Semiconductor Device Having an InGaN Layer

Field of Invention

The present invention relates to the manufacture of a semiconductor device comprising an InGaN layer on a carrier substrate and, particularly, the manufacture of a vertical optoelectronic structure comprising an InGaN layer as an active layer.

Background of the invention

The formation of high-quality thin III-nitride layers poses a demanding problem in the context of recent high-performance semiconductor devices, for example, transistor devices and optoelectronic devices, in particular, laser devices as vertical cavity surface-emitting lasers (VCSELs).

Conventionally, a high-quality thin III-nitride layer is formed by epitaxial growth on a seed substrate, for example, a sapphire substrate, by molecular beam epitaxy, metalorganic vapour phase epitaxy or hybrid vapour phase epitaxy. Epitaxial growth on the seed substrate commonly involves the growth of a thick III-nitride layer, commonly referred to as a buffer, prior to high quality thin III-nitride layer growth, wherein the thick III-nitride layer promotes an improvement in the quality of the III-nitride material.

The grown layer can subsequently be transferred to a target wafer by some wafer transfer process known in the art, for example, bonding and laser lift-off or the SMART Cut™ process. Thinning of the III-nitride layer to produce the high quality thin III-nitride layer can be achieved by removal of the thick buffer layer after the wafer transfer.

Such a thinning process can be achieved, for example, by grinding, polishing or plasma etching. Controlled uniform thinning of the III-nitride material can be complex due to the thickness of the buffer layer and this can impact the thickness uniformity of the thin high quality III-nitride layer.

The defect density of the transferred III-nitride layer proves crucial for the performance characteristics of the eventually finished semiconductor device. A main reason for the defects can be seen in strain induced in the III-nitride layer due to growth on a layer exhibiting a different crystal structure, i.e., a mismatch of the crystal lattice constant of the III-nitride layer and the seed layer whereupon it is epitaxially grown.

In addition, the strain state and polarity of the transferred III-nitride layer can prove crucial for performance characteristics of the eventually finished semiconductor device. Such characteristics may include, for example, the carrier recombination efficiency. Strain between the transferred III-nitride layer and a subsequent active layer can affect internal piezoelectric fields within the semiconductor device. Furthermore, the polarity of the transferred III-nitride layer can also affect the piezoelectric fields within the semiconductor structure and polarity selection may be utilized in order to mitigate the affect of strain on the internal electric fields.

Thin III-nitride layers represent main elements of recent down-scaled optoelectronic devices, particularly, laser devices as vertical cavity surface-emitting lasers (VCSELs). US 6,320,206 B1 discloses a method for the manufacture of a VCSELs having wafer bonded aluminum gallium indium nitride structures and mirror stacks. According to the teaching of US 6,320,206 B1 p- and n-doped InAlGaN layers are grown on a sapphire substrate and subsequently transferred to a target substrate. In the resulting structure the InAlGaN layers are sandwiched by mirror layers to obtain a VCSEL.

However, despite the recent engineering progress there is still a need for providing III-nitride layers with enhanced uniformity and reduced defect density in general and, in particular, improved VCSELs based on III-nitride layers.

Description of the Invention

The present invention addresses the above-mentioned need and, accordingly, provides a method for the manufacture, comprising the steps of

a) providing a stack of a first substrate and a InGaN seed layer, in particular, a relaxed InGaN seed layer, formed on the first substrate; and

b) growing an InGaN layer on the InGaN seed layer to obtain an InGaN-on-substrate structure.

By growing the InGaN layer on a thin InGaN seed layer, in particular, a relaxed InGaN seed layer and, more particularly, a relaxed polar, relaxed semi-polar or a relaxed non-polar InGaN seed layer, an InGaN-on-substrate structure can be obtained that can be used for further manufacturing a semiconductor device without the need for removal of a thick layer on which the InGaN layer is grown during subsequent processing steps. Thereby, a high uniformity of the grown InGaN layer can be achieved.

The method further comprises the steps of

c) forming a first mirror layer overlaying a surface of the InGaN layer;

d) detaching the first substrate; and

e) forming a second mirror layer overlaying an opposing surface (surface opposing the one on which the first mirror layer is overlaid) of the InGaN.

The inventive method according to an example further comprises

providing a second substrate with the first mirror layer formed thereon, in particular, formed from distributed Bragg reflectors;

bonding the InGaN-on-substrate structure to the first mirror layer formed on the second substrate;

detaching the first substrate and removing the InGaN seed layer to expose a surface of the InGaN layer; and

forming the second mirror layer, in particular, formed from distributed Bragg reflectors, on the exposed surface of the InGaN layer.

Alternatively, the structure comprising the mirror layers may be obtained by the steps of

forming the first mirror layer on the InGaN layer;

bonding a second substrate to the first mirror layer, in particular, formed from distributed Bragg reflectors;

detaching the first substrate and removing the InGaN seed layer to expose a surface of the InGaN layer; and

forming the second mirror layer, in particular, formed from distributed Bragg reflectors, on the exposed surface of the InGaN layer.

In both alternatives, the removal of the InGaN seed layer may be achieved by etching or polishing. In other embodiments of the invention the removal of the InGaN seed layer may be achieved by thermal oxidation/deoxidation processes, or by photo-electrochemical (PEC) etching processes. Since the InGaN seed layer can be provided as a relatively thin layer perfect removal of this layer in order to expose a surface of the underlying InGaN can be readily performed.

According to another alternative the inventive method comprises the steps of

forming a first mirror layer, in particular, formed from distributed Bragg reflectors, on the InGaN layer;

bonding a second substrate to the first mirror layer;

detaching the first substrate and exposing a surface of the InGaN seed layer; and

forming a second mirror layer, in particular, formed from distributed Bragg reflectors, on the exposed surface of the InGaN seed layer. Since the InGaN seed layer is provided as a high-quality thin layer it may be preferred to omit the step of removing this layer thereby simplifying the overall procedure.

According to the alternative processes a vertical optoelectronic structure comprising mirror layers can be manufactured. The InGaN layer plays the role of an active layer in such a vertical optoelectronic structure that, for example, may be a vertical cavity surface-emitting laser (VCSEL). The inventive method results in a high uniformity and low dislocation density active InGaN layer grown on an InGaN seed layer, in particular, a relaxed InGaN seed layer rather than some thick intermediate substrate, for example, an intermediate GaN substrate or GaN buffer layer. Thus, no intensive processing for thinning of the cavity region formed between the mirrors is necessary thereby improving the quality of the cavity region as compared to the art. In addition a relaxed InGaN seed layer may reduce the strain between said seed layer and the active InGaN layer grown there upon. Such a reduction in strain may improve internal electric fields and operational characteristics of a VCSEL structure, for example, improving carrier recombination efficiency. Such an improvement in VCSEL operational characteristics may further be accomplished utilizing relaxed semi-polar or non-polar InGaN seeds. It is, furthermore, noted that in the above-described embodiments the first substrate may be a sapphire substrate and the second substrate may be a silicon comprising substrate, for example, a silicon substrate.

The provided stack mentioned-above may comprise a dielectric layer between the first substrate and the InGaN seed layer, i.e. the InGaN seed layer is not provided directly on a surface of the first substrate but on a surface of the dielectric layer that was previously formed on a surface of the first substrate. This dielectric layer may be provided for facilitating transfer of the relaxed InGaN seed layer to the first substrate. Appropriate examples for the dielectric layer are SiO_x or Si_xN_y layers. The dielectric layer may

be used for facilitating wafer transfer to the second substrate. In certain embodiments of the invention the dielectric layer may include an electromagnetic absorption layer for facilitating laser lift-off processes. After removal of the first substrate remaining material of the dielectric layer is removed from the surface of the InGaN seed layer, for example, by etching or grinding.

In more detail, according to the present invention, the stack may be formed by the following steps

growing the InGaN seed layer on a third substrate;

bonding the grown InGaN seed layer to a fourth substrate by a bonding layer, in particular, comprising or consisting of a borophosphosilicate glass layer or an SiO_2 - compound layer comprising boron or phosphorous;

relaxing the InGaN seed layer by heat treatment before or after removal of the third substrate; and

transferring the relaxed InGaN seed layer to the first substrate.

Alternatively, the stack is formed by the following steps

growing the InGaN seed layer on a third substrate;

bonding the grown InGaN seed layer to a fourth substrate by a bonding layer, in particular, comprising or consisting of a borophosphosilicate glass layer or an SiO_2 - compound layer comprising boron or phosphorous;

relaxing the InGaN seed layer by heat treatment before or after removal of the third substrate; and

transferring the relaxed InGaN seed layer to the first substrate by means of the dielectric layer.

According to both alternatives the third substrate whereon the InGaN layer is grown can be a GaN substrate. Advantageously, the GaN substrate has a dislocation density of less than 5 x 10^8 cm^{-2}, or less than 10^7 cm^{-2}. This low dislocation density is inherited by the grown InGaN seed layer thus allowing to obtain a high-quality (active) InGaN layer grown on the InGaN seed layer. The InGaN layer can be grown to a thickness within the range of 100 nm to 2000 nm, particularly, 500 to 1500 nm. According to the inventive method the InGaN seed layer is grown to relatively low thickness on the GaN substrate that has a dislocation density of less than 10^7 cm^{-2}. The thickness of the InGaN seed layer may lie in the range of 5 nm to 500 nm. The composition of the InGaN seed layer may lie in the range of 1 to 30% indium, i.e., $In_{0.01}Ga_{0.99}N$ to $In_{0.3}Ga_{0.7}N$. Due to the thin InGaN seed layer used for growing the (active) InGaN layer the cavity thickness of a VCSEL device formed according to the present invention can be reduced as compared to the art thereby improving (reducing) the threshold current needed for the operation of the device.

As already mentioned all of the above examples of the inventive method can be used for the manufacture of a vertical optoelectronic structure, in particular, a vertical cavity surface-emitting laser (VCSEL) thereby obtaining devices of unprecedented quality in terms of homogeneity of the cavity / active layer, threshold current, position alignment of anti-nodes with respect to the multiple quantum wells of the active layer, etc. In particular, it is provided a vertical cavity surface-emitting laser, comprising two mirror layers, in particular, formed from distributed Bragg reflectors, sandwiching a) an active InGaN layer or b) an active InGaN layer and an InGaN seed layer and obtainable by a method according to one of the above-described embodiments.

Furthermore it is provided a vertical cavity surface-emitting laser, comprising a stack comprising the following layers in this order:

a substrate;

a first mirror layer, in particular, formed from distributed Bragg reflectors;

an active InGaN layer;

an InGaN seed layer; and

a second mirror layer, in particular, formed from distributed Bragg reflectors.

Additional features and advantages of the present invention will be described with reference to the drawings. In the description, reference is made to the accompanying figures that are meant to illustrate preferred embodiments of the invention. It is understood that such embodiments do not represent the full scope of the invention.

Figure 1 illustrates an example of the inventive method for the manufacture of a VCSEL comprising an InGaN active layer.

Figure 2 illustrates another example of the inventive method for the manufacture of a VCSEL comprising an InGaN active layer.

Figure 1 illustrates an example of the herein disclosed method for the manufacture of a target wafer including an InGaN layer. Figure 1 shows the growth of an InGaN layer upon an InGaNoS (InGaN on substrate) engineered substrate. According to this example, the InGaNoS structure comprises a sapphire substrate 1, a dielectric bonding layer 2 and a relaxed InGaN seed layer 3 which can be a polar relaxed, semi-polar relaxed or non-polar relaxed InGaN layer.

The relaxed InGaN seed layer 3 on the sapphire substrate 1 may be obtained by the following process. A GaN template (free-standing substrate) is provided that may exhibit polar, semi-polar or no polarity that will be inherited by the InGaN layer grown thereon. The GaN template has advantageously a low dislocation density (e.g., below 10^7 cm^{-2}) that is also inherited by the InGaN seed layer 3 grown thereon. After the InGaN layer has been grown on the GaN template it might be subject to ion implantation to form a weakened region to facilitate transfer to another substrate. The ion implanta-

tion process can be utilized to define the thickness and thickness uniformity of the InGaN seed layer. For example, the implantation dose can be selected to form the weakened region at a desired thickness within the InGaN layer thereby defining the thickness of the seed layer. In addition, implantation dose and splitting parameters can be selected to produce a desired thickness uniformity in the InGaN seed layer.

For example, the InGaN seed layer 3 may be bonded to a glassy reflowable bonding layer, for example, a borophosphosilicate glass (BPSG) or an SiO_2 - compound comprising B (BSG) or P (PSG). Borophosphosilicate glass exhibits reflow characteristics at temperatures exceeding about 800 °C or 850 °C (depending on the actual composition of the glass) thereby allowing for relaxation of strain induced in the InGaN seed layer 3. Alternatively, one reflowable bonding layer is formed upon the InGaN seed layer 3 and another one is formed on the surface of a substrate and the two bonding layers are bonded to each other. In certain embodiments, the InGaN seed layer 3 may comprise a blanket layer over the glassy reflowable bonding layer, alternatively InGaN seed layer 3 may be patterned and etched, as known in the art, into one or more InGaN seed layers with geometries including, but not limited to, circular, rectangular, etc.

Before or after removal of the GaN template the structure is subject to heat treatment in order to relax the InGaN seed layer 3. After relaxation the relaxed InGaN seed layer 3 is transferred to the sapphire substrate 1 in order to function as the relaxed InGaN seed layer 3 for the further processing. It might be preferred to form a dielectric layer 2, for example, an SiO_x or Si_xN_y layer directly on the surface of the sapphire substrate 1 to facilitate transfer of the relaxed InGaN seed layer 3 to the sapphire substrate 1. In any way, the InGaN seed layer 3 is obtained from growth on a donor material of high quality with respect to the defect density (the above-mentioned GaN template) and, thus, the thickness of the relaxed InGaN seed layer 3 can be rather low (e.g., in the range of 5 nm to 500 nm) without affecting the material quality. An InGaN layer 4 can subsequently epitaxially grown on the relaxed InGaN seed layer 3 provided on the sapphire substrate 1. The thickness of the InGaN layer lies within the range of 200 nm to 2000 nm, particularly, 500 to 1500 nm.

As shown in Figure 1 the resulting structure is bonded to a mirror layer 6 formed on a carrier substrate 5. The mirror layer 5 may be fabricated from distributed Bragg reflectors (DBR) of high reflexivity (about 99 %) as known in the art. After the bonding process the sapphire substrate 1 is removed by chemical etching, grinding, polishing. In certain embodiments of the invention sapphire substrate 1 is removed by laser lift-off processes. In laser lift-off embodiments, dielectric bonding layer 2 may include an electromagnetic absorption layer to facilitate absorption of electromagnetic radiation, e.g., by laser irradiation of the dielectric bonding layer 2 through the sapphire substrate 1. Such irradiation of the dielectric bonding layer including an electromagnetic absorption layer facilitates the removal of sapphire substrate 1. The remaining material of the dielectric bonding layer 2 can be removed from the InGaN seed layer 3 by etching, grinding and/or polishing.

Subsequently, the InGaN seed layer 3 is removed to expose the InGaN layer 4 as illustrated in Figure 1. Since the relaxed InGaN seed layer 3 is relatively thin, it can be accurately and uniformly removed by etching or polishing. In other embodiments of the invention the removal of the relaxed InGaN seed layer 3 may be achieved by thermal oxidation/deoxidation processes, or by photo-electrochemical (PEC) etching processes. In a next step, a second mirror layer 7 that also may be fabricated from distributed Bragg reflectors (DBR) of high reflexivity (about 99 %) is formed upon the exposed surface of the InGaN layer 4 that becomes the active layer of the resulting VCSEL structure. Further processing steps, including contacting, follow as known in the art to complete the VCSEL device.

Contrary to the art, according to the present invention the relaxed InGaN seed layer 3 can be removed almost perfectly without significant residuals. No etch back of a relatively thick active layer is necessary. Thereby, it is made possible to perfectly align the anti-node of the optical mode with the multiple quantum wells of the active InGaN region defined by the InGaN layer 4 alone (without residuals). This alignment results in a better coupling of the laser field of the VCSEL with the cavity as compared to the art.

Figure 2 illustrates an alternative example of the inventive method compared to the one shown in Figure 1. According to this example, an InGaNoS structure is formed as

described with reference to Figure 1. Dielectric bonding layer 2 may include an electromagnetic absorbing layer 8 to promote subsequent detachment. Additionally, a mirror layer (DBR) 6 is formed on the InGaN layer 4 that later will play the role of an active layer. The resulting structure is bonded to the carrier substrate 5. Detachment of the sapphire substrate 1 is mediated by irradiation of the electromagnetic absorption layer 8 to facilitate laser lift-off removal of sapphire substrate 1. Whereas the remaining material of the dielectric layer 2 is removed from the InGaN seed layer 3, the latter, according to this example, is maintained atop of the InGaN layer 4. Rather than removing the InGaN seed layer 3 it is used as a seed layer for growing the second mirror (DBR) layer 7. This is made possible by the low thickness and uniformity of the relaxed InGaN seed layer 3. Usage of the InGaN seed layer 3 may improve adherence of the mirror layer 7 grown thereon

In both examples described above and illustrated in Figures 1 and 2 the mirror layers 6 and 7 can, for example, consist of stacked pairs of low loss dielectrics. The mirrors may comprise all-oxide distributed Bragg reflectors or alternatively III-nitride based Bragg reflectors. Paired layers of silicon dioxide with titanium dioxide, zirconium dioxide, tantalum oxide of hafnium dioxide may be chosen, in principle for all-oxide distributed Bragg reflectors. Paired layers of $Al_xGa_{1-x}N$ with GaN may be chosen, in principle, for III-nitride based Bragg reflectors. In further examples the mirror layers 6 and 7 may comprise metallic materials. Moreover, where appropriate an intermediate bonding layer may be provided between a respective mirror layer and the active InGaN layer 4.

All previously discussed embodiments are not intended as limitations but serve as examples illustrating features and advantages of the invention. It is to be understood that some or all of the above described features can also be combined in different ways.

Claims

1. Method for the manufacture of a vertical optoelectronic structure comprising

a) providing a stack of a first substrate (1) and a InGaN seed layer (3) formed on the first substrate (1);
b) growing an InGaN layer (4) on the InGaN seed layer (3) to obtain an InGaN-on-substrate structure;
c) forming a first mirror layer (6) overlaying a surface of the InGaN layer (4);
d) detaching the first substrate (1); and
e) forming a second mirror layer (7) overlaying an opposing surface of the InGaN (4).

2. The method according to claim 1, further comprising
providing a second substrate (5) with the first mirror layer (6) formed thereon;
bonding the InGaN-on-substrate structure to the first mirror layer (6) formed on the second substrate (5); and
removing the InGaN seed layer (3) to expose the opposing surface of the InGaN layer (4).

3. The method according to claim 1, further comprising
forming the first mirror layer (6) on the InGaN layer (4);
bonding a second substrate (5) to the first mirror layer (6);
removing the InGaN seed layer (3) to expose the opposing surface of the InGaN layer (4).

4. The method according to claim 1, further comprising
forming the first mirror layer (6) on the InGaN layer (4);
bonding a second substrate (5) to the first mirror layer (6);
exposing a surface of the InGaN seed layer (3); and
forming the second mirror layer (7) on the exposed surface of the InGaN seed layer (3).

5. The method according to one of the preceding claims wherein the provided stack comprises a dielectric layer (2) between the first substrate (1) and the InGaN seed layer (3).

6. The method according to one of the preceding claims, wherein the stack is formed by the following steps

growing the InGaN seed layer (3) on a third substrate;
bonding the grown InGaN seed layer (3) to a fourth substrate by a bonding layer, in particular, comprising or consisting of a borophosphosilicate glass layer or an SiO_2 - compound layer comprising boron or phosphorous;
relaxing the InGaN seed layer (3) by heat treatment before or after removal of the third substrate; and
transferring the relaxed InGaN seed layer (3) to the first substrate (1).

7. The method according to claim 5, wherein the stack is formed by the following steps

growing the InGaN seed layer (3) on a third substrate;
bonding the grown InGaN seed layer (3) to a fourth substrate by a bonding layer, in particular, comprising or consisting of a borophosphosilicate glass layer or an SiO_2 - compound layer comprising boron or phosphorous;
relaxing the InGaN seed layer (3) by heat treatment before or after removal of the third substrate; and
transferring the relaxed InGaN seed layer (3) to the first substrate (1) by means of the dielectric layer (2).

8. The method according to claim 6 or 7, wherein the third substrate is a GaN substrate, in particular, a GaN substrate with a dislocation density of less than 5×10^8 cm^{-2}.

9. The method according to one of the preceding claims, wherein the InGaN layer (4) is grown to a thickness within the range of 100 nm to 2000 nm and/or wherein the InGaN seed layer (3) is grown to a thickness within the range of 5 nm to 500 nm.

10. The method according to claim 3, wherein the InGaN seed layer (3) is removed by etching or polishing.

11. Method for the manufacture of a vertical optoelectronic structure, in particular, a vertical cavity surface-emitting laser, comprising the steps of the method according to one of the preceding claims.

12. The method according to one of the preceding claims wherein the first mirror layer (6) and the second mirror layer (7) comprise all-oxide distributed Bragg reflectors or III-nitride distributed Bragg reflectors.

13. The method according to one of the preceding claims wherein the thickness of the InGaN seed (3) on the first substrate (1) is defined by an ion implantation produced weakened region.

14. Vertical cavity surface-emitting laser, comprising

two mirror layers (6, 7), in particular, formed from all-oxide distributed Bragg reflectors, sandwiching an InGaN seed layer (3) and an active InGaN layer (4) grown on the InGaN seed layer (3) and obtainable by a method according to one of the claims 1 or 4.

15. Vertical cavity surface-emitting laser, comprising a stack comprising the following layers in this order:

a substrate (5);
a first mirror layer (6), in particular, formed from distributed Bragg reflectors;
an InGaN seed layer (3);

an active InGaN layer (4) grown on the InGaN seed layer (3); and

a second mirror layer (7), in particular, formed from distributed Bragg reflectors.