

METHOD FOR TREATING A SILICON CARBIDE SUBSTRATE

FIELD OF THE INVENTION

The present invention relates generally to the field of manufacturing silicon carbide
5 substrates for forming electronic components. More particularly, it provides a process for
treating a surface of a monocrystalline silicon carbide substrate.

PRIOR ART

Monocrystalline silicon carbide (m-SiC) is used for the formation of electronic
10 components, for example for power electronics or radio frequency applications. In some
applications, bulk monocrystalline SiC substrates are used, in other applications substrates
for example of polycrystalline silicon carbide, including a surface layer of monocrystalline
SiC.

Microelectronics manufacturing processes often involve heat treatments of
15 substrates, for example to activate dopants, to heal defects in the crystal lattice caused by
implantation of ionic species, or to modify the crystal structure of the substrate. Such
treatments are often performed at high temperatures of up to 2000°C or more.

However, the surface of monocrystalline SiC is susceptible to destabilization under
the effect of high temperature. This destabilization can result in a degradation of the surface,
20 in particular by a modification of the morphology and/or the composition of the latter.

In particular, as illustrated in Figure 1, smooth SiC surfaces are sensitive to high
temperature treatments, typically from about 1200°C. In the absence of adequate protection
of said surface, the morphology reorganizes to minimize the surface energy, forming
terraces 22. This effect is known as “step bunching”. The reorganization of the surface 222
25 is due to a diffusion of atoms on the surface when it is exposed to high temperatures. It also
depends on the atmosphere and the pressure to which the surface is exposed.

In order to obtain smooth surfaces, it is therefore sought to avoid the formation of
terraces or to remove them in a later step. For example, mechanical or chemical-mechanical
polishing (CMP) can be carried out after heat treatment. However, if the height of the
30 terraces formed is too great, for example greater than 80 nm between two consecutive
plates, the thickness to be removed is too great, which implies a long and laborious process.
In addition, the remaining thickness of m-SiC is often too thin for the intended applications.

Another process is to use very fast annealing ramps to limit the appearance of
terraces. This process requires temperature increases of around 400°C per minute and is
35 therefore not compatible with industrial furnaces.

Alternatively, a silane overpressure can be applied which limits the sublimation of silicon into SiC, thus avoiding the formation of terraces. This process is described in the article by R. Zhang et al. However, it requires the introduction of a SiH₄ gas and the equipment to create the overpressure. Furthermore, silicon droplets can appear on the SiC surface at temperatures above 1600 °C.

Another possibility to avoid terrace formation is to use a protective layer. The article by J. Bao et al. proposes a carbon protective layer obtained by a process of centrifugation of a resin on a SiC surface. The resin is annealed at 750°C – 900°C to form a carbon film of about 1 µm thickness. This technique involves the addition of additional steps in the formation process, the use of additional equipment and causes a risk of contamination of the substrate by the resin.

In some cases, the protective layer can also be formed from aluminum nitride (AlN). However, this material is difficult to remove, especially after heat treatment at high temperature.

DISCLOSURE OF THE INVENTION

A purpose of the invention is to provide a process for treating a surface of a monocrystalline silicon carbide substrate that allows to reduce the formation of terraces by a step that is easy to implement. Such a treatment must be easy to integrate into the process for manufacturing a substrate including a monocrystalline silicon carbide surface, and must not have any risk of contamination of such a substrate.

For this purpose, the invention proposes a process for treating a substrate comprising at least one surface layer of monocrystalline silicon carbide, said process comprising

- placing said substrate in a furnace,
- lowering the pressure in the furnace to a pressure comprised between 0.01 and 0.5 Pa,
- heating the substrate to a temperature greater than a sublimation temperature of silicon at said pressure, so as to form a carbon layer on the monocrystalline silicon carbide layer by sublimation of silicon from the surface of said monocrystalline silicon carbide layer, and,
- after the formation of the carbon layer (30), heat treating the substrate at a heat treatment temperature (T_T) strictly greater than 1300°C and under a pressure (p_T) greater than the pressure (p_F) of formation of the carbon layer, the carbon layer protecting the surface of the monocrystalline silicon carbide layer against the formation of steps.

The carbon layer serves to protect the silicon carbide during heat treatment at a higher temperature, and thus to minimize the formation of steps on the surface of the silicon carbide.

Pumping at a pressure below 0.01 to 0.5 Pa (0.1 to 5 μ bar) allows the rapid removal of silicon atoms evaporating from the substrate surface. In addition, in the case of a plurality of substrates in the same furnace, silicon atoms are removed from the space between the silicon carbide substrates. Such removal allows a relatively homogeneous atmosphere to be obtained on the substrate surface, thereby forming a protective layer having a small variation in thickness between the edge and the center of each substrate.

Advantageously, the carbon layer formation temperature is comprised between 1200°C and 1500°C.

Preferably, the carbon layer is a graphene layer.

Advantageously, the carbon layer has a thickness comprised between 0.2 nm and 1.2 nm.

Advantageously, a plurality of substrates is treated simultaneously in the same furnace.

The substrates can be vertically stacked in the furnace so that a vertical space is provided between two adjacent substrates.

Preferably, said vertical space between two adjacent substrates has a height comprised between 4 and 10 mm.

In some embodiments the process comprises, after forming the carbon layer, heat treating the substrate at a temperature greater than the carbon layer formation temperature and under a pressure greater than the carbon layer formation pressure.

Advantageously, the heat treatment temperature is greater than or equal to 1500°, preferably greater than or equal to 1700°C.

The temperature (T_T) of the heat treatment can be less than or equal to 2000.

The heat treatment pressure is preferably greater than or equal to 2 Pa.

Advantageously, the formation of the carbon layer and the heat treatment are carried out in the same furnace.

Preferably, the process further comprises a step of removing the carbon layer after the heat treatment.

Advantageously, the process further comprises a chemical-mechanical polishing step after the heat treatment to remove steps formed on the surface of the silicon carbide layer during said heat treatment.

Said chemical-mechanical polishing can lead to the removal of a silicon carbide thickness of less than 200 nm.

The invention also relates to a process for manufacturing a structure comprising a layer of monocrystalline silicon carbide on a support substrate, successively comprising:

- forming a weakening area in a monocrystalline silicon carbide donor substrate by implantation of ionic species, so as to delimit a layer of monocrystalline silicon carbide to be transferred,
- bonding the donor substrate to the support substrate,
- detaching the donor substrate along the weakening area so as to transfer the monocrystalline silicon carbide layer onto the support substrate,
- implementing the treatment as described above on the transferred monocrystalline silicon carbide layer.

Preferably, the monocrystalline silicon carbide layer comprises dopants and in that the heat treatment is carried out at a temperature suitable for activating said dopants.

Advantageously, the silicon carbide layer comprises defects due to the implantation of ionic species and in that the heat treatment is carried out at a temperature suitable for curing at least part of said defects.

Advantageously, the process further comprises, after the chemical-mechanical polishing, a step of resuming epitaxy of monocrystalline silicon carbide on the surface of the monocrystalline silicon carbide layer.

BRIEF DESCRIPTION OF THE FIGURES

Other features and advantages of the invention will emerge from the detailed description which follows, with reference to the appended drawings, in which:

Figure 1 illustrates the formation of terraces on a front face of a monocrystalline semiconductor material.

Figure 2 illustrates a substrate including a monocrystalline SiC portion on its front face.

Figure 3A illustrates the substrate of Figure 2 after formation of a carbon layer.

Figure 3B illustrates the substrate of Figure 2 during the formation of a carbon layer.

Figure 3C illustrates the substrate of Figure 2 after formation of a particular embodiment of the carbon layer.

Figure 3D illustrates the distribution of different thicknesses of a carbon layer on the surface of a substrate.

Figure 4 shows the thermal profile used for a process according to the invention.

Figures 5A to 5C illustrate the manufacture of a substrate including a m-SiC surface portion on its front face.

Figure 6 illustrates an annealing furnace adapted for forming a carbon layer according to a preferred embodiment of the invention.

Figure 7 shows the roughness of a monocrystalline SiC surface as a function of radial position on the substrate.

5 Figure 8 shows the step height between terraces formed on a monocrystalline SiC surface as a function of the radial position on the substrate.

Figures 9A and 9B are scanning electron beam microscopy images of a substrate after heat treatment according to a known process.

10 Figures 10A and 10B are electron beam scanning microscopy images of a substrate after heat treatment according to a process according to the invention.

DETAILED DESCRIPTION OF EMBODIMENTS

In general, a protective carbon layer is formed on a substrate including a surface portion of monocrystalline silicon carbide. The carbon layer temporarily protects the
15 substrate surface from terrace formation during heat treatment. The protective layer is formed by transforming the surface into m-SiC under temperature and pressure conditions suitable for causing sublimation of silicon atoms present on said surface while minimizing terrace formation. After heat treatment, the protective layer is removed from the substrate surface.

20 Figure 2 illustrates a substrate of which a surface layer 20 is made of monocrystalline silicon carbide. Said layer 20 is arranged on a support 11 formed of one or more materials different from monocrystalline silicon carbide. The support may comprise a monocrystalline or polycrystalline semiconductor material, for example polycrystalline silicon carbide. Alternatively, the substrate may be a solid substrate of monocrystalline silicon carbide, the
25 layer 20 forming a surface portion of said substrate.

Formation of the carbon layer

With reference to Figure 3A, a carbon layer 30 is formed on the surface 200 of the m-SiC layer 20. The carbon layer 30 protects the surface of the layer 20 against the
30 formation of terraces during heating to a high temperature. It thus stabilizes the crystalline structure of the surface.

The carbon layer 30 is formed by sublimation of silicon on the surface of the m-SiC layer. Advantageously, the formation of the carbon layer is carried out in a furnace which will be described later. In order to obtain such sublimation, the pressure in the furnace is lowered to a pressure p_F . The pressure p_F is preferably comprised between 0.01 and 0.5 Pa
35 (0.1 and 5 μ bar).

No additional gas is injected into the furnace, which keeps the pressure low and avoids any risk of contamination by impurities that may be present in such gas.

During pressure reduction to pressure p_F , the substrate is started to be heated to a temperature T_F . The pressure reduction and heating processes are adjusted so that the pressure p_F is reached before or simultaneously with reaching the temperature T_F .

Alternatively, the temperature is increased after the pressure has been lowered to the pressure p_F . The temperature T_F is greater than the sublimation temperature of silicon at said pressure p_F in the furnace. Typically, the temperature T_F is comprised between 1200°C and 1500°C.

A temperature below 1200°C does not allow the sublimation of silicon in the pressure range p_F that can be obtained in a substrate treatment furnace. A temperature above 1500°C generates a phenomenon of terrace formation that competes with the sublimation of silicon, leading to the formation of steps that are too high between the terraces.

Indeed, the aim is to limit the formation of steps between terraces to a height of less than 25 nm in order to minimize the polishing required to remove said steps. The formation of higher terraces would require long and laborious polishing. In addition, such polishing often leads to the creation of defects such as scratches in the m-SiC, which increases the number of defective substrates.

Lowering the pressure in the furnace allows silicon to sublime at a temperature T_F lower than the temperature at which terrace formation becomes significant. The pressure p_F is thus adjusted to avoid or reduce terrace formation during carbon layer formation.

The pressure p_F and the temperature T_F are maintained until a carbon layer covering the entire surface of the monocrystalline silicon carbide is obtained. In order to maintain the pressure p_F , vacuum pumping of the furnace is maintained throughout the carbon layer formation step. Continuous pumping causes the silicon atoms to be evacuated from the furnace. Such evacuation is necessary to lower the silicon partial pressure and thus allow the sublimation of other silicon atoms from the substrate surface.

When the carbon layer is finalized, the carbon layer prevents the silicon from sublimating. At this stage, the terraces and the height of the steps are fixed. As a result, it is possible to continue the heat treatment at a higher temperature without degrading the surface condition. Typically, the pressure is increased by injecting an inert gas into the furnace, for example argon.

Structure of the carbon layer

The free face 200 of the m-SiC layer 20 is a monocrystalline silicon carbide surface of the 4H or 6H polytype with one face (0001). This crystal orientation favors the growth of carbon as two distinct layers on the surface.

Optionally, the free face 200 forms an angle comprised between 0 and 8 degrees, for example between 3 and 5 degrees, with the face (0001) of the SiC monocrystalline. The free face 200 is, in particular, formed by a set of facets (0001) separated from each other

by atomic steps. Such a disorientation limits, during epitaxy on this free face, the risks of generating 3C polytype areas.

By convention, the face (0001) of m-SiC is generally called the “Si face”, and the face (000-1) is called the “carbon face”.

5 When the silicon sublimation of the surface of the layer 20 begins, with reference to Figure 3B, a first carbon layer 31 is formed on the surface. The layer 31 extends over the entire surface 200 of the m-SiC layer 20 and takes on the function of a buffer layer arranged between the surface 200 of the substrate and any carbon layers formed subsequently. The first layer 31 is made of hexagonal carbon with a low proportion of sp³ hybridization bonded
10 to the silicon atoms of the layer 20. The proportion of sp³ bonds decreases from the face in contact with the layer 20 towards the free face of the layer 31.

As the silicon sublimation continues, further carbon layers are formed on the buffer layer 31. The carbon layers on the buffer layer 31 are graphene monolayers, which means that these layers comprise only sp² bonds between the carbon atoms. The superimposed
15 graphene monolayers together form a surface layer 32.

The formation and characterization of such a carbon layer on an m-SiC surface are for example described by Strupinski et al. and by Razado-Colambo et al.

Thus, with reference to Figure 3C, the carbon layer 30 is typically composed of a buffer layer 31 in contact with the m-SiC surface of the substrate, and a surface layer 32
20 arranged on the surface of the buffer layer 31. Preferably, the surface layer 32 comprises between one and three graphene monolayers. The presence of a carbon layer composed of a buffer layer 31 and a surface layer 32 greatly limits the formation of terraces during a high temperature heat treatment.

The m-SiC surfaces of the 4H and 6H polytype promote graphene growth in a plane
25 parallel to the surface of the buffer layer 31. Such parallel growth limits the evaporation of silicon from the surface during subsequent heat treatment and thus prevents thermal decomposition of the silicon carbide layer. The growth in the form of graphene also limits the mobility of silicon and carbon atoms on the substrate surface. In addition, m-SiC surfaces of such a crystal structure are particularly affected by the terrace formation.

30 In the case of a substrate with a large surface, it is possible that the thickness of the carbon layer may have inhomogeneities. By forming a buffer layer and a surface layer, it is ensured that the entire surface of the substrate is protected by a carbon layer and the risk of forming areas without a carbon layer on the surface of the substrate is prevented.

In some embodiments, only a buffer layer 31 is formed. In this case, the carbon layer
35 formation process is stopped when the buffer layer is finalized, and no surface layer 32 is formed. Such a buffer layer alone can also limit the formation of terraces on the surface of the m-SiC layer 20.

Generally, the buffer layer 31 extends over the entire surface of the substrate. On the other hand, the graphene surface layer 32 may be arranged over the entire surface or only over certain areas of the buffer layer 31, and/or have different thicknesses depending on the position on the substrate.

5 Typically, with increasing distance from the substrate center, the thickness of the carbon layer increases due to the presence of graphene monolayers. Such distribution of graphene monolayers typically occurs when simultaneously processing several stacked substrates, due to more efficient evacuation of silicon atoms in the areas close to the edge B of the substrate.

10 In an illustrative and non-limiting manner, with reference to Figure 3D, the carbon layer may consist of a bare buffer layer 31 in a first area close to the center C of the substrate. The carbon layer may comprise a second area 321 in which the carbon layer comprises a single graphene monolayer arranged on the buffer layer 31, and a third area 322 in which the carbon layer comprises two graphene monolayers arranged on the buffer
15 layer 31. In a fourth area extending from the edge B, the carbon layer comprises three graphene monolayers arranged on the buffer layer 31.

The buffer layer 31 typically has a thickness of about 0.2 nm. The surface layer 32 typically has a thickness comprised between 0 and 1 nm. Thus, the thickness of the carbon layer 30 is comprised between 0.2 and 1.2 nm.

20 A carbon layer thickness comprised between 0.2 and 1.2 nm is sufficient to limit the formation of terraces during heat treatment to a height of less than 25 nm. At the pressure p_F and the temperature T_F in the furnace, it is possible to cover the entire surface of the substrate with a carbon layer of such thickness. A greater thickness is difficult to obtain because the sublimation of silicon atoms from the upper face of the substrate is blocked by
25 the presence of the already formed carbon layer. The formation of additional graphene monolayers is therefore longer than the formation of the first monolayers and would unnecessarily prolong the process.

High temperature steps requiring a protective layer

30 After the formation of the carbon layer, further steps may be performed on the substrate at a heat treatment temperature T_T , typically greater than the carbon layer formation temperature T_F . Such steps are, for example, annealing for the activation of dopants or annealing to heal defects in the crystal lattice caused during ionic species implantation. Such implantation may be used for the transfer of the m-SiC layer onto a base substrate as described below. Ionic species implantation may also be performed for the
35 doping of the m-SiC.

During the annealing step(s), the surface of the monocrystalline semiconductor material is protected by the carbon layer and the formation of terraces on said surface is thus avoided. An annealing step is typically carried out at a heat treatment temperature T_T

strictly greater than 1300°C, preferably greater than 1500° and more preferably greater than 1700°. Advantageously, the heat treatment temperature is less than or equal to 2000°C. Typically, the heat treatment is carried out under an atmosphere of a shielding gas, for example argon. During this step, the heat treatment pressure p_T in the furnace is comprised
 5 between the pressure P_F and atmospheric pressure, for example greater than or equal to 2 Pa.

Advantageously, such heat treatments are carried out directly after the formation of the carbon layer in the same furnace. The temperature rise to the heat treatment temperature can be carried out from the temperature T_F without intermediate cooling. The
 10 pressure rise can be carried out from the pressure p_F under a shielding gas atmosphere, without exposing the substrate to ambient air. The subsequent treatment in the same furnace avoids intermediate cooling steps, exposure to ambient air and removal and loading into different enclosures. This reduces the labor required, the cooling and heating time, and the risk of contamination of the substrate.

15 Temperature profile

In an illustrative and non-limiting manner, Figure 4 shows a temperature profile of such a process. The substrate is placed in the furnace at time t_0 . The pressure is lowered to reach the pressure p_F . Subsequently, the temperature is increased to the temperature T_F at time t_1 . This temperature is for example approximately 1450°C for a pressure p_F of $2 \cdot 10^{-1}$ Pa. The carbon layer is formed by sublimation until time t_2 . The duration of the formation of the carbon layer is typically comprised between 10 and 120 minutes. The pressure is then increased in the furnace to stop the sublimation of the silicon and the formation of carbon on the surface of the substrate. Typically, the pressure is increased to approximately 2 Pa under an argon atmosphere. The substrate is heated until time t_3 where the
 20 temperature T_T required for the heat treatment is reached, for example 1700°C. The heat treatment temperature T_T is maintained according to the type of substrate and the purpose of the heat treatment. After the heat treatment, at time t_4 , the furnace temperature is lowered. After the substrate has cooled, at time t_5 , the substrate can be removed from the furnace for further treatments such as polishing.

30 Removal of terraces and the carbon layer

At the end of the carbon layer formation and heat treatment steps, the temperature is lowered in order to remove the substrate from the furnace.

The terraces formed during the heat treatment can then be removed, for example by mechanical or chemical-mechanical polishing. The carbon layer is removed in the same
 35 step. The low thickness of the carbon layer avoids additional steps of carbon layer removal.

The low height of the steps that can appear during heat treatment and the low thickness of the carbon layer allow to limit the removal of the silicon carbide to a thickness of less than or equal to 200 nm. This allows to considerably limit the polishing time and

material consumption compared to the polishing steps of a substrate treated using a process without a protective layer.

At the end of this step, the substrate is finalized. The free m-SiC surface can then be used for the epitaxial growth of a layer of a monocrystalline semiconductor material, for example another layer of m-SiC or a layer of GaN, and/or for the manufacture of a power or radiofrequency electronic component.

Process for manufacturing a semiconductor structure

A process for manufacturing a semiconductor structure for electronic applications, having a surface layer 20 of monocrystalline silicon carbide will now be described.

A donor substrate 220 made of monocrystalline silicon carbide is provided from which the surface layer of monocrystalline silicon carbide will be formed. Typically, the donor substrate also comprises dopants incorporated in the crystal matrix. With reference to Figure 5A, as shown schematically by the arrows, an implantation of ionic species, such as hydrogen and/or helium, is implemented so as to form a weakening area 21 in the donor substrate 220. Said weakening area 21 defines a layer 20 made of monocrystalline silicon carbide to be transferred.

With reference to Figure 5B, the donor substrate 220 thus implanted is bonded to a base substrate 11. The donor substrate can be bonded directly to the base substrate as illustrated in Figure 5B, or via one or more intermediate layers which can be arranged on the donor substrate and/or on the base substrate before bonding (not shown).

With reference to Figure 5C, the donor substrate 220 is then detached along the weakening area 21, which leads to the transfer of the monocrystalline silicon carbide layer onto the base substrate 11, thereby forming the substrate 10 as shown in Figure 2. The detached portion 221 of the donor substrate can be reused for the transfer of other monocrystalline silicon carbide layers onto other base substrates.

A treatment process is then carried out, successively comprising a step of stabilizing the surface by forming a protective carbon layer 30, high-temperature annealing intended to activate the dopants and/or heal the defects created in the monocrystalline silicon carbide layer during the implantation of the ionic species, and the subsequent removal of the protective carbon layer.

Presentation of the furnace

In order to make a process for treating a plurality of substrates efficient and rapid, an annealing furnace is preferably used which can simultaneously treat a batch of substrates under identical conditions. Such a furnace is conventionally called a "batch anneal" furnace in the field of microelectronics.

Figure 6 illustrates a furnace 70 adapted to receive an amount comprised between 120 and 150 substrates in an annealing chamber. The substrates 10 are positioned horizontally in the furnace and are stacked vertically in order to treat a maximum number of

substrates. A free space is maintained between each substrate 10 and the adjacent substrates 10 to optimize the gas flow and to obtain a homogeneous pressure when the pressure is lowered. A homogeneous pressure allows to facilitate the formation of the carbon layer and to obtain a more homogeneous thickness of the carbon layer over the extent of each substrate. The optimal vertical distance depends on the diameter of the substrates. Typically, the vertical distance between two stacked substrates is comprised between 4 and 10 mm for substrates with a diameter comprised between 150 and 200 mm. The distance between substrates can be increased for large substrate diameters, and decreased for smaller diameters to allow the flow of gas between two adjacent substrates, while optimizing the space in the furnace to allow the simultaneous treating of a large number of substrates.

Such a furnace uses a "top flow" type configuration, that is to say a gas flow can be fed into the furnace from the top 71 and/or be discharged through an outlet 79 at the bottom of the furnace. During the formation of the carbon layer, no gas is injected into the furnace. The pressure is lowered by pumping at the outlet 79 of the furnace. During the pressure increase, a gas flow can be fed into the furnace from the top 71.

All the elements of the annealing chamber inside the furnace, that is to say the inner walls 75, the substrate holders for holding the substrates in a horizontal and vertically stacked position, and the gas contained in the annealing chamber are at the same temperature during use of the furnace, with the exception of the outer elements such as the outer wall 76 and the ends of the gas supply pipes. The same temperature means that the temperature difference between the top end 74 of the furnace and the bottom end 78 of the furnace is minimal, typically a few degrees °C, for example less than 3 degrees for a temperature in the furnace between 800 and 1200 °C.

The substrates are heated mainly by conduction from the furnace walls. The gases are injected at the same temperature as the temperature inside the furnace.

An annealing furnace is not intended for the formation of layers but for the application of a heat treatment of the substrates placed in the furnace. These furnaces are therefore optimized for a high temperature homogeneity of the substrates received there, but not to ensure homogeneity of the gas evacuation in the space between the substrates. The stacked positioning of the substrates is particularly detrimental to this homogeneity since, when the pressure is lowered, it is more difficult to lower the pressure in the space between the substrates close to the center of the substrates than at their edges. It is also more difficult to eliminate the silicon atoms following sublimation during the creation of the carbon layer.

In order to obtain a homogeneous carbon layer, it is necessary to control the thickness so as to obtain a sufficient thickness over the entire surface of all the substrates contained in the furnace, in particular in the central area of the substrates.

The pressure p_F between 0.01 and 0.5 Pa is particularly suitable for the treatment of a batch of substrates in such a furnace.

On the one hand, a pressure greater than 0.5 Pa causes insufficient evacuation of silicon atoms between two adjacent substrates, in particular near the center of the substrate.

5 Insufficient evacuation results in the presence of a large number of silicon atoms near the substrate surface and thus prevents the sublimation of other silicon atoms from the m-SiC of the lower substrate surface. Such blocking of silicon sublimation therefore prevents the formation of the carbon layer.

On the other hand, a pressure below 0.01 Pa is difficult to achieve in an industrial

10 furnace and requires significant pumping effort and time. Such pumping requires additional equipment and slows down the process considerably. In addition, it is difficult to ensure sufficient sealing of the furnace to reliably achieve lower pressures.

The formation of a buffer layer and one or more thicknesses of graphene on the surface of each substrate allows to obtain a sufficient thickness and sufficiently

15 homogeneous to limit the formation of terraces on each substrate. When the substrates are stacked in a furnace, a greater thickness of the carbon layer near the edge of each substrate, and a thinner thickness near the center of the substrate are typically obtained. Using a pressure p_F for forming the carbon layer comprised between 0.01 and 0.5 Pa, the carbon layer typically has a thickness comprised between 0.2 and 1.2 nm over the entire

20 extent of the substrate.

Unlike a deposition enclosure, such a furnace allows a large number of substrates to be treated simultaneously thanks to the vertical superposition arrangement.

Homogeneity of the protective layer and the effect on the formation of terraces

Figure 7 shows the root mean square (RMS) value of the surface roughness caused

25 by terrace formation on a monocrystalline SiC surface, measured by AFM. The roughness is measured according to the radial position on the substrate.

The curve r_1 corresponds to the roughness measured on substrates that have undergone a heat treatment at 1700 °C for 30 minutes without the formation of a protective carbon layer. Due to the limited gas flow between the substrates, a significant

30 inhomogeneity is observed between the measurement points close to the center C of the substrate, and the measurement points close to the edge B of the substrate. The average roughness is greater than 15 nm near the center C, and comprised between about 7 and 9 nm near the edge B.

The curve r_2 corresponds to the roughness of substrates after a treatment

35 comprising the formation of a carbon layer and a heat treatment at 1700°C for 30 minutes. The temperature and duration of the heat treatment are therefore identical to the temperature and duration of the treatment of the substrate of curve r_1 . During the heat treatment, each substrate was therefore protected by a respective carbon layer. The

roughness is approximately 5 nm near the center C and comprised between 3 and 4 nm near the edge B of each substrate. The roughness of a substrate including a carbon layer formed by a process as described above (curve r_2) is therefore clearly lower than the roughness of a substrate treated without a carbon layer (curve r_1).

5 In both processes (curves r_1 and r_2), the substrates were arranged within a batch of substrates in a furnace as presented above. The vertical distance between two adjacent substrates was 4 mm. The difference in roughness at the center and near the edge is due to the limited gas flow and the difference in partial pressures of different gases in the center area between two substrates stacked in the furnace.

10 Figure 8 shows the step height between two terraces formed on the monocrystalline SiC surfaces of the same substrates as in Figure 7. The step height is evaluated as the average height in a $30 \times 30 \mu\text{m}^2$ surface. The abscissa axis corresponds to the radial position on the substrate.

The step height of the substrates heat treated without carbon layer formation is 15 illustrated by the curve H_1 . The average step height H_1 is about 80 nm near the center C and about 40 nm near the edge B of the substrate. The curve H_2 shows the average step height for substrates after a process comprising the formation of a carbon layer as described above, followed by a heat treatment identical to the heat treatment of the substrates of the curve H_1 . The step height H_2 on the substrate protected by a carbon layer is comprised 20 between 30 and 40 nm near the center C of the substrate, and comprised between 25 nm and 30 nm near the edge B of the substrate. The step height formed during the heat treatment is therefore considerably reduced by the presence of a carbon layer for the two respective radial positions.

Figures 9A and 9B are scanning electron beam microscopy images of the m-SiC 25 surface of a substrate after heat treatment by a known process without carbon layer formation. Each image represents a $5 \times 5 \mu\text{m}^2$ surface. Figure 9A is an image of an area near the center of the substrate. Figure 9B is an image of an area near the edge of the same substrate. The terraces have a greater extent and height in the area near the center of the substrate.

30 Figures 10A and 10B are electron beam scanning microscopy images of the m-SiC surface of a substrate after heat treatment by a process as described above, comprising the formation of a carbon layer by sublimation of silicon. Each image represents a $5 \times 5 \mu\text{m}^2$ surface. Figure 10A is an image of an area near the center of a substrate. Figure 10B is an image of an area near the edge of the same substrate. As for the substrate of Figures 9A and 9B, the terraces are larger in width and height in the area near the center of the 35 substrate. However, the terraces are considerably smaller in extent and size than all terraces obtained on the substrate after heat treatment without formation of a carbon layer.

The extent of the terraces near the center of the substrate that is protected by a carbon layer (Figure 10A) is smaller than the size of the terraces at the edge and center of the substrate treated without the formation of such a protective layer (Figure 9A). In addition, in the area near the edge of the substrate (Figures 9B and 10B), the terrace formation was almost suppressed by the presence of the carbon layer.

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CLAIMS

1. A process for treating a substrate (10) comprising at least one surface layer
5 of monocrystalline silicon carbide, said process comprising:
 - placing said substrate (10) in a furnace,
 - lowering the pressure in the furnace to a pressure (p_F) comprised between 0.01 and 0.5 Pa,
 - heating the substrate to a temperature (T_F) greater than a sublimation
10 temperature of silicon at said pressure (p_F), so as to form a carbon layer on the monocrystalline silicon carbide layer by sublimation of silicon from the surface of said monocrystalline silicon carbide layer, and,
 - after the formation of the carbon layer (30), heat treating the substrate at a heat treatment temperature (T_T) strictly greater than 1300°C and under a pressure (p_T)
15 greater than the pressure (p_F) of formation of the carbon layer, the carbon layer protecting the surface of the monocrystalline silicon carbide layer against the formation of steps.
2. The process according to claim 1, wherein the carbon layer (30) formation temperature (T_F) is comprised between 1200°C and 1500°C.
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3. The process according to any of the preceding claims, wherein the carbon layer (30) is a graphene layer.
4. The process according to any of the preceding claims, wherein the carbon
25 layer (30) has a thickness comprised between 0.2 nm and 1.2 nm.
5. The process according to any of the preceding claims, wherein a plurality of substrates (10) is treated simultaneously in the same furnace (70).
- 30 6. The process according to claim 5, wherein the substrates (10) are vertically stacked in the furnace (70) so that a vertical space is provided between two adjacent substrates.
7. The process according to claim 6, wherein said vertical space between two
35 adjacent substrates (10) has a height comprised between 4 and 10 mm.

8. The process according to any one of the preceding claims, wherein the heat treatment temperature (T_T) is greater than or equal to 1500°, preferably greater than or equal to 1700°C.

5 9. The process according to any of the preceding claims, wherein the heat treatment temperature (T_T) is less than or equal to 2000.

10. The process according to one of the preceding claims, wherein the heat treatment pressure (p_T) is greater than or equal to 2 Pa.

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11. The process according to one of the preceding claims, wherein the formation of the carbon layer and the heat treatment are carried out in the same furnace.

12. The process according to one of the preceding claims, further comprising a
15 step of removing the carbon layer (30) after the heat treatment.

13. The process according to one of the preceding claims, further comprising a chemical-mechanical polishing step after the heat treatment to remove steps formed on the surface of the silicon carbide layer during said heat treatment.

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14. The process according to claim 13, wherein said chemical-mechanical polishing leads to the removal of a silicon carbide thickness of less than 200 nm.

15. A process for manufacturing a structure comprising a layer of
25 monocrystalline silicon carbide on a support substrate, successively comprising:

- forming a weakening area in a monocrystalline silicon carbide donor substrate by implantation of ionic species, so as to delimit a layer of monocrystalline silicon carbide to be transferred,

- bonding the donor substrate to the support substrate,
- 30 - detaching the donor substrate along the weakening area so as to transfer the monocrystalline silicon carbide layer onto the support substrate,

- implementing the treatment according to one of the preceding claims on the transferred monocrystalline silicon carbide layer.

16. The process according to claim 13, wherein the monocrystalline silicon carbide layer comprises dopants and in that the heat treatment is carried out at a temperature suitable for activating said dopants.

5 17. The process according to one of claims 15 or 16, wherein the silicon carbide layer comprises defects due to the implantation of ionic species and in that the heat treatment is carried out at a temperature suitable for curing at least part of said defects.

10 18. The process according to one of claims 15 to 17 in their relationship of dependence on claims 13 or 14, further comprising, after the chemical-mechanical polishing, a step of resuming epitaxy of monocrystalline silicon carbide on the surface of the monocrystalline silicon carbide layer.