METHOD FOR TREATING A SUBSTRATE HAVING A POLYCRYSTALLINE SILICON CARBIDE REAR FACE

FIELD OF THE INVENTION

The present invention relates to a method for treating a substrate having a back face made of polycrystalline silicon carbide and a front face for manufacturing an electronic component. The treatment method comprises forming a glassy carbon layer on the back face, transferring a layer of a monocrystalline semiconductor material onto the front face, and a heat treatment step.

PRIOR ART

Semiconductor materials, particularly silicon carbide (SiC), are widely used in the manufacture of power and radio frequency electronic components. In some applications, substrates made of bulk monocrystalline SiC, substrates having a monocrystalline SiC surface layer, or substrates having other semiconductor materials such as aluminum nitride (AlN), gallium nitride (GaN), alloys of these nitrides, indium phosphide (InP), or gallium arsenide (GaAs) are used. In some cases, the semiconductor substrates or semiconductor layers are polycrystalline. In many applications, the substrate comprises a support substrate made of a polycrystalline semiconductor and one or more layers of another semiconductor material disposed on a front face of the support substrate. Typically, the back face of the support substrate, opposite the front face, is a free surface during the manufacture of the electronic components.

Substrates for electronic applications often require thermal treatments during their manufacture, for example annealing to heal defects in the crystal lattice caused during implantation of ionic species or to modify the crystal structure of the substrate. Such treatments are often carried out at high temperatures of up to 2000 °C.

However, the surface of the semiconductor materials considered is likely to be destabilized under the effect of a high temperature. This destabilization can result in a degradation of the surface, 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 starting from about 1300°C. In the absence of adequate protection of said surface, the morphology reorganizes to minimize the surface energy, forming terraces. This effect is known as “step bunching”. The reorganization of the surface 222 is due to a diffusion of atoms on the surface when it is exposed to high temperatures. It also depends on the atmosphere and pressure to which the surface is exposed. It also

depends on the misorientation angle of the surface relative to a high symmetry axis of the semiconductor material crystal. Such misorientation is used to facilitate the control of the 4H polytype of SiC during subsequent epitaxy of monocrystalline SiC and to avoid polytype changes during the growth of monocrystalline SiC. An angle of 4° is often selected for such an epitaxy method. However, the greater this inclination angle, the higher the steps between the terraces.

Such misorientations can also appear spontaneously on a polycrystalline SiC surface, whose grain orientation is random.

Surfaces of other semiconductor materials can have the same type of steps. On surfaces containing GaN, gallium beads can appear on the surface during exposure to high temperature.

In order to obtain smooth surfaces, it is therefore sought to avoid the formation of terraces or to remove them in a later step, and, where appropriate, to avoid the appearance of gallium beads or other material.

For example, mechanical or chemical-mechanical polishing (CMP) can be carried out after heat treatment. However, if the height of the 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 method. In addition, the remaining thickness is often too thin for the intended applications.

The article by J. Bao et al. proposes to use very fast annealing ramps to limit the appearance of terraces. This method requires very rapid temperature increases of around 400°C per minute and is 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 method is described in the article by R. Zhang et al. However, it requires the introduction of a SiH_4 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 the formation of terraces is to use a protective layer, typically a carbon film of about 1 µm thickness. This technique involves the addition of additional steps in the formation method such as the deposition of a resin, the carbonization of said resin at a temperature comprised between 600°C and 1000°C, and the use of additional equipment and entails a risk of contamination of the substrate and the furnace by the resin. In addition, the deposition of resin and the removal of a micrometric layer of carbon are time-consuming and expensive steps.

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.

The presence of oxygen in the furnace atmosphere can limit the formation of terraces, however it may form surface pits incompatible with epitaxial recovery. In addition, high temperature furnaces typically comprise graphite elements that are sensitive to the presence of oxygen during annealing.

Moreover, the back face of the support substrate is likely to become destabilized under the effect of a high temperature. This destabilization can result in surface degradation. In particular, in polycrystalline SiC faces, whose grain orientation is random, the degradation can depend on the orientation of each grain and thus vary greatly over the extent of the back face of the substrate. This causes significant roughness of the back face, degrading the quality of certain operations carried out on the back face, such as metallizations.

In order to maintain a smooth back face without requiring smoothing treatment, it is therefore also sought to avoid degradation of the polycrystalline SiC back face during the heat treatment steps of one or more active layers on the front face of the substrate.

DISCLOSURE OF THE INVENTION

A purpose of the invention is to provide a method for treating a substrate having a back face made of polycrystalline silicon carbide, said method comprising a step of stabilizing the back face allowing to limit the increase in its roughness during heat treatment.

The stabilization step must be easy to integrate into the method for manufacturing a substrate including one or more layers of a monocrystalline semiconductor material on its front face, and not have any risk of contamination of the front face.

For this purpose, the invention proposes a method for treating a substrate having a back face made of polycrystalline silicon carbide and a front face intended for the manufacture of an electronic component, said method comprising:

- the formation of a layer of glassy carbon on the back face,
- a transfer of a layer of a monocrystalline semiconductor material onto the front face,
- a heat treatment of the substrate after the formation of the carbon layer, said carbon layer limiting the increase in roughness of the back face during the heat treatment.

Advantageously, the glassy carbon layer has a thickness less than or equal to 100 nm.

Preferably, the heat treatment is carried out at a temperature greater than 900°C, preferably greater than 1300°C.

Advantageously, the layer of a monocrystalline semiconductor material is made of silicon carbide or gallium nitride.

The formation of the glassy carbon layer may be achieved by a gas-phase carbon reaction on said surface or by deposition of a polymer layer followed by carbonization of said polymer layer.

Advantageously, the formation of the glassy carbon layer further comprises the formation of a carbon layer on the front face of the substrate.

In some embodiments, transferring the layer of a monocrystalline semiconductor material onto the front face comprises the following steps:

- implanting ionic species in a donor substrate to form a weakening area delimiting the layer to be transferred,
- bonding the donor substrate to the front face of the support substrate,
- detaching the donor substrate along the weakening area.

Preferably, the formation of each carbon layer is carried out after detachment from the donor substrate, such that the carbon layer on the front face protects the front face during at least part of the heat treatment against the formation of terraces and/or beads on the front face.

Advantageously, the formation of each carbon layer is carried out after bonding and before detachment from the donor substrate, so as to remove the carbon layer on the front face with the donor substrate.

Advantageously, the method further comprises a step of removing the carbon layer from the front face of the substrate, the formation of the carbon layer and the removal of the carbon layer on the front face of the substrate being carried out before bonding the donor substrate to the front face of the support substrate.

Preferably, the method further comprises, after the formation and removal of the carbon layer on the front face, a step of epitaxially growing a monocrystalline semiconductor material on the layer into a monocrystalline semiconductor material, in which the carbon layer on the back face limits the increase in roughness of said back face during epitaxy.

Advantageously, the method further comprises, after the step of epitaxially growing the monocrystalline semiconductor material, a step of manufacturing an electronic component on the front face of the substrate, in which the carbon layer on the back face limits the increase in roughness of said back face when manufacturing said electronic component.

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 one face of a monocrystalline semiconductor material.

Figure 2 illustrates a substrate including a portion of a monocrystalline semiconductor material on its front face.

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

Figure 4 illustrates the substrate of Figure 3 after ablation of the carbon layer.

Figures 5A to 5C illustrate the manufacture of a substrate having a portion of a monocrystalline semiconductor material on its front face.

Figure 6A shows an example of a thermal profile used for a first embodiment of a method according to the invention.

Figure 6B shows an example of a thermal profile used for a second embodiment of a method according to the invention.

Figure 7A is an atomic force microscopy (AFM) image illustrating the terrace-induced roughness on the surface of a substrate heat-treated at 1500°C without application of a carbon layer.

Figure 7B is an atomic force microscopy image illustrating the surface roughness of a substrate heat treated at 1500°C with a glassy carbon layer according to the invention.

Figure 8A is an AFM image showing the surface roughness of a carbon layer obtained by deposition at 900°C for 10 min after implementing annealing at 1700°C.

Figure 8B is an AFM image showing the surface roughness of a carbon layer obtained by deposition at 1000°C for 10 min after implementing annealing at 1700°C.

Figure 9 illustrates an annealing furnace suitable for forming a carbon layer according to a preferred embodiment of the invention.

Figure 10 illustrates a substrate comprising a carbon layer on the back face.

Figure 11 illustrates a support substrate having a front face and a back face.

Figure 12 illustrates a substrate having a carbon layer on the front face and a carbon layer on the back face.

Figure 13A and Figure 13B illustrate steps of a treatment method according to one embodiment.

Figures 14A-14D illustrate steps of a treatment method according to another embodiment.

Figure 15 illustrates a step of epitaxially growing a monocrystalline semiconductor material on a layer of a monocrystalline semiconductor material arranged on the front face of the substrate.

Figure 16A shows the low roughness of a part of a polycrystalline silicon carbide face before heat treatment.

Figure 16B shows the increased roughness of the part of Figure 16A after heat treatment.

Figure 17A shows the low roughness of another part of a polycrystalline silicon carbide face before heat treatment.

Figure 17B shows the increased roughness of the part of Figure 17A after heat treatment.

Figure 18 shows maximum depth and roughness of different parts of a substrate annealed under different conditions.

DETAILED DESCRIPTION OF EMBODIMENTS

Figure 2 illustrates a substrate 10 including a support substrate 11 and a portion 20 made of a monocrystalline or polycrystalline semiconductor material on its front face. The support substrate 11 may be any type of support substrate suitable for the deposition or transfer of a portion 20 made of a monocrystalline or polycrystalline semiconductor material, for example a support substrate made of a polycrystalline semiconductor material.

Alternatively, the substrate 10 may be a bulk substrate made of a monocrystalline or polycrystalline semiconductor material, that is to say that the support substrate 11 and the portion 20 together constitute a single portion made of a bulk monocrystalline or polycrystalline semiconductor material.

Preferably, the portion 20 on the front face of the substrate is made of a monocrystalline semiconductor material. However, the semiconductor material which forms the front face of the substrate 10, and which therefore composes either the portion 20 (in the case of a substrate 10 including a support substrate 11 and a portion 20) or the substrate 10 (in the case of a bulk substrate) is also likely to be a polycrystalline material.

In the remainder of the description, since the case of a substrate 10 including a support substrate 11 and a monocrystalline portion 20 is detailed, the material which composes the portion 20 will be designated by the expression “monocrystalline semiconductor material” to distinguish it from the material composing the support substrate 11. However, the method described below is also applicable to the case of a polycrystalline semiconductor material, each grain then being capable of being considered as a monocrystal.

According to a preferred embodiment, the monocrystalline semiconductor material is silicon carbide.

According to other embodiments, the monocrystalline semiconductor material is selected from: aluminum nitride (AlN), gallium nitride (GaN), alloys of these nitrides $Al_xGa_{(1-}$

$_{x)}$N, x being a number comprised between 0 and 1, indium phosphide (InP) or gallium arsenide (GaAs).

Typically, the surface 200 of the portion 20 made of a monocrystalline semiconductor material or, if applicable, of the substrate made of a bulk monocrystalline semiconductor material, is slightly off-axis. For example, if the semiconductor material is SiC, the surface may be off-axis relative to the crystal structure of the SiC to facilitate control of the 4H polytype during growth.

In the case of a polycrystalline semiconductor material, some of the grains may have such an offset relative to the crystalline structure of the SiC. For example, following the cutting or polishing of the substrate 10 so as to reveal a specific face of the substrate 10, grains whose orientation is randomly oriented relative to this face will have an offset.

Formation of the protective layer

With reference to Figure 3, a layer of glassy carbon 30 is subsequently formed on the surface 200 of the portion 20 made of a monocrystalline semiconductor material. The layer of glassy carbon is continuous and covers the entire surface to be protected, that is to say the front face of the monocrystalline material. Typically, the layer of glassy carbon 30 is deposited on all the free surfaces of the substrate and therefore simultaneously covers the front face and the back face of the substrate. This allows to simultaneously protect the back face against the formation of terraces and, in the case of a silicon carbide substrate, against evaporation of the silicon during the heat treatment. In the case of a polycrystalline silicon carbide substrate, the layer of glassy carbon prevents roughening of the back face, as will be detailed below.

Said carbon layer protects the surface of the substrate against the formation of terraces during heating at a high temperature. Thus, it stabilizes the crystalline structure of the surface. The carbon layer is removed after completion of the high-temperature treatments to obtain a clean surface of the monocrystalline semiconductor material with good crystalline quality. The thickness of the carbon layer is preferably less than 100 nm to allow easy removal at the end of a high-temperature method.

The glassy character of the carbon layer is obtained from a carbon thickness of a few nanometers; for a lower thickness, the carbon is in the form of one or two monolayers of graphene. When the thickness is sufficient to obtain glassy carbon, the protective layer has a three-dimensional, unorganized structure on a long distance scale, which is stable over the entire range of temperatures to which the surface is exposed during the method, and which allows a total coverage of the substrate surface. The uniformity of a glassy carbon layer is easier to control over the extent of the substrate surface.

Advantageously, the formation of the glassy carbon layer is carried out in a furnace which will be described later. The carbon layer is formed in the gas phase, that is to say that the carbon is present in the furnace in a gas form. The substrate is heated in the furnace to a deposition temperature of the protective layer, and the gas carbon phase is transformed into solid carbon by a reaction with the hot surface of the substrate.

The temperature and gas pressure in the furnace are selected to avoid degradation of the surface to be protected during the deposition of the carbon layer. The temperature in the furnace is, during the formation of the carbon layer, greater than 700°C and strictly less than 1000°C, advantageously less than 950°C. Preferably, the temperature during the formation of the carbon layer is comprised between 800°C and 900°C to protect the surface of the substrate effectively.

Temperatures below 800°C cause the method to slow down. For temperatures below 700°C, the slowdown is such that it impairs the efficiency of the method.

During the formation of the carbon layer and the subsequent heat treatment, an appearance of carbon particles is often observed on the surface of the substrate. The density and size of said carbon particles is considerably reduced at a carbon layer formation temperature strictly less than 1000°C and more advantageously less than 900°C. Higher temperatures, in particular from 1000°C, cause an appearance of particles of a large size, which can be up to approximately 60 nm. These particles are formed on the surface of the substrate during the formation of the carbon layer and the subsequent heat treatment. A carbon layer formation temperature from 1000°C therefore increases the roughness of the surface of the substrate.

A polishing step, for example chemical-mechanical polishing for removal of the carbon layer, is easier to implement and involves less risk of surface scratching when the number and size of such particles are reduced.

In addition, by reducing the density and size of carbon particles on the surface, the risk of contamination of other substrates or components by such particles is reduced, for example in an electronics production environment.

Reducing surface roughness also makes it easier to control the thickness of the deposited carbon layer.

The temperature range comprised between 700 and 950°C, preferably between 800 and 900°C, thus allows to easily control the thickness of the carbon layer deposited by an efficient method, avoiding the appearance of carbon particles having a size and density too large for the manufacture of power and radiofrequency electronic components.

Advantageously, the carbon source is a carbon gas, for example propane (C_3H_8). Alternatively, the carrier gas may be methane (CH_4) or ethane (C_2H_6). Using propane as the

carrier gas allows the carbon layer to be formed more rapidly because the C-C bond of the carbon atoms is easier to break than the C-H bonds in methane and ethane.

The carbon gas is mixed with a carrier gas, for example argon or a mixture of argon and hydrogen. The carrier gas is a neutral gas that does not participate in the chemical reaction of layer formation. Typically, the mixing of the gases is carried out in the furnace enclosure at the deposition temperature. The gas flow rate can be easily controlled and adjusted to the deposition conditions of the carbon layer.

Typically, the deposition of the carbon layer is carried out under a gas pressure comprised between 0.1 and 100 kPa (between 1 mbar and 10 mbar), which is easy to maintain in an industrial furnace. The partial pressure of the carbon gas is typically adjusted to a value comprised between 0.1 and 1 kPa (between 1 mbar and 10 mbar). Such a concentration avoids saturation of the furnace atmosphere, which allows better control of the thickness of the deposited carbon layer.

Advantageously, the thickness of the protective carbon layer is less than 100 nm, for example comprised between 50 nm and 100 nm. The time required to obtain such a layer depends on the temperature and the partial pressure of the carbon gas and is typically comprised between two seconds and two hours. The temperature during the formation of the layer, the pressure and type of carbon gas and the duration of the step allow to adjust the thickness of the deposited carbon layer.

The carbon layer can be characterized by surface analysis techniques, for example by atomic force microscopy (AFM), X-ray reflectometry (XRR), Raman spectroscopy or low energy electron microscopy (LEEM).

The carbon layer is stable at least up to a temperature of 2000°C and allows to limit the formation of terraces while the substrate is exposed to a temperature greater than the terrace formation temperature.

<u>High temperature steps requiring the protective layer</u>

After the formation of the carbon layer, further steps may be performed on the substrate at a temperature higher than the terrace formation temperature. Such steps are, for example, annealing to heal defects in the crystal lattice caused during implantation of ionic species, to modify the crystal structure of the substrate, or for the activation of dopants. During these steps, the surface of the monocrystalline semiconductor material is protected by the carbon layer and the formation of terraces on said surface is prevented. The annealing steps are performed at temperatures comprised between 1300°C and 1900°C, typically greater than 1500°C.

The formation of the carbon layer and the heat treatment are carried out in the same furnace, which is advantageously a furnace conventionally used to carry out batch annealing of substrates.

A furnace rising to temperatures above 1500° generally comprises graphite elements due to the good stability of this material at high temperatures. In any case, the formation of the carbon layer in such a furnace only causes the deposition of a very thin layer of carbon which does not affect the operation of these elements made of the same material as the layer.

Removing the protective layer

At the end of the annealing steps, the temperature is lowered to a temperature below the terrace formation temperature, that is to say below 1300°C.

In some embodiments, the removal may be performed in the same furnace in which the steps of forming the carbon protective layer and/or the high temperature steps were carried out. In this case, the temperature is lowered to a temperature for ablation of the carbon layer, for example about 900°C. The carbon layer can then be removed because the temperature is low enough that no terrace formation occurs on the surface of the semiconductor material. The low thickness of the carbon layer promotes rapid and residue-free removal on the substrate.

The removal of the carbon layer can be carried out by a reactive plasma, for example an oxygen plasma according to the reaction:

$$C(\text{solid}) + O_2\ (\text{gas}) \rightarrow CO_2\ (\text{gas})$$

In other embodiments, the substrate is cooled after the heat treatment step and transferred to another enclosure or device for removal of the carbon layer. Such transfer is necessary, for example, if elements of the furnace are made of unprotected graphite or other materials that may be damaged by contact with the reactive plasma, and the ablation of the carbon layer is performed by plasma.

Alternatively, the carbon layer can be removed by reactive ion etching (RIE), for example by oxygen ions or a mixture of oxygen and sulfur hexafluoride after transfer to a suitable enclosure.

In order to remove possible carbon residues and/or to ensure good surface quality of the monocrystalline semiconductor material, a suitable chemical-mechanical polishing step can be carried out after removal of the carbon layer.

In some cases, the carbon layer is removed during a substrate finishing step after removal from the furnace, for example during a chemical-mechanical polishing or mechanical polishing step.

At the end of the removal step, with reference to Figure 4, the substrate 11 is finalized and the carbon layer is removed. The substrate 11 and the free surface of the monocrystalline semiconductor material can now be used for the epitaxial growth of a layer of a monocrystalline semiconductor material (identical or different from that of the substrate 11) and/or the manufacture of a power or radiofrequency electronic component.

In some cases, the carbon layer on the back face of the substrate is removed with the layer on the front face. In other embodiments, the glassy carbon layer arranged on the back face of the substrate is retained at this step and during the manufacture of an electronic device on the front face to protect the back face during these steps. In this case, the carbon layer on the back face is removed before or during a step of thinning the substrate, for example by grinding.

Sequence of a method for manufacturing a semiconductor structure

A method for manufacturing a semiconductor structure for electronic applications, having a monocrystalline silicon carbide surface will now be described.

A donor substrate 220 is provided, said donor substrate is preferably made of monocrystalline silicon carbide, from which the surface layer of monocrystalline silicon carbide will be formed. 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 of monocrystalline silicon carbide to be transferred.

With reference to Figure 5B, the donor substrate 220 thus implanted is bonded to a support substrate 11. The donor substrate can be bonded directly to the support substrate as illustrated in Figure 5B, or via one or more intermediate layers which can be applied to the donor substrate and/or to the support 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 support 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 method for treating the substrate 10 is then carried out, said method successively comprising a step of stabilizing the surface by forming a protective layer of glassy carbon, a high-temperature annealing intended to heal the defects created in the layer of monocrystalline silicon carbide during the implantation of the ionic species, and a subsequent removal of the protective carbon layer.

The method comprising the formation of the carbon layer and the heat treatment is carried out in the same furnace. Thus, this avoids the need to transfer the substrate from a

deposition chamber dedicated to the deposition of the protective layer to an annealing furnace, thereby obtaining a simpler, faster method and minimizing the risk of contamination of the substrate.

Figure 6A illustrates a temperature profile for one embodiment of such a method as a function of time. Three main sequences of the method can be distinguished, which correspond to the formation of a protective carbon layer (S1), a high-temperature annealing (S2), that is to say above the temperature at which the formation of terraces begins, and a step of removing the protective layer (S3).

The gas injected at the top of the furnace is evacuated under a flow of carrier gas from the bottom of the furnace during all sequences of the method.

The first sequence S1 begins at a time t0. The substrate is at room temperature which is typically about 20°C or at a temperature lower than the terrace formation temperature. The substrate is introduced into the deposition chamber. The substrate is started to be heated at a temperature T1 of deposition of the glassy carbon layer. The deposition temperature T1 is greater than 700°C and strictly less than 1000°C. Thus, T1 is lower than the temperature at which terraces begin to form which is about 1300°C at a pressure of 101 kPa (1 atm), or even about 1200 or 1100°C at lower pressures. The temperature T1 is also less than the temperature of about 1000°C which can cause an increase in surface roughness.

From a time t1, a gas flow comprising a carbon gas and a carrier gas is injected into the furnace.

The deposition of the carbon layer starts at time t1. The duration of the formation of the carbon layer is typically comprised between two seconds and two hours until time t2. During this time, the deposition temperature T1 is kept constant. The pressure in the furnace is maintained between 0.1 and 100 kPa (between 1 mbar and 1 bar).

The flow rate of the injected gases depends on the volume of the chamber and is controlled to obtain a partial pressure of the carbon gas comprised between 0.1 and 1 kPa (between 1 mbar and 10 mbar). The deposition temperature T1 and the flow rate of the carbon gas can be adjusted to obtain a carbon layer with a desired thickness and homogeneity adapted for optimal protection during the following sequence, and for a time short enough to optimize the method in terms of duration and cost.

The carbon gas supply is stopped at the end of sequence S1. The carbon gas residues are evacuated under the flow of the carrier gas.

When the deposition of the carbon layer is completed at a time t2, the second sequence S2 is carried out. The second sequence S2 comprises heating from the deposition temperature T1 to an annealing temperature T2 and a temperature plateau of a

duration which is for example comprised between 30 and 120 min. The annealing temperature T2 and the duration of the treatment are selected according to the state and the substrate before the current method, and the intended crystalline structure of the substrate. Typically, the annealing is carried out at a temperature T2 greater than 1500°C, for example comprised between 1600°C and 1900°C.

The heat treatment of the second sequence is carried out in the same furnace as the formation of the carbon layer of the first sequence.

At the end of sequence S2, the substrate is cooled to preserve the crystalline properties obtained during annealing. At a time t3, the substrate reaches a third temperature T3 of 900°C.

In some embodiments, with reference to Figure 6A, a third sequence S3 is directly carried out during which the carbon protective layer is removed by oxidation, as previously described. During this step, oxygen may be injected into the furnace to create a reactive plasma.

During this step, the temperature T3 = 900°C is kept constant. The removal time is typically comprised between 10 and 120 s at a stripping rate of about 100 nm per minute. The total duration of the sequence S3 also comprises a stabilization of the furnace and is typically comprised between five minutes and one hour. When, at time t4, the carbon layer is completely removed, the furnace is cooled in order to remove the substrate.

Figure 6B illustrates a temperature profile for an embodiment in which the step of removing the carbon layer is carried out outside the furnace. Sequences S1 and S2 are carried out as described above. At the end of sequence S2, the substrate is cooled to a temperature close to room temperature allowing the furnace to be opened and the substrate to be removed. The removal of the carbon layer is carried out during sequence S3' outside the furnace. In this case, a transfer step is carried out from the annealing furnace to a protective layer removal enclosure or to a polishing device at time t3. When the substrate treatment method comprises a transfer step, the different sequences can be carried out separately in time. Depending on the technique for ablation of the glassy carbon layer implemented, sequence S3 may comprise heating to a temperature below the terrace formation temperature or be carried out at room temperature.

Effect of protective layer on terrace formation

Figures 7A and 7B are atomic force microscopy (AFM) images on a 30x30 μm^2 surface of two respective substrates each having a monocrystalline silicon carbide surface.

Figure 7A is an AFM image of a substrate heat treated at 1500 °C without application of carbon layer. Terraces have formed on the substrate surface, visible as vertical lines in

the AFM image. The root mean square (RMS) value of the surface roughness induced by the terraces is approximately 16 nm.

Figure 7B is an AFM image illustrating the surface roughness of a substrate of the same type, also heat treated at 1500°C. The substrate of Figure 7B was protected by a glassy carbon layer formed at a temperature of 900°C and a pressure below 5 kPa (50 mbar) for 10 minutes before heat treatment. The carbon layer was formed in an atmosphere comprising argon as the carrier gas and propane as the carbon gas. The propane content in the mixture was less than 30%.

The image of the protected substrate does not show any parallel line structures indicating the presence of terraces. The root mean square value of the surface roughness is about 0.2 nm. The roughness of the substrate protected by the carbon layer is therefore considerably lower than the roughness of the substrate without a protective layer.

Effect of temperature during carbon layer formation

Figures 8A and 8B are AFM images on a 5x5 μm^2 surface of two respective substrates having a monocrystalline silicon carbide surface. Each substrate has a protective carbon layer. The carbon layers were deposited at different temperatures. Each respective substrate was heat treated at 1500°C under identical conditions.

The substrate of Figure 8A is protected by a carbon layer deposited for 10 minutes at a temperature of 900°C, in accordance with a preferred embodiment of the invention. The curve below the AFM image shows the height profile of the magnified portion of the image over a length l of 100 nm. In this area, the largest particles on the surface have a height h of about 1.5 nm.

The substrate of Figure 8B is protected by a carbon layer deposited for 10 minutes at a temperature of 1000°C, that is to say under conditions not covered by the invention. This image has a more granular structure than the image of Figure 8A, indicating a greater roughness of the surface. A height profile over a length l of 500 nm of this surface is shown under the AFM image. In this profile, larger grains can be distinguished, reaching a height h of approximately 15 nm.

The carbon layer formed at 900°C therefore has a considerably lower roughness than the layer formed at 1000°C. Since the roughness increases with the temperature of the formation of the carbon layer, it is necessary to form the carbon layer at a temperature strictly lower than 1000°C.

Presentation of the furnace

In order to make a method for treating a plurality of substrates efficient and fast, use is preferably made of an annealing furnace that can simultaneously treat a maximum

number of substrates under identical conditions. Such a furnace is conventionally called a “batch anneal” furnace in the field of microelectronics.

Figure 9 illustrates a furnace 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 superimposed vertically in order to treat a maximum number of substrates in the same flow 73 of hot gas. A free space is maintained between each substrate 10 and the adjacent substrates 10 to optimize the gas flow and facilitate the formation of the carbon layer. Typically, the vertical distance between two adjacent substrates is comprised between 2 and 20 mm.

Such a furnace uses a “top flow” type configuration, that is to say a gas flow is fed into the furnace from the top 71 and, after passing through the furnace, is discharged through an outlet 79 at the bottom of the furnace. Typically, a carrier gas flow carries the carbon gas (typically propane) for the formation of the carbon layer. In some cases, other gases are added to the furnace, for example catalyst type gases to promote the decomposition of the carbon gas.

All 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 superimposed 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 Celsius, 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 gas streams are injected at the same temperature as the temperature inside the furnace.

An annealing furnace is not intended for the deposition 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 therein, but not to allow an optimization of a material deposition, in particular to ensure a homogeneity of gas flow on the surface of the substrates. The superimposed positioning of the substrates is particularly detrimental to this homogeneity since the gases have more difficulty accessing the center of the substrates than their edges. However, this type of furnace is nevertheless suitable for the deposition of carbon layers to protect the surface of a semiconductor material against the formation of terraces, in particular because the homogeneity of the thickness of the carbon layer is not a determining criterion as long as the entire surface to be protected is covered. The temporary use of the carbon layer does

not require increased homogeneity of this layer. However, it is necessary to control the thickness so as to obtain a sufficient thickness over the extent of the surface of all the substrates contained in the furnace. The use of graphite elements inside the furnace is compatible with the deposition of the carbon layer because it is the same material and the thickness of the deposited layer is small compared to the dimensions of said elements.

Unlike an epitaxy enclosure, such a furnace allows a large number of substrates to be treated simultaneously thanks to the vertically stacked arrangement. In addition, such a furnace allows the carbon layer deposition and annealing steps to be carried out in the same chamber, which avoids the risk of contamination during a transfer between two different enclosures. Steps of transfer between a carbon layer deposition enclosure and an annealing furnace are avoided, thus avoiding cooling between the respective steps, the need for labor for the transfer and thus a loss of time and efficiency.

Protection of the back face

In some embodiments, particularly in the case of a polycrystalline silicon carbide support substrate, a carbon layer 40 is used to protect the back face of the substrate as illustrated in Figure 10. Said carbon layer can be formed simultaneously with that formed on the front face; however, such a carbon layer on the back face has advantages independent of those provided with respect to the front face, and can therefore be used even when no carbon layer is formed on the front face.

With reference to Figure 11, the back face 204 of the support substrate 11 is opposite the free front face 203, intended to receive one or more functional layers for the manufacture of one or more electronic components. Typically, the carbon layer 40 is maintained on the back face 204 during one or more steps of the manufacture of the electronic component, for example steps of transferring a layer onto the front face 203, an epitaxy step and/or annealing operations to activate dopants. The carbon layer 40 on the back face of the substrate typically has a thickness less than or equal to 100 nm. The carbon layer on the back face is removed at the end of the method for manufacturing the component, typically before metallization or other finishing steps on the back face of the substrate.

In a first embodiment, a substrate 10 is first manufactured, comprising the transfer of a layer 20 onto a support substrate 11, preferably by a method as described above and illustrated in Figures 5A to 5C. Subsequently, a carbon layer 30 is simultaneously formed on the front face 200 of the layer of a monocrystalline semiconductor material 20 and a carbon layer 40 on the back face of the support substrate 11 as illustrated in Figure 12. Typically, the carbon layers 30, 40 are deposited on the front face and the back face of the substrate in a single step by a gas-phase carbon reaction on the opposite faces 204, 200

of the substrate 10, or by deposition of two respective polymer layers, followed by carbonization of said polymer layers to obtain glassy carbon layers 30, 40. During possible subsequent heat treatments, the layer 30 on the front face 200 protects the front face against the formation of terraces and/or beads, and the layer 40 on the back face 204 protects the back face against the increase in roughness.

In a second embodiment, first, a support substrate 11 is provided, a weakening area is formed in a donor substrate 220, and said donor substrate 220 is bonded to the support substrate as described above and illustrated in Figures 5A and 5B. Then, with reference to Figure 13A, a carbon layer 40 is formed on the back face 204 of the support substrate 11. Simultaneously, a carbon layer 31 is formed on the free face 223 of the donor substrate 220, opposite the face of the donor substrate forming the bonding interface with the support substrate 11. The carbon layers 31, 40 are deposited in a single step by a gas-phase carbon reaction on the external faces of the support substrate and the donor substrate, or by a deposition of two respective polymer layers, followed by the carbonization of said polymer layers to obtain carbon layers 31, 40.

In this embodiment, the carbon layers 31, 40 are preferably formed at a temperature below 900°C so as not to cause detachment of the donor substrate 220 along the weakening area during deposition of the carbon layers 31, 40.

Detachment of the donor substrate along the weakening area 21 is performed in a subsequent step. With reference to Figure 13B, the carbon layer 31 on the donor substrate 220 is removed along with the donor substrate 220. The carbon layer 40 protects the back face 204 of the substrate 10 during detachment and in some cases during one or more subsequent steps and may be removed later.

In a third embodiment, with reference to Figure 14A, a carbon layer 40 is formed on the back face of the support substrate 11 prior to the transfer of a functional layer and prior to the bonding of a donor substrate for the transfer of a layer onto the support substrate 11. This method, for example vapor deposition or by carbonization of a polymer layer as in the other embodiments, typically results in the formation of a carbon layer 32 on the front face 203 of the support substrate 11. In a subsequent step, with reference to Figure 14B, the carbon layer 32 is removed from the front face 203, and the front face 203 is prepared to receive a functional layer 20 transferred from a donor substrate.

Subsequently, a donor substrate 220 may be subjected to implantation of ionic species, to form a weakening area 21 in the donor substrate 220 as described above and illustrated in Figure 5A.

With reference to Figure 14C, the donor substrate 220 thus implanted can be bonded to the front face 203 of the support substrate 11. The donor substrate can be

bonded directly to the support substrate as illustrated in Figure 14C, or via one or more intermediate layers which can be applied to the donor substrate and/or to the support substrate before bonding (not shown).

With reference to Figure 14D, the donor substrate 220 is then detached along the weakening area 21, which results in the transfer of the monocrystalline silicon carbide layer onto the support substrate 11, thereby forming the substrate 10 comprising the carbon layer 40 on its back face 204. The detached portion 221 of the donor substrate can be reused for the transfer of other monocrystalline silicon carbide layers onto other base substrates. The carbon layer 40 protects the back face 204 of the substrate 10 during the detachment and in some cases during one or more subsequent steps and can be removed later.

In all embodiments, with reference to Figure 15, the transferred layer 20 is preferably made of silicon carbide or gallium nitride. The transferred layer 20 can be used as a seed layer to form a portion 50 of a monocrystalline semiconductor material by epitaxial growth. In the case where the layer 20 was protected by a carbon layer 30, the epitaxial growth is carried out after the removal of the carbon layer 30 from the front face of the substrate. Preferably, the carbon layer 40 is maintained on the back face of the substrate 11 during the epitaxial growth.

After completion of the steps comprising heat treatments, the carbon layer 40 is removed from the back face 204 of the substrate, preferably by chemical mechanical polishing (CMP) and/or by reactive ion etching and/or by plasma etching.

Figure 16A is an atomic force microscopy (AFM) image of a 5 µm x 5 µm area of the back face of a polycrystalline silicon carbide substrate before heat treatment. Figure 16B is an AFM image of the same surface after heat treatment at 1700°C for 30 seconds, protected by a carbon layer. Figure 17A is an image of a 30 µm x 30 µm area of the back face before the same heat treatment, and Figure 17B is an AFM image of the same area after heat treatment at 1700°C for 30 seconds. These images clearly show that roughness increases, even during short-term annealing. Such an increase in roughness is prevented by the presence of a carbon layer on the back face.

Figure 18 shows the root mean square (RMS) roughness and the peak-to-valley (PV) value at several points in different areas A, B, C, D of a substrate that has undergone heat treatments under different conditions. In area A, the back face of the substrate was treated by mechanical polishing after transferring a layer to the front face. No annealing was performed in area A. The back face in this area has a low roughness, the value of the root mean square (RMS) roughness obtained by AFM is less than 2 nanometers. In area B, the substrate was subjected to annealing without a carbon layer on the back face. Area C was

subjected to annealing at 850 °C in the presence of a carbon layer on the back face. Area D was subjected to annealing at 900 °C in the presence of a carbon layer on the back face.

In area B subjected to annealing without a carbon layer, the roughness increased significantly. On the other hand, the roughness of the back faces in areas C and D, which were protected by a carbon layer, is comparable to the initial roughness in area A after removal of the carbon layers. The carbon layer therefore allows to significantly limit the increase in roughness caused by the heat treatments of the substrate.

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CLAIMS

1. A method for treating a substrate (10) having a back face (204) made of polycrystalline silicon carbide and a front face (203) intended for the manufacture of an electronic component, said method comprising:

- the formation of a layer of glassy carbon (40) on the back face (204),
- a transfer of a layer (20) of a monocrystalline semiconductor material onto the front face (203),
- a heat treatment of the substrate after the formation of the carbon layer (40), said carbon layer (40) limiting the increase in roughness of the back face (204) during the heat treatment.

2. The treatment method according to claim 1, wherein the glassy carbon layer (40) has a thickness less than or equal to 100 nm.

3. The treatment method according to claim 1 or claim 2, wherein the heat treatment is carried out at a temperature greater than 900°C, preferably greater than 1300°C.

4. The treatment method according to any one of the preceding claims, wherein the layer (20) of a monocrystalline semiconductor material is made of silicon carbide or gallium nitride.

5. The treatment method according to any one of the preceding claims, wherein the formation of the glassy carbon layer (40) is achieved by a gas-phase carbon reaction on said surface or by deposition of a polymer layer followed by carbonization of said polymer layer.

6. The treatment method according to any one of the preceding claims, wherein the formation of the glassy carbon layer (40) further comprises the formation of a carbon layer (30) on the front face (200) of the substrate (10).

7. The treatment method according to any one of the preceding claims, wherein transferring the layer (20) of a monocrystalline semiconductor material onto the front face (203) comprises:

- implanting ionic species in a donor substrate (220) to form a weakening area (21) delimiting the layer (20) to be transferred,
- bonding the donor substrate (220) to the front face of the support substrate (11),
- detaching the donor substrate (220) along the weakening area (21).

8. The treatment method according to claim 7 in combination with claim 6, wherein the formation of each carbon layer (40, 30) is carried out after detachment from the donor substrate (220), such that the carbon layer (30) on the front face (200) protects the front face (200) during at least part of the heat treatment against the formation of terraces and/or beads on the front face.

9. A method for manufacturing a semiconductor structure according to claim 7 in combination with claim 6, wherein the formation of each carbon layer (30, 40) is carried out after bonding and before detachment from the donor substrate (220), so as to remove the carbon layer (30) on the front face with the donor substrate (220).

10. The treatment method according to claim 7 in combination with claim 6, said method further comprising a step of removing the carbon layer (30) from the front face (200) of the substrate (10), the formation of the carbon layer (30) and the removal of the carbon layer (30) on the front face (200) of the substrate (10) being carried out before bonding the donor substrate (220) to the front face (203) of the support substrate (10).

11. The treatment method according to any one of the preceding claims, further comprising, after the formation and removal of the carbon layer (30, 31, 32) on the front face, a step of epitaxially growing a monocrystalline semiconductor material (50) on the layer (20) into a monocrystalline semiconductor material, in which the carbon layer (40) on the back face (204) limits the increase in roughness of said back face (204) during epitaxy.

12. The treatment method according to claim 11, further comprising, after the step of epitaxially growing the monocrystalline semiconductor material (50), a step of manufacturing an electronic component on the front face of the substrate, in

which the carbon layer (40) on the back face (204) limits the increase in roughness of said back face (204) when manufacturing said electronic component.