

GALLIUM NITRIDE SEMICONDUCTOR STRUCTURE AND PROCESS FOR FABRICATING THEREOF

FIELD OF THE INVENTION

This invention relates to semiconductor structures and, more particularly to gallium nitride (GaN) semiconductor structures and processes for fabricating thereof.

5 BACKGROUND OF THE INVENTION

Gallium Nitride (GaN) is a wide-gap semiconductor that is used today for optoelectronic and electronic devices, such as visible light-emitting diodes and lasers, and high-power microwave electronic transistors. Such devices produce a high amount of heat requiring a heat spreader to be attached to GaN layers to ensure that electrical
10 properties of the semiconductor remain within a safe temperature operating region. One of the known approaches is to use a GaN layer disposed on a SiC substrate configured for thermal management.

For example, U.S. Pat. No. 9,111,750 to Kashyap et al. describes a monolithically integrated semiconductor assembly. The semiconductor assembly
15 includes a substrate including silicon carbide (SiC), and a gallium nitride (GaN) semiconductor device is fabricated on the substrate.

However, although this approach has been shown to be a viable solution for fabrication of GaN microwave devices, it still cannot overcome heat loads, and suffers from rather insufficient thermal conductivity of the SiC substrate. Accordingly, to
20 further enhance thermal management, a logical approach was to replace the SiC substrate, having a thermal conductivity around 350 – 400 W/mK, with the highest thermal conductivity material available, such as diamond. Although natural diamond is an excellent thermal conductor, this material cannot be widely used for electronic applications due to its scarcity and cost.

25 Integration of a synthetic polycrystalline diamond, that can have a thermal conductivity in the range of 800–2000 W/mK, deposited by chemical-vapor deposition (CVD) into semiconductor processing techniques, has evolved over the past several

years. A polycrystalline diamond means that it consists of diamond crystals variously oriented or composed of more than one crystal.

For example, GaN-on-diamond technology and resulting devices involving structures which feature atomically attached GaN epilayers to synthetic diamond
5 substrates are described in U.S. Pat. Nos. 7,595,507 and 9,359,693 to Fransis et al. This technology enables bringing together the best heat conductor (i.e., diamond) with electronic and optoelectronic devices based on GaN-related compounds.

However, integration of a CVD diamond introduces many challenges due to interface issues associated with material lattice mismatch and with different thermal
10 expansion of the GaN and diamond layers that can be a reason for bowing and warping of the GaN-on-diamond structure and its delamination. Moreover, diamond-based composite substrates require careful attention to thermal resistance of the interface layer formed between the GaN and the diamond, which can diminish the benefits of using this high conductivity material.

15 **GENERAL DESCRIPTION**

Disclosed herein is a process of fabrication of a semiconductor substrate structure, comprising:

(i) fabricating a first intermediate structure comprising:

a silicon carbide (SiC) wafer substrate;

20 a microcrystalline diamond (MCD) layer bonded to the silicon carbide (SiC) wafer substrate, the MCD layer having a first MCD surface and a second MCD surface;

a first bonding material layer disposed between the MCD layer and the silicon carbide (SiC) wafer substrate, said first bonding material layer being bonded to the SiC wafer substrate and to the first MCD surface of the first MCD layer; and

25 a second bonding material layer disposed on the second MCD surface of the MCD layer and having an outer surface being exposed;

(ii) fabricating a second intermediate structure comprising:

a gallium nitride (GaN) active layer, a Si carrier substrate, and an adhesive layer therebetween; the GaN active layer having a first GaN surface bonded to the Si carrier
30 substrate via the adhesive layer, and a second GaN surface being exposed;

(iii) bonding said first intermediate structure to said second intermediate structure, where the second GaN surface of the GaN active layer of the structure is bonded to the outer surface of the second bonding material layer;

(iv) removing the Si carrier substrate together with the adhesive layer formed
5 between the Si carrier substrate and the first GaN surface of the GaN active layer;

thereby obtaining said semiconductor substrate structure comprising:

the SiC wafer substrate;

the GaN active layer; and

the MCD layer disposed between the SiC wafer substrate and the GaN active
10 layer, and bonded to the SiC wafer substrate via the first bonding material layer and to the GaN active layer via the second bonding material layer.

Disclosed herein is also a semiconductor substrate structure comprising:

a silicon carbide (SiC) wafer substrate;

an active gallium nitride (GaN) layer;

a layer of microcrystalline diamond (MCD) layer disposed between the SiC wafer substrate and the GaN active layer, and bonded to the SiC wafer substrate and to the GaN active layer; and

a first bonding material layer for bonding the MCD layer to the SiC wafer substrate, and a second bonding material layer for bonding the MCD layer to the GaN active layer;

wherein the first bonding material layer and the second bonding material layer are made of silicone oxide (SiO₂) and provide direct bonding.

Thus, there is still a need in the art for, and it would be useful to have, a novel GaN semiconductor substrate structure that allows efficient heat removal from heat generating electronic and optoelectronic elements fabricated on the basis of GaN
15 semiconductors.

The present invention partially eliminates disadvantages of the above reference techniques and provides a novel semiconductor substrate structure. The semiconductor substrate structure includes a silicon carbide (SiC) wafer substrate, an active gallium nitride (GaN) layer and a layer of microcrystalline diamond (MCD) disposed between
20 the SiC wafer substrate and the GaN active layer. The MCD layer is bonded to the SiC wafer substrate and to the GaN active layer.

According to an embodiment of the present invention, the semiconductor substrate structure includes a first bonding material layer for bonding the MCD layer to the SiC wafer substrate, and a second bonding material layer for bonding the SiC wafer substrate to the GaN active layer.

5 According to an embodiment of the present invention, the GaN active layer has a thickness in the range of about 0.8 micrometers to 1.0 micrometer.

According to an embodiment of the present invention, the MCD layer has a thickness in the range of about 5 micrometers to 95 micrometers.

According to an embodiment of the present invention, the first bonding material
10 layer and the second bonding material layer are made of silicone oxide (SiO_2) and provide direct bonding.

According to an embodiment of the present invention, the first bonding material layer and the second bonding material layer are made of an adhesive material and provide adhesive bonding.

15 The semiconductor substrate structure of the present invention can, for example be used for manufacturing high-electron mobility transistors, bipolar transistors, Schottky diodes, microwave diodes, semiconductor lasers, light-emitting diodes, super-luminescent diodes and other electronic and optoelectronic devices.

According to another aspect, the present application discloses a process for
20 integrating a gallium nitride (GaN) layer, a micro-crystalline diamond (MCD) layer and a silicon carbide (SiC) wafer substrate to form a GaN/MCD/SiC engineered semiconductor substrate structure on which electronic or optoelectronic devices can be manufactured using standard semiconductor processing technology.

According to an embodiment of the present invention, the process of fabrication
25 of the semiconductor substrate structure includes fabricating first and second intermediate structures. The first intermediate structure includes a silicon carbide (SiC) wafer substrate, a microcrystalline diamond (MCD) layer bonded to the silicon carbide (SiC) wafer substrate, a first bonding material layer, and a second bonding material layer. The MCD layer has a first MCD surface on one side of the MCD layer and a
30 second MCD surface on the other side of the MCD layer. The first bonding material layer is bonded to the SiC wafer substrate and to the first surface of the first MCD surface. The second bonding material layer is disposed on the second MCD surface of

the MCD layer and has an outer surface that is exposed. The second intermediate structure includes a gallium nitride (GaN) active layer, a Si carrier substrate, and an adhesive layer therebetween. The GaN active layer has a first GaN surface bonded to the Si carrier substrate via the adhesive layer, and a second GaN surface that is exposed.

5 Further, the process of fabrication of the semiconductor substrate structure includes bonding the first intermediate structure to the second intermediate structure. Specifically, the second GaN surface of the GaN active layer of the second intermediate structure is bonded to the outer surface of the second bonding material layer of the first intermediate structure.

10 Then, the process of fabrication of the GaN/MCD/SiC semiconductor substrate structure of the present invention includes removing the Si carrier substrate together with the adhesive layer formed between the carrier substrate and the first GaN surface of the GaN active layer.

According to an embodiment of the present invention, fabricating the first
15 intermediate structure includes providing a first Si host wafer substrate and growing the MCD layer on the first Si host wafer substrate. Growing of the MCD layer on the first host Si wafer substrate can, for example, be carried out by a chemical-vapor deposition (CVD) technique.

The first and second MCD surfaces of the MCD layer grown on the first Si host
20 wafer substrate have surface topographical irregularities. Specifically, these surface topographical irregularities include peaks, ridges and valleys. To reduce such surface topographical irregularities, the first MCD surface is polished to decrease surface topographical irregularities up to a predetermined first degree of smoothness. For example, the predetermined first degree of smoothness is at least 2 nanometers.

25 Then, fabricating of the first intermediate structure includes forming the first bonding material layer on the first MCD surface.

According to an embodiment, the first bonding material layer provides direct bonding. In this case, forming of the first bonding material layer on the first MCD surface of the MCD layer includes forming a silicone oxide (SiO₂) layer having a
30 thickness sufficient to cover the surface topographical irregularities on the first MCD surface. Forming of the silicone oxide (SiO₂) layer can, for example, be carried out by a plasma enhanced chemical vapor deposition (PECVD) technique. The SiO₂ layer is

further annealed to provide hardening thereof, and is then polished to decrease surface topographical irregularities to the second degree of smoothness. Thus, the exposed surface of the first bonding material layer made of SiO₂ has a predetermined second degree of smoothness, smoother than the first degree of smoothness. For example, the
5 predetermined second degree of smoothness is at least 0.5 nanometers.

According to another embodiment, the first bonding material layer provides adhesive bonding. In this case, the forming of the first bonding material layer on the first MCD surface of the MCD layer includes providing an adhesive material on the first MCD surface of the MCD layer. Examples of an adhesive material suitable for adhesive
10 bonding include, but are not limited to polyimide polymer, Bisbenzocyclobutene (BCB) Electronic Resin, spin-on glass materials and other spin-on dielectric materials used in microelectronic fabrication. An exposed surface of this adhesive layer is polished to the predetermined second degree of smoothness.

Further, fabricating of the first intermediate structure includes providing the SiC
15 wafer substrate, and bonding the SiC wafer substrate to the MCD layer via the first bonding material layer. According to one embodiment, bonding of the SiC wafer substrate to the MCD layer via the bonding material layer is carried out by direct bonding. According to another embodiment, bonding of the SiC wafer substrate to the MCD layer via the bonding material layer is carried out by adhesive bonding.

20 Further, fabricating of the first intermediate structure includes removing the first Si host wafer substrate. After removing the first Si host wafer substrate, the second MCD surface is exposed. Thus, the second MCD surface is polished to decrease its surface topographical irregularities up to the predetermined first degree of smoothness.

Finally, fabricating of the first intermediate structure includes forming the
25 second bonding material layer on the second MCD surface. Forming of the second bonding material layer can be similar to forming of the first bonding material layer.

According to an embodiment of the present invention, fabricating of the second intermediate structure includes providing a fourth intermediate structure comprising a gallium nitride (GaN) layer grown on a second Si host substrate. The GaN layer
30 includes the GaN active layer and a GaN nucleation layer. The GaN active layer has a first GaN surface that is exposed in the fourth intermediate structure. The GaN nucleation layer is bonded to the second Si host substrate.

Then, fabricating of the second intermediate structure includes providing a Si carrier substrate and bonding the Si carrier substrate to the first GaN surface using an adhesive material forming an adhesive layer between the Si carrier substrate and the first GaN surface.

5 Then, fabricating of the second intermediate structure includes removing the second Si host substrate and removing the GaN nucleation layer to expose a second GaN surface of the GaN active layer.

Finally, fabricating of the second intermediate structure includes an edge trimming of the GaN active layer.

10 According to an embodiment of the present invention, bonding of the second GaN surface of the GaN active layer of the second intermediate structure to the outer surface of the second bonding material layer is by direct bonding.

According to an embodiment of the present invention, the second bonding material layer is directly bonded to the second MCD surface of the MCD layer.

15 According to an embodiment of the present invention, bonding of the second GaN surface of the GaN active layer of the second intermediate structure to the outer surface of the second bonding material layer is by adhesive bonding.

According to an embodiment of the present invention, the second bonding material layer is adhesively bonded to the second MCD surface of the MCD layer.

20 There has thus been outlined, rather broadly, the more important features of the invention in order that the detailed description thereof that follows hereinafter may be better understood. Additional details and advantages of the invention will be set forth in the detailed description, and in part will be appreciated from the description, or may be learned by practice of the invention.

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BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

30 **Fig. 1** is a cross- sectional side view of a semiconductor substrate structure, according to an embodiment of the present invention;

Fig. 2 is a diagram illustrating main steps in a process of fabrication of the semiconductor substrate structure shown in **Fig. 1**, according to an embodiment of the present invention;

Fig. 3 is a diagram illustrating main steps in a process of fabrication of the first intermediate structure **100** shown in **Fig. 2**, according to an embodiment of the present invention; and

Fig. 4 is a diagram illustrating main steps in a process of fabrication of the second intermediate structure **200** shown in **Fig. 2**, according to an embodiment of the present invention.

10 DETAILED DESCRIPTION OF EMBODIMENTS

The principles of the semiconductor structure and fabrication method according to the present invention may be better understood with reference to the drawings and the accompanying description, wherein like reference numerals have been used throughout to designate identical elements. It is to be understood that these drawings, which are not necessarily to scale, are given for illustrative purposes only and are not intended to limit the scope of the invention. For example, the dimensions of some of the elements in the figures may be exaggerated relative to other elements to help improve understanding of various embodiments. In addition, the description and drawings do not necessarily require the order illustrated. It will be further appreciated that certain actions and/or steps may be described or depicted in a particular order of occurrence while those skilled in the art will understand that such specificity with respect to sequence is not actually required.

Embodiments of the present invention are described herein with reference to illustrations of cross-sections of semiconductor structures that are schematic illustrations of idealized embodiments of the present invention. Embodiments of the present invention should not be construed as limited to the particular shapes of regions of the structures illustrated herein, but are to include deviations in shapes that result, for example, from manufacturing. Thus, the regions illustrated in the drawings are schematic in nature and their shapes are not intended to illustrate the precise shape of a region of a structure and are not intended to limit the scope of the present invention. For

example, a region illustrated in the drawings as a rectangle block may, typically, be tapered, rounded or curved.

Referring to **Fig. 1**, a cross-sectional side view of a semiconductor substrate structure **10** is illustrated, according to an embodiment of the present invention. The semiconductor substrate structure **10** includes a silicon carbide (SiC) wafer substrate **11**, an GaN active layer **212**, and a microcrystalline diamond (MCD) layer **101** disposed between the SiC wafer substrate **11** and the GaN active layer **212**. The GaN active layer **212** is bonded to the SiC wafer substrate **11** and to the GaN active layer **212**.

For the purpose of this application, the term "GaN active layer" refers to an epilayer structure required for realization of electronic devices, such as a high-frequency transistor, high-voltage switch, Schottky diode, and/or optoelectronic devices, such as laser diodes, light-emitting diodes, etc.

As used in this description, the term "layer" refers to a material disposed on at least a portion of an underlying surface in a continuous or discontinuous manner. Further, the term "layer" does not necessarily mean a uniform thickness of the disposed material, and the disposed material may have either a uniform or a variable thickness. Furthermore, the term "a layer" as used herein refers to a single layer or a plurality of layers, unless the context clearly dictates otherwise. As used herein, the terms "disposed on" and "disposed between" refer to layers disposed directly in contact with each other or indirectly by having intervening layers therebetween, unless otherwise specifically indicated. Further, the term "on" describes the relative position of the layers/devices to each other and does not necessarily mean "on top of" since the relative position above or below depends upon the orientation of the device to the viewer.

According to an embodiment of the present invention, the MCD layer **101** is relatively thin and has a thickness in the range of about 5-95 micrometers, while the SiC wafer substrate **11** is relatively thick and has a thickness in the range of about 90-110 micrometers. It was found from thermal modelling and simulations that replacing a monolithic SiC substrate in a GaN semiconductor device with a composite MCD/SiC substrate of the present invention having the same thickness as the monolithic substrate, can improve the power density per unit area of the GaN semiconductor device three-fold. Moreover, thermal simulations indicate that insertion of a relatively thin MCD layer **101** of about 5-95 micrometers between the GaN active layer **212** and the SiC

wafer substrate **11** can provide in practice the same effect for heat spreading as the heat spreading of a relatively thick microcrystalline diamond layer of 90-110 micrometers, which is extremely difficult to fabricate and is costly. This advantageous effect is due to the great thermal conductivity of the MCD layer **101**, which allows enhanced lateral
5 heat spreading from hot spots of the device with further heat removal achieved by the SiC wafer substrate **11**. Accordingly, a GaN semiconductor device formed using the GaN/MCD/SiC semiconductor structure of the present invention may provide operation of the semiconductor device at much greater power.

Moreover, since the thickness of the MCD layer **101** is relatively lower when
10 compared to the diamond substrates of prior art GaN semiconductor devices aggregated with diamond, mechanical stress due to heating may be absorbed in the MCD layer **101** rather than in the GaN active layer **212** disposed on the MCD layer **101**.

As shown in **Fig. 1**, the MCD layer **101** is bonded to the SiC wafer substrate **11** via a first bonding material layer **102** and to the GaN active layer **212** via a second
15 bonding material layer **105**. Bonding or wafer bonding refers to a semiconductor technology in which two surfaces are brought into proximity and are caused to adhere firmly. Such bonding can be achieved either by direct bonding by Van der Waals forces, or by using an adhesive.

Thus, according to one embodiment of the present invention, the first bonding
20 material layer **102** can provide direct bonding of the optically polished surfaces of the SiC wafer substrate **11** to the MCD layer **101**. Likewise, second bonding material layer **105** can provide direct bonding of the optically polished surfaces the GaN active layer **212** to the MCD layer **101**, as will be described here below.

According to another embodiment of the present invention, the first bonding
25 material layer **102** and/or the second bonding material layer **105** are made of an adhesive material and provide adhesive bonding. According to this embodiment, the MCD layer **101** is "glued" to the SiC wafer substrate **11** via a first bonding material layer **102** and to the GaN active layer **212** via a second bonding material layer **105**.

The first and second bonding material layers **102** and **105** are very thin relatively
30 to the MCD layer **101**, the SiC wafer substrate **11** and the GaN active layer **212**, and therefore the first and second bonding layers **102** and **105** have insignificant thermal

resistance. The thickness of the first and second bonding material layers **102** and **105** can, for example, be in the range of about 5 nm to 50 nm.

Fig. 2 is a diagram illustrating main steps in a process of fabrication of the semiconductor substrate structure shown in **Fig. 1**, according to an embodiment of the present invention. The method of fabrication a semiconductor substrate structure **10** includes fabrication of a first intermediate structure **100** including the silicon carbide (SiC) wafer substrate **11** and the microcrystalline diamond (MCD) layer **101** bonded to the SiC wafer substrate **11**. The MCD layer **101** has a first MCD surface **111** and a MCD second surface **112**. The SiC wafer substrate **11** has a first SiC surface **121** that is an outer exposed surface and a second SiC surface **122** that is an inner surface.

The first bonding material layer **102** is disposed between the SiC wafer substrate **11** and the MCD layer **101**, and is bonded to the second SiC surface **122** of the SiC wafer substrate **11** and to the first MCD surface **111** of the MCD layer **101**. The first intermediate structure **100** also includes the second bonding material layer **105** covering the MCD second surface **112**. The second bonding material layer **105** has an outer surface **106** that is exposed in the first intermediate structure **100**.

The method of fabrication of a semiconductor substrate structure **10** also includes fabrication of a second intermediate structure **200** that includes the gallium nitride (GaN) active layer **212** and a Si carrier substrate **23** bonded to the GaN active layer **212** via an adhesive layer **24** disposed therebetween. The GaN active layer **212** has a first GaN surface **213**, which is bonded to the Si carrier substrate **23**, and a second GaN surface **214**, which is an outer surface in the second intermediate structure **200** and therefore is exposed in the second intermediate structure **200**.

The method of fabrication of a semiconductor substrate structure **10** further includes bonding the first intermediate structure **100** to the second intermediate structure **200**, thereby obtaining a third intermediate structure **300**. Specifically, the second GaN surface **214** of the GaN active layer **212** of the structure **200** is bonded to the outer exposed surface **106** of the second bonding material layer **105** of the first intermediate structure **100**. Thus, the GaN active layer **212** is aggregated with the MCD layer **101** via the second bonding material layer **105**.

According to an embodiment of the present invention, bonding of the first intermediate structure **100** to the second intermediate structure **200** can be carried out by

any suitable technique, for example, by a room-temperature bonding (RTB) technique without the use of high temperatures. This technique is known *per se*, and therefore is not expounded herebelow.

After the bonding, the Si carrier substrate **23** and the adhesive layer **24** formed
5 between the Si carrier substrate **23** and the first GaN surface **213** of the GaN active layer **212** are removed in the third intermediate structure **300**, thereby obtaining the GaN semiconductor structure (**10** in **Fig. 1**). Removing of the Si carrier substrate **23** and the adhesive layer **24** can, for example, be carried out by a Chemical Mechanical Planarization (CMP) technique that is known *per se*. This technique utilizes a chemical
10 slurry formulation and mechanical polishing process to remove unwanted Si carrier substrate **23** and the adhesive layer **24**, and to achieve a required flat and smooth surface of the GaN active layer **212** upon which layers of integrated circuitry of optoelectronic and electronic devices can be built.

Referring to **Fig. 3**, a diagram illustrating main steps in a process of fabrication
15 of the first intermediate structure **100** shown in **Fig. 2** is illustrated, according to an embodiment of the present invention. The process of fabrication of the first intermediate structure **100** starts from providing a first Si host wafer substrate **110** and growing the MCD layer **101** on the first Si host wafer substrate **110**. Growing the MCD layer **101** can, for example, be carried out by a suitable Chemical Vapor Deposition (CVD)
20 process. In particular, diamond wafers can be manufactured by one of three CVD processes: plasma enhanced diamond CVD where the energy to dissociate the reactants comes from a microwave source, hot-filament enhanced diamond CVD where the energy for dissociating gases comes from a hot tungsten filament, and a high voltage torch where ions are accelerated using a high DC voltage. These processes are known
25 *per se*, and need not be described in detail herein.

The thickness of the first Si host wafer substrate **110** may typically be 3-4 millimeters, while thickness of the MCD layer **101** may, for example, be in the range of 5-95 micrometers.

The first MCD surface **111** (that is an upper surface in **Fig. 3**) and the MCD
30 second surface **112** (that is a lower surface in **Fig. 3**) of the MCD layer **101** may have significant surface topographical irregularities, such as peaks, ridges and valleys. A degree of smoothness of the first and second MCD surfaces **111** and **112** after growing

on the first Si host wafer substrate **110** may, for example, be in the range of 0.5-1 micrometers.

Thus, to reduce surface topographical irregularities, the first MCD surface **111** of the MCD layer **101** is polished using any suitable diamond polishing technique to
5 decrease surface topographical irregularities up to a predetermined first degree of smoothness. The first degree of smoothness can, for example, be in the order of about 2 nanometers. The polishing of the first MCD surface **111** may, for example, be carried out by a Chemical Mechanical Planarization (CMP) technique.

Then, the process of fabrication of the structure **100** includes forming the first
10 bonding material layer **102** on the first surface **111** of the MCD layer **101**.

According to one embodiment of the present invention, the first bonding material layer **102** provides direct bonding of the first MCD surface **111** of the MCD layer **101**. According to this embodiment, fabricating the first bonding material layer **102** includes covering the first MCD surface **111** with a layer of Silicon dioxide (SiO₂)
15 also known as silica. Silica is a white or colorless vitreous insoluble solid having a low coefficient of thermal expansion. The silica layer can, for example, have a thickness in the range of 30 nanometers to 100 nanometers. Rapid thermal annealing (RTA) of the structure is then carried out. This method is known *per se*, and involves rapid heating of a semiconductor structure from ambient to approximately 1000K to 1500 K. As soon as
20 the wafer reaches this temperature, it is held there for about 10 seconds to 100 seconds, and then quenched. Finally, fabricating of the first bonding material layer **102** includes polishing a surface **104** of the silica layer to a predetermined second degree of smoothness smoother than the first degree of smoothness. The second degree of smoothness can, for example, be in the order of about 0.5 nanometers. Polishing of the
25 surface **104** of the silica layer may, for example, be carried out by a Chemical Mechanical Planarization (CMP) technique.

According to another embodiment of the present invention, the first bonding material layer **102** provides adhesive bonding of the first MCD surface **111** of the MCD layer **101**. According to this embodiment, fabricating the first bonding material layer
30 **102** includes covering the first MCD surface **111** with a layer of an adhesive material. Examples of an adhesive material suitable for the adhesive bonding include, but are not limited to polyimide polymer, Bisbenzocyclobutene (BCB) Electronic Resin, spin-on

glass materials and other spin-on dielectric materials used in microelectronic fabrication. The layer of an adhesive material can, for example, have a thickness in the range of 30 micrometers to 100 nanometers. An exposed surface **104** of this adhesive layer is polished to the predetermined second degree of smoothness.

5 Then, the process of fabrication of the structure **100** includes providing the SiC carrier wafer substrate **11**, and bonding the SiC carrier wafer substrate **11** to the MCD layer **101** via the first bonding material layer **102**. As shown in **Figs. 2 and 3**, the SiC carrier wafer substrate **11** has a first SiC surface **121** that is an outer exposed surface and a second SiC surface **122** that is an inner surface.

10 The SiC material of the SiC substrate **11** should be of a type suitable for the semiconductor industry. An example of SiC suitable for the purpose of the present invention includes, but is not limited to, 6H polytype SiC.

 The thickness of the SiC carrier wafer substrate **11** may, for example, be in the range of 300 micrometers to 600 micrometers. Depending on the type of the first
15 bonding material layer **102**, the bonding of the SiC wafer substrate **11** to the MCD layer **101** can be either by direct bonding or by adhesive bonding. Such bonding involves a known room-temperature bonding (RTB) technique.

 After bonding of the SiC carrier wafer substrate **11** to the MCD layer **101**, the process of fabrication of the structure **100** includes removing the first Si host wafer
20 substrate **110**, thereby exposing the second surface **112** of the MCD layer **101**. Removing of the first Si host wafer substrate **110** can, for example, be carried out by a known wet etching removal process that typically uses liquid chemicals or etchants to remove materials from a wafer.

 The second surface **112** of the MCD layer **101** is then polished to decrease
25 surface topographical irregularities up to a predetermined first degree of smoothness. Polishing of the second MCD surface **112** can, for example, be carried out by a suitable Chemical Mechanical Planarization (CMP) technique.

 Further, the second bonding material layer **105** is formed on the second MCD surface **112** of the MCD layer **101**. A process of forming the second bonding material
30 layer **105** is similar to the process of forming the first bonding material layer **102** as described above.

As shown in **Figs. 2 and 3**, the second bonding material layer **105** has an outer surface **106**. The smoothness of the outer surface **106** has a predetermined second degree of about 0.5 nanometers.

According to one embodiment of the present invention, the second bonding
5 material layer **105** provides direct bonding of the second MCD surface **112** of the MCD layer **101**. According to another embodiment of the present invention, the second bonding material layer **105** provides adhesive bonding of the second surface **112** of the MCD layer **101**.

Referring to **Fig. 4**, a diagram illustrating main steps in a process of fabrication
10 of the second intermediate structure **200** shown in **Fig. 2** is illustrated, according to an embodiment of the present invention. According to this embodiment, the process of fabrication of the second intermediate structure **200** starts from fabricating a fourth intermediate structure **220** comprising a gallium nitride (GaN) layer **21** grown on a second Si host substrate **22**.

15 GaN has lattice constants that differ from the lattice constants of Si. The layers grown directly on top of the lattice-mismatched substrate are commonly referred to as transition or nucleation layer(s). These layers are highly dislocated. A GaN active layer, having dislocation density that is sufficiently low and suitable for fabrication of electronic and optoelectronic devices, is formed on the nucleation layer. The phrase
20 "formed on," is used herein in a broad context and means a layer that is "formed on" another layer above, but is not necessarily in direct physical contact with another layer. For instance, there may be one or more other buffer layers interposing the active and nucleation layers.

As illustrated in **Fig. 4**, the GaN layer **21** includes the GaN active layer **212**
25 having a thickness of approximately 0.8–2 micrometers and a nucleation layer **211** having a thickness of approximately 0.5–1.5 micrometers. An interface **205** separates a GaN material (active layer) that is required for proper device functioning from the material of the nucleation layer **211** that is not suitable for fabrication of electronic devices.

30 The GaN active layer **212** has a first GaN surface **213** that is exposed in the fourth intermediate structure **220**. The nucleation layer **211** is grown directly on the Si host substrate **22**.

The process of fabrication of the second intermediate structure **200** further includes providing a Si carrier substrate **23** and bonding the Si carrier substrate **23** to the first GaN surface **213** with an adhesive material forming an adhesive layer **24** between the Si carrier substrate **23** and the first GaN surface **213**.

5 Further, the second Si host substrate **22** is removed. Removing of the second host wafer substrate **22** can, for example, be carried out by a known wet etching removal process that typically uses liquid chemicals or etchants to remove materials from a wafer. Then, the process includes removing the nucleation layer **211** to leave only the GaN active layer **212**. After removing of the nucleation layer **211** a second
10 GaN surface **214** of the GaN active layer **212** is exposed. The second GaN surface **214** of the GaN active layer **212** has the predetermined second degree of smoothness of about 0.5 nanometers. Removing of the nucleation layer **211** and polishing of the second GaN surface **214** of the GaN active layer **211** can, for example, be carried out by a suitable Chemical Mechanical Planarization (CMP) technique.

15 The process of fabrication of the second intermediate structure **200** finally includes carrying out an edge trimming of the GaN active layer **212**. Edge trimming is a process that prevents wafer breakage and chipping during back side grinding and transfer by trimming the wafer edge beforehand. The edge trimming process is known per se and is carried out using a suitable edge trim machine.

20 As such, those skilled in the art to which the present invention pertains, can appreciate that while the present invention has been described in terms of preferred embodiments, the concept upon which this disclosure is based may readily be utilized as a basis for the designing of other structures and processes for carrying out the several purposes of the present invention.

25 Also, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting.

Approximate language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary within a statistically meaningful range of a value without resulting in a change in the
30 basic function to which it is related. Accordingly, a value modified by the terms "about" and "approximately" is not to be limited to the precise value specified. In particular, the term "about" refers to a value, amount, or degree that is approximate or near the

reference value. The extent of variation from the reference value encompassed by the term "about" is that which is typical for the tolerance levels or measurement conditions. In some instances, the approximate language may also correspond to the precision of an instrument for measuring the value. The allowable variation encompassed by the term
5 "about" depends on the particular system and/or structure under consideration, and can be readily appreciated by one of ordinary skill in the art. Specifically, this approximation for the purpose of the present invention should be interpreted so as to include an error of 10% at least, as long as there is no considerable change in the performance of the device fabricated from the GaN semiconductor structure of the
10 present invention, due to the deviation.

It is important, therefore, that the scope of the invention is not construed as being limited by the illustrative embodiments set forth herein. Other variations are possible within the scope of the present invention as defined in the appended claims. Other combinations and sub-combinations of features, functions, elements and/or properties may
15 be claimed through amendment of the present claims or presentation of new claims in this or a related application. Such amended or new claims, whether they are directed to different combinations or directed to the same combinations, whether different, broader, narrower or equal in scope to the original claims, are also regarded as included within the subject matter of the present description.

20 Throughout this specification, unless the context requires otherwise, the word "comprise", and variations such as "comprises" and "comprising", will be understood to imply the inclusion of a stated integer or step or group of integers or steps but not the exclusion of any other integer or step or group of integers or steps.

The reference to any prior art in this specification is not, and should not be taken
25 as, an acknowledgment or any form of suggestion that the prior art forms part of the common general knowledge in Singapore.

CLAIMS:

1. A process of fabrication of a semiconductor substrate structure, comprising:
 - (i) fabricating a first intermediate structure comprising:
 - 5 a silicon carbide (SiC) wafer substrate;
a microcrystalline diamond (MCD) layer bonded to the silicon carbide (SiC) wafer substrate, the MCD layer having a first MCD surface and a second MCD surface;
a first bonding material layer disposed between the MCD layer and the silicon carbide (SiC) wafer substrate, said first bonding material layer being bonded to the SiC
10 wafer substrate and to the first MCD surface of the first MCD layer; and
a second bonding material layer disposed on the second MCD surface of the MCD layer and having an outer surface being exposed;
 - (ii) fabricating a second intermediate structure comprising:
a gallium nitride (GaN) active layer, a Si carrier substrate, and an adhesive layer
15 therebetween; the GaN active layer having a first GaN surface bonded to the Si carrier substrate via the adhesive layer, and a second GaN surface being exposed;
 - (iii) bonding said first intermediate structure to said second intermediate structure, where the second GaN surface of the GaN active layer of the structure is bonded to the outer surface of the second bonding material layer;
 - 20 (iv) removing the Si carrier substrate together with the adhesive layer formed between the Si carrier substrate and the first GaN surface of the GaN active layer;
thereby obtaining said semiconductor substrate structure comprising:
the SiC wafer substrate;
the GaN active layer; and
25 the MCD layer disposed between the SiC wafer substrate and the GaN active layer, and bonded to the SiC wafer substrate via the first bonding material layer and to the GaN active layer via the second bonding material layer.
 2. The process of claim 1, wherein the bonding of the second GaN surface of the GaN active layer of the second intermediate structure to the outer surface of the second bonding material layer is by direct bonding.
- 30 3. The process of claim 1, wherein the second bonding material layer provides direct bonding to the second MCD surface of the MCD layer.

4. The process of claim 1, wherein the bonding of the second GaN surface of the GaN active layer of the second intermediate structure to the outer surface of the second bonding material layer is by adhesive bonding.
5. The process of claim 1, wherein the second bonding material layer provides adhesive bonding to the second MCD surface of the MCD layer.
6. The process of claim 1, wherein said fabricating of the second intermediate structure comprises:
 - providing a fourth intermediate structure comprising a gallium nitride (GaN) layer grown on a second Si host substrate, said GaN layer comprising:
 - 10 the GaN active layer having a first GaN surface being exposed in the fourth intermediate structure, and
 - a nucleation layer grown on the second Si host substrate;
 - providing a Si carrier substrate and bonding said Si carrier substrate to the first GaN surface using an adhesive material forming an adhesive layer between the Si carrier substrate and the first GaN surface;
 - 15 removing said second Si host substrate;
 - removing the nucleation layer to expose a second GaN surface of the GaN active layer; and
 - carrying out an edge trimming of the GaN active layer.
- 20 7. The process of claim 6, wherein the surface topographical irregularities include peaks, ridges and valleys.
8. The process of claim 1, wherein the fabricating of the first intermediate structure comprises:
 - providing a first Si host wafer substrate;
 - 25 growing the MCD layer on the first Si host wafer substrate, the first MCD surface and the second MCD surface of the MCD layer having surface topographical irregularities;
 - polishing the first MCD surface to decrease the surface topographical irregularities up to a predetermined first degree of smoothness;
 - 30 forming the first bonding material layer on the first MCD surface, a surface of the bonding material layer having a predetermined second degree of smoothness smoother than the first degree of smoothness;

providing the SiC wafer substrate;
bonding the SiC wafer substrate to the MCD layer via the first bonding material layer;

removing the first Si host wafer substrate;

5 polishing the second MCD surface to decrease the surface topographical irregularities up to the predetermined first degree of smoothness;

forming a second bonding material layer on the second MCD surface, the surface of the second bonding material layer having the predetermined second degree of smoothness smoother than the first degree of smoothness.9. The process of claim 8,
10 wherein the bonding of the SiC wafer substrate to the MCD layer via the bonding material layer is by direct bonding.

9. The process of claim 8. wherein the bonding of the SiC wafer substrate to the MCD layer via the bonding material layer is by direct bonding.

10. The process of claim 8, wherein the bonding of the SiC wafer substrate to the
15 MCD layer via the bonding material layer is by adhesive bonding.

11. The process of claim 8, wherein said predetermined first degree of smoothness is at least 2 nanometers, and said predetermined second degree of smoothness is at least 0.5 nanometers.

12. The process of claim 8, wherein the growing of the MCD layer on the first host
20 Si wafer substrate is carried out by a chemical-vapor deposition (CVD) technique.

13. The process of claim 8, wherein said forming of the bonding material layer on the first MCD surface of the MCD layer includes:

forming a silicone oxide (SiO.sub.2) layer having a thickness sufficient to cover the surface topographical irregularities on the first MCD surface;

25 carrying out annealing of the SiO.sub.2 layer to provide hardening thereof; and
polishing a surface of the SiO.sub.2 layer to decrease the surface topographical irregularities to the second degree of smoothness.

14. A semiconductor substrate structure comprising:

a silicon carbide (SiC) wafer substrate;

30 an active gallium nitride (GaN) layer;

a layer of microcrystalline diamond (MCD) layer disposed between the SiC wafer substrate and the GaN active layer, and bonded to the SiC wafer substrate and to the GaN active layer; and

a first bonding material layer for bonding the MCD layer to the SiC wafer substrate, and a second bonding material layer for bonding the MCD layer to the GaN active layer;

wherein the first bonding material layer and the second bonding material layer are made of silicone oxide (SiO_2) and provide direct bonding.

15. The semiconductor substrate structure of claim 14, wherein the GaN active layer has a thickness in the range of about 0.8 micrometers to 1.0 micrometer.

16. The semiconductor substrate structure of claim 14, wherein the MCD layer has a thickness in the range of about 5 micrometers to 95 micrometers.

17. The semiconductor substrate structure of claim 14, wherein the first bonding material layer and the second bonding material layer has a thickness in the range of about 5 nm to 50 nm.