtue of an image recognition algorithm trained on various types of defects likely to be present on and/or in a thin film, such as voids, bubbles, scratches, defects of crystalline origin; with, on completion of step b), each secondary defect being associated with an identified type of defect, with a certain level of similarity;
- c)** finally classifying at least some secondary defects by applying the following first conditions:
 - if the level of similarity associated with a secondary defect is greater than a high level, said secondary defect is definitively classified as the identified type of defect;
 - if the level of similarity associated with the secondary defect ranges between a low level and the high level, the photoluminescence image of said defect is analysed by an image recognition algorithm trained

on various tagged types of defect; if the secondary defect is associated with a tagged type of defect, said secondary defect is definitively classified as the identified type of defect;

- in other cases, the secondary defect is definitively classified as not being a defect.

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

- the secondary defects to which the first conditions apply are those that on completion of step b) are associated with voids or defects of crystalline origin;
- the high level, called first high level, and/or the low level, called first low level, used in step c) for a secondary defect associated with a void in step b), are different from the high level, called second high level, and/or the low level, called second low level, used in step c) for a secondary defect associated with a defect of crystalline origin in step b);
- the final classification step c) is also based on applying the following second conditions:
 - if a secondary defect is identified as a bubble-type defect in step b) with a level of similarity that is greater than a third level, said secondary defect is definitively classified as a bubble;
 - if a secondary defect is identified as a bubble-type defect in step b) with a level of similarity that is less than or equal to the third level, said secondary defect is definitively classified as not being a defect;
- the final classification step c) is also based on applying the following third conditions:
 - if a secondary defect is identified as a scratch-type defect in step b) with a level of similarity that is greater than a fourth level, said secondary defect is definitively classified as a scratch;
 - if a secondary defect is identified as a scratch-type defect in step b) with a level of similarity that is less than or equal to the fourth level, said secondary defect is definitively classified as not being a defect;
- the size of each secondary defect detected in step a) is greater than 1 μm , 5 μm or even 10 μm ;
- step c) results in grading of the composite structure and in physical sorting for separating declassified composite structures and composite structures meeting the specifications;
- a composite structure is declassified when it has a density of defects of crystalline origin that is greater than 0.25 defects/cm² and/or an overall density of bubbles and voids that is greater than 0.2 defects/cm².

The invention also relates to a composite structure formed by a thin film made of single-crystal silicon carbide disposed on a carrier substrate made of polycrystalline silicon carbide, with said composite structure having a density of defects of crystalline origin that is less than or equal to 0.25 defects/cm² and an overall density of bubbles and voids that is less than or equal to 0.2 defects/cm².

BRIEF DESCRIPTION OF THE FIGURES

Further features and advantages of the invention will become apparent from the following detailed description of the invention, 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] Figure 2a and figure 2b illustrate various types of defects with their final classification by applying the particular conditions of the checking method according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

In the following description, “primary defects” will conventionally refer to defects present on and/or in a donor substrate 1, “secondary defects” will conventionally refer to defects present on and/or in the thin film 10 of a composite structure 100, and “tertiary defects” will conventionally refer to defects present on and/or in the epitaxial film 150 grown on the thin film of a composite structure 100.

In a principal plane (x, y), the donor substrate 1 and the composite structure 100, with or without an epitaxial film 150, 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.

Before starting to manufacture a composite structure 100 comprising a thin film made of single-crystal silicon carbide (c-SiC) transferred onto a carrier substrate made of polycrystalline silicon carbide (p-SiC), it is important to check the quality of the donor substrate 1 (made of c-SiC, for example, of the 4H-SiC type) that the thin film will be obtained from.

An inspection of the front face 1a of the donor substrate 1 using a photoluminescence imaging technique, as described in references [1] and [2] cited in the introduction, is preferably carried out in order to detect and classify any defects, hereafter called primary defects.

Primary defects 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 inspection 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 an optical microscopy image and a 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 also assigns a typology criterion (predefined defect classes) to each of the primary defects, based on a learning algorithm. The predefined classes typically correspond to defects such as micro-pipes, stacking faults (SF), pits, bumps, scratches and particles.

After inspecting and potentially declassifying some donor substrates 1 with a defect density and/or typology that would be incompatible with transferring a viable thin film, the composite structure 100 can be manufactured. Any thin-film transfer technique can be used, in particular the Smart Cut method. This method, which is based on light ion implantation and direct assembly by molecular adhesion, will not be described in detail herein as it is well known. In order to obtain the composite structure 100, it is used with a donor substrate 1 made of c-SiC and a carrier substrate 20 made of p-SiC.

Typically, the thickness of the thin film 10 ranges between 20 nm and 1,000 nm, and the roughness of its free surface is less than or equal to 0.5 nm RMS, or even 0.1 nm RMS (measured by Atomic Force Microscopy (AFM), on scans from 10 x 10 μm^2 to 30 x 30 μm^2 , for example). The thickness of the carrier substrate 20 can range between approximately 50 μm and several hundred micrometres, for example, between 200 μm and 700 μm . Optionally, the composite structure 100 can comprise an intermediate film, interposed between the thin film 10 and the carrier substrate 20. 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.). A bonding interface is present between the thin film 10 and the carrier substrate 20, or adjacent to the intermediate film.

The present invention relates to a method for checking the quality of a composite structure 100 comprising a thin film 10 made of c-SiC disposed on a carrier substrate 20 made of p-SiC (figure 1).

The checking method comprises a step a) of inspecting a free surface 10a of the thin film 10 using a technique combining visible light confocal microscopy (Differential Interference Contrast - DIC) and photoluminescence imaging, in order to detect defects, called secondary defects, present on and/or in the thin film 10. The size (or equivalent diameter) of the detected defects is typically greater than or equal to 1 μm , greater than or equal to 5 μm , or even greater than or equal to 10 μm .

Differential interference contrast (also called Nomarski) is an illumination technique used to discern minute variations in the topography of a surface by exploiting the interference of light waves.

Photoluminescence imaging is based on local variations in the intensity of a photoluminescence (PL) signal emitted by the free surface 10a, following excitation by an incident electromagnetic beam. 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. Local variations in the PL signal intensity reflect altered properties of the material (stresses, roughness, flatness, etc.), corresponding to the secondary defect. The latter may appear on the generated PL image in the form of white or black spot(s) depending on its characteristics.

In step a), a visible light image, called DIC image hereafter, and a photoluminescence image, called PL image hereafter, are formed for each detected secondary defect.

The secondary defects can be induced by primary defects or by particles or other surface contaminations that have not been completely eliminated before assembling the donor substrate 1 and the carrier substrate 20. These therefore can be defects of crystalline origin, bonding defects, such as voids (local absence of thin film 10) or bubbles (defect at the bonding interface 40, where the thin film 10 is not bonded and forms a blister), or even surface defects such as scratches or flakes present on the front face 10a of the thin film.

The checking method then comprises a step b) corresponding to the initial identification of secondary defects, by similarity, based on their DIC image.

The aforementioned equipment (and in particular the SICA88) is capable of identifying secondary defects based on images captured by visible light microscopy, using an image recognition algorithm. The algorithm is supplied and trained with verified images of defects likely to be present on and/or in a thin film 10, such as voids, bubbles, scratches, chips, defects of crystalline origin: it can thus learn to recognise each of these defects and compute a level of similarity between the DIC image of the detected defect and its database, taking into account size, shape, colour, contrast criteria, etc.

On completion of step b), each secondary defect is associated with an identified type of defect (for example, void, bubble, scratch, chip or defect of crystalline origin), with a certain level of similarity (ranging between 0 and 1).

Due to the presence of a polycrystalline carrier substrate 20 under the thin film 10, the initial identification automatically carried out by the equipment is not reliable enough to decide on the quality of the composite structure 100. Indeed, this identification can be affected by the underlying grains and the level of similarity assigned to the secondary defect does not in itself make it possible to determine whether said defect is indeed of the identified type or whether it is a “false defect”, for example, linked to the p-SiC grains.

The checking method therefore comprises a step c) of finally classifying any secondary defects by applying particular conditions, set forth below.

The first conditions particularly apply to the secondary defects identified in step b) as being voids or defects of crystalline origin:

- (i) if the level of similarity associated with a secondary defect is greater than a high level, said secondary defect is definitively classified as the identified type of defect;
- (ii) if the level of similarity associated with the secondary defect ranges between a low level and the high level, the PL image of said defect is analysed by an image recognition algorithm trained on various tagged types of defect. Two cases may then arise:
 - if the secondary defect is associated with a tagged type of defect, said secondary defect is definitively classified as the identified type of defect;
 - if the secondary defect is not recognised as being a tagged type of defect, said secondary defect is definitively classified as not being a defect (i.e., considered to be a “false defect”);
- (iii) finally, if the level of similarity associated with the secondary defect is less than the low level, said secondary defect is also definitively classified as not being a defect.

A “false defect” refers to a defect that is detected and associated with a given type (with a certain level of similarity) in step b), but which does not actually correspond to said type: it can either correspond to another type of defect in the thin film, to a measurement artefact or to the image of a grain in the underlying carrier substrate 20.

The PL image recognition algorithm is supplied and trained with verified PL images of defects likely to be present on and/or in a thin film 10: it can thus learn to recognise each of these defects and to classify them in predefined categories (i.e., associate them with tagged types of defect), taking into account size, shape, contrast criteria, etc. A tagged type of defect therefore corresponds to a real defect, whose signature on the PL image is reflected by particular criteria (such as those mentioned above).

In condition (ii), when the PL image associated with the analysed secondary defect corresponds to one of the tagged types of defect, this confirms that it is a “real defect” and the secondary defect is thus classified in the type identified in step b); however, when the PL image does not correspond to any of the tagged types of defects and/or the PL image does not exhibit any particular contrast (no PL signal), the secondary defect is considered to be a “false defect”, even though it was associated with an identified type of defect in step b).

It should be noted that the high level (called first high level) and/or the low level (called first low level) used in step c) to judge the level of similarity of the DIC image, for a secondary defect associated with a void, can differ from the high level (called second high level) and/or the low level (called second low level) used for a secondary defect associated with a defect of crystalline origin.

Second conditions can apply to the secondary defects identified in step b) as being bubbles:

- (iv) if the level of similarity associated with a secondary defect identified as being a bubble is greater than a third level, said secondary defect is definitively classified as a bubble;
- (v) if the level of similarity is less than or equal to the third level, said secondary defect is definitively classified as not being a defect.

Third conditions can apply to the secondary defects identified in step b) as scratches:

- (vi) if the level of similarity associated with a secondary defect identified as being a scratch is greater than a fourth level, said secondary defect is definitively classified as a scratch;

- (vii) if the level of similarity is less than or equal to the fourth level, said secondary defect is definitively classified as not being a defect.

This final classification step c) allows the critical defects present on and/or in the thin film 10 to be reliably categorised, and avoids taking into account “false defects”, notably related to the detection of the underlying grains of the carrier substrate 20.

By way of an example, the checking method is applied to a composite structure 100 comprising a 600 nm thick thin film made of c-SiC disposed on a 150 mm diameter carrier substrate made of p-SiC. The equipment used is the SICA88. In the examples shown in figure 2a and figure 2b, the first low level and the first high level of similarity used in step c) to judge the level of similarity associated with the secondary defects identified as voids are set to 0.3 and 0.85, respectively. The second low level and the second high level of similarity used in step c) to judge the level of similarity associated with the secondary defects identified as defects of crystalline origin are set to 0.3 and 0.85, respectively. The third level used in step c) to judge the level of similarity associated with the secondary defects identified as bubbles is set to 0.85. Finally, the fourth level used in step c) to judge the level of similarity associated with the secondary defects identified as scratches is set to 0.97.

Figures 2a and 2b illustrate defects of the void, crystalline origin, bubble and scratch type detected on and/or in the thin film 10.

On completion of step c) of the checking method a grade can be assigned to the checked composite structures 100. In particular, a higher quality grade can be assigned to structures 100 with an overall density of bubbles and voids that is less than or equal to 0.2 defects/cm². Preferably, such a grade will be assigned to composite structures 100 with an overall density of bubbles, voids and scratches that is less than or equal to 0.2 defects/cm². Even more preferably, the superior quality grade can be assigned to structures 100 with an overall defect density, excluding defects of crystalline origin, that is less than or equal to 0.2 defects/cm².

The acceptable density of defects of crystalline origin is defined as a function of the quality level of the donor substrate 1 from which the thin film 10 is derived. Advantageously, a density of defects of crystalline origin that is less than or equal to 0.25/cm² for a structure 100 affords it a higher quality grade.

Conversely, a lower grade, leading to the declassification of a composite structure 100 on completion of step c), can be defined for an overall density of defects that is greater than the aforementioned thresholds.

Therefore, the present invention also relates to a composite structure 100 formed from a thin film 10 made of single-crystal silicon carbide disposed on a carrier substrate 20 made of polycrystalline silicon carbide. Said composite structure, which is ultimately inspected using the checking method according to the invention, has:

- a density of defects of crystalline origin that is less than or equal to 0.25 defects/cm², less than or equal to 0.2 defects/cm², or even less than or equal to 0.18 defects/cm², or even less than or equal to 0.15 defects/cm²; and
- an overall density of bubbles and voids (and optionally scratches) that is less than or equal to 0.2 defects/cm², less than or equal to 0.18 defects/cm², less than or equal to 0.15 defects/cm², or even less than or equal to 0.12 defects/cm², or even less than or equal to 0.1 defects/cm².

After grading, the composite structures 100 are physically sorted in order to separate the declassified structures 100 from the structures 100 that meet the specifications.

In a subsequent manufacturing step, SiC can be epitaxially grown on the thin film 10 of the composite structures 100 within specifications in order to form the epitaxial film 150 on and in which the devices will be produced (figure 1). The epitaxial growth step can be carried out using techniques that are known in the prior art.

The method for checking the quality of composite structures 100, before the epitaxy step, ensures that the density of tertiary killer defects, linked to the quality of the thin film 10, will be managed, or even lower than a given specification, because this method allows reliable classification of any defects present on and/or in the thin film 10, yet without compromising on quality by declassifying expensive composite structures 100, based on "false defects" notably induced by an underlying polycrystalline substrate.

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

CLAIMS

1. **Method for checking the quality of 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:

a) inspecting a free surface (10a) of the thin film (10) using a technique combining confocal visible light microscopy and photoluminescence imaging, allowing defects, called secondary defects, to be detected that are present on and/or in the thin film (10), and allowing a visible light image and a photoluminescence image to be formed for each defect;

b) initially identifying secondary defects, by similarity, based on their visible light image, by virtue of an image recognition algorithm trained on various types of defects likely to be present on and/or in a thin film (10), such as voids, bubbles, scratches, defects of crystalline origin; with, on completion of step b), each secondary defect being associated with an identified type of defect, with a certain level of similarity;

c) finally classifying at least some secondary defects by applying the following first conditions:

- if the level of similarity associated with a secondary defect is greater than a high level, said secondary defect is definitively classified as the identified type of defect;

- if the level of similarity associated with the secondary defect ranges between a low level and the high level, the photoluminescence image of said defect is analysed by an image recognition algorithm trained on various tagged types of defect; if the secondary defect is associated with a tagged type of defect, said secondary defect is definitively classified as the identified type of defect;

- in other cases, the secondary defect is definitively classified as not being a defect.

2. **Method for checking the quality of a composite structure (100)** according to Claim 1, wherein the secondary defects to which the first conditions apply are those that on completion of step b) are associated with voids or defects of crystalline origin.

3. **Method for checking the quality of a composite structure (100)** according to Claim 2, wherein the high level, called first high level, and/or the low level, called first low level, used in step c) for a secondary defect associated with a void in step b), are different from the high level, called second high level, and/or the low level, called second low level, used in step c) for a secondary defect associated with a defect of crystalline origin in step b).

4. Method for checking the quality of a composite structure (100) according to any of Claims 1 to 3, wherein the final classification step c) is also based on applying the following second conditions:

- if a secondary defect is identified as a bubble-type defect in step b) with a level of similarity that is greater than a third level, said secondary defect is definitively classified as a bubble;
- if a secondary defect is identified as a bubble-type defect in step b) with a level of similarity that is less than or equal to the third level, said secondary defect is definitively classified as not being a defect.

5. Method for checking the quality of a composite structure (100) according to any of Claims 1 to 4, wherein the final classification step c) is also based on applying the following third conditions:

- if a secondary defect is identified as a scratch-type defect in step b) with a level of similarity that is greater than a fourth level, said secondary defect is definitively classified as a scratch;
- if a secondary defect is identified as a scratch-type defect in step b) with a level of similarity that is less than or equal to the fourth level, said secondary defect is definitively classified as not being a defect.

6. Method for checking the quality of a composite structure (100) according to any of Claims 1 to 5, wherein the size of each secondary defect detected in step a) is greater than 1 μm , 5 μm or even 10 μm .

7. Method for checking the quality of a composite structure (100) according to any of Claims 1 to 6, wherein step c) results in grading of the composite structure (100) and in physical sorting for separating declassified composite structures and composite structures meeting the specifications.

8. Method for checking the quality of a composite structure (100) according to Claim 7, wherein a composite structure (100) is declassified when it has a density of defects of crystalline origin that is greater than 0.25 defects/cm² and/or an overall density of bubbles and voids that is greater than 0.2 defects/cm².

9. **Composite structure** (100) formed by a thin film (10) made of single-crystal silicon carbide disposed on a carrier substrate (20) made of polycrystalline silicon carbide, said composite structure (100) having a density of defects of crystalline origin that is less than or equal to 0.25 defects/cm² and an overall density of bubbles and voids that is less than or equal to 0.2 defects/cm².