



US010600935B2

(12) **United States Patent**  
**Chuo et al.**

(10) **Patent No.:** **US 10,600,935 B2**  
(45) **Date of Patent:** **Mar. 24, 2020**

(54) **NITRIDE BASED SEMICONDUCTOR DEVICE WITH IMPROVED LATTICE QUALITY**

(58) **Field of Classification Search**  
None  
See application file for complete search history.

(71) Applicant: **XIAMEN SAN'AN OPTOELECTRONICS CO., LTD.**,  
Xiamen (CN)

(56) **References Cited**

U.S. PATENT DOCUMENTS

(72) Inventors: **Chang-Cheng Chuo**, Xiamen (CN);  
**Shengchang Chen**, Xiamen (CN);  
**Heqing Deng**, Xiamen (CN)

2002/0020850 A1\* 2/2002 Shibata ..... H01L 21/0242  
257/183  
2009/0001409 A1\* 1/2009 Takano ..... H01L 33/12  
257/103

(Continued)

(73) Assignee: **Xiamen San'An Optoelectronics Co., Ltd.**, Fujian (CN)

FOREIGN PATENT DOCUMENTS

(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

CN 105489723 A 4/2016  
CN 106784216 A 5/2017  
CN 107634128 A 1/2018

OTHER PUBLICATIONS

(21) Appl. No.: **16/423,492**

Cheng, Kai, et al., "Flat GaN Epitaxial Layers Grown on Si(111) by Metalorganic Vapor Phase Epitaxy Using Step-Graded AlGaIn Intermediate Layers." *Journal of Electronic Materials*, vol. 35, No. 4, 2006, pp. 592-598., doi:10.1007/s11664-006-0105-1. (Year: 2006).\*

(Continued)

(22) Filed: **May 28, 2019**

*Primary Examiner* — J. E. Schoenholtz

(65) **Prior Publication Data**

US 2019/0280160 A1 Sep. 12, 2019

(74) *Attorney, Agent, or Firm* — Rosenberg, Klein & Lee

**Related U.S. Application Data**

(63) Continuation-in-part of application No. PCT/CN2018/078652, filed on Mar. 12, 2018.

(57) **ABSTRACT**

(30) **Foreign Application Priority Data**

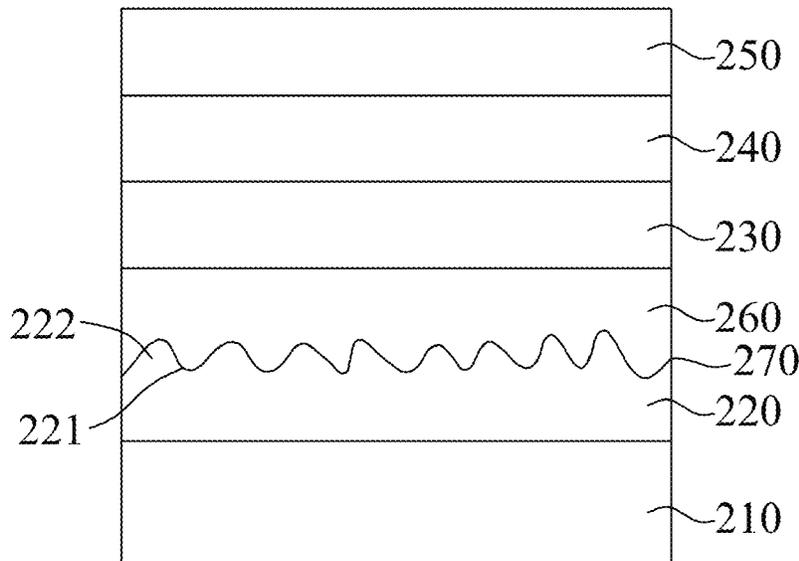
Sep. 14, 2017 (CN) ..... 2017 1 0827123

A nitride based semiconductor device including a buffer layer, a three-dimensional stress tuning layer formed on the buffer layer, a first-type semiconductor layer formed on the three-dimensional stress tuning layer, an active layer formed on the first-type semiconductor layer, and a second-type semiconductor layer formed on the active layer. The three-dimensional stress tuning layer and the buffer layer cooperatively define an interface therebetween. The interface has a three-dimensional composition distribution.

**9 Claims, 3 Drawing Sheets**

(51) **Int. Cl.**  
**H01L 33/32** (2010.01)  
**H01L 33/12** (2010.01)

(52) **U.S. Cl.**  
CPC ..... **H01L 33/325** (2013.01); **H01L 33/12** (2013.01)



(56)

**References Cited**

U.S. PATENT DOCUMENTS

2014/0332849 A1\* 11/2014 Jang ..... H01L 29/7783  
257/190  
2018/0145214 A1 5/2018 Chen et al.

OTHER PUBLICATIONS

He, Chengyu, et al. "Growth and Characterization of Ternary AlGa<sub>N</sub> Alloy Nanocones across the Entire Composition Range." ACS Nano, vol. 5, No. 2, 2011, pp. 1291-1296., doi:10.1021/nn1029845 (Year: 2011)\*

Search Report issued to PCT application No. PCT/CN2018/078652 by the CNIPA dated May 31, 2018.

Search Report appended to an Office Action, which was issued to Chinese counterpart application No. 201710827123.6 by the CNIPA dated Oct. 8, 2018, with an English translation thereof.

\* cited by examiner

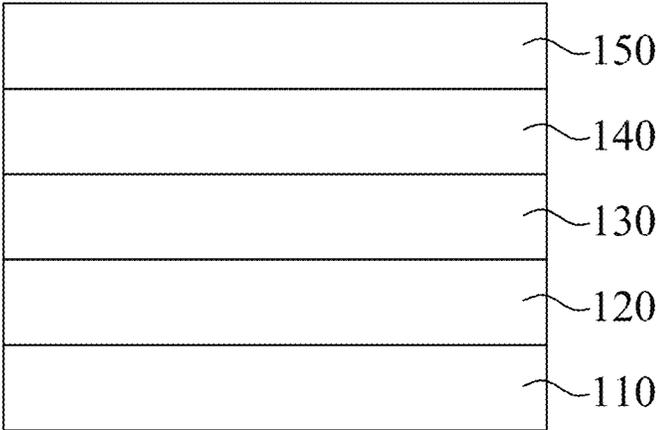


FIG. 1

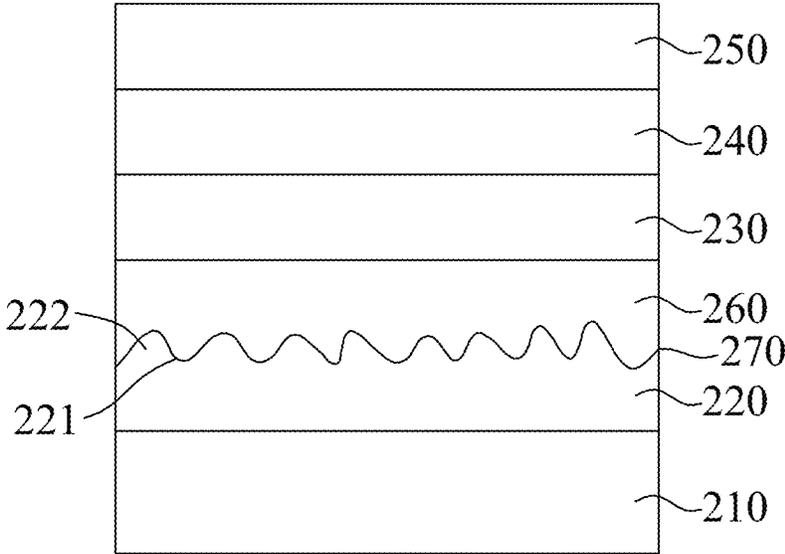


FIG. 2

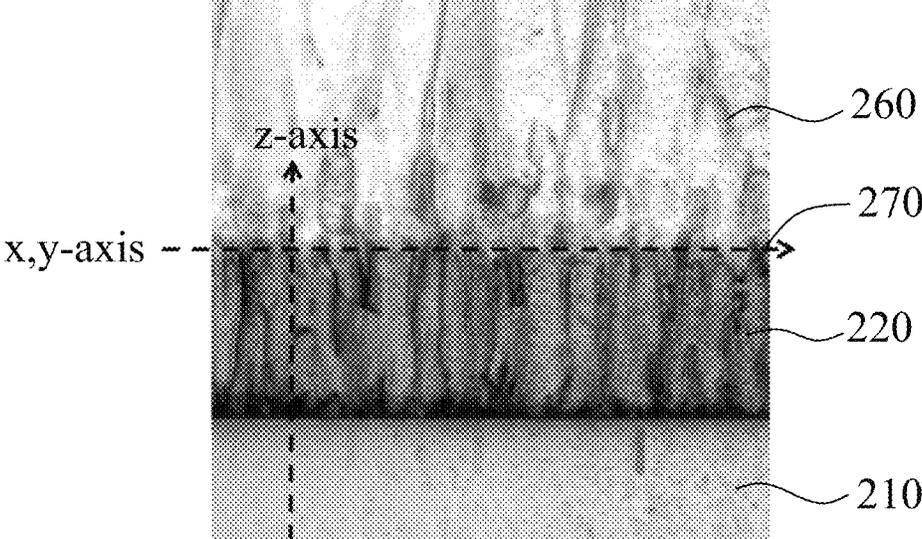


FIG.3

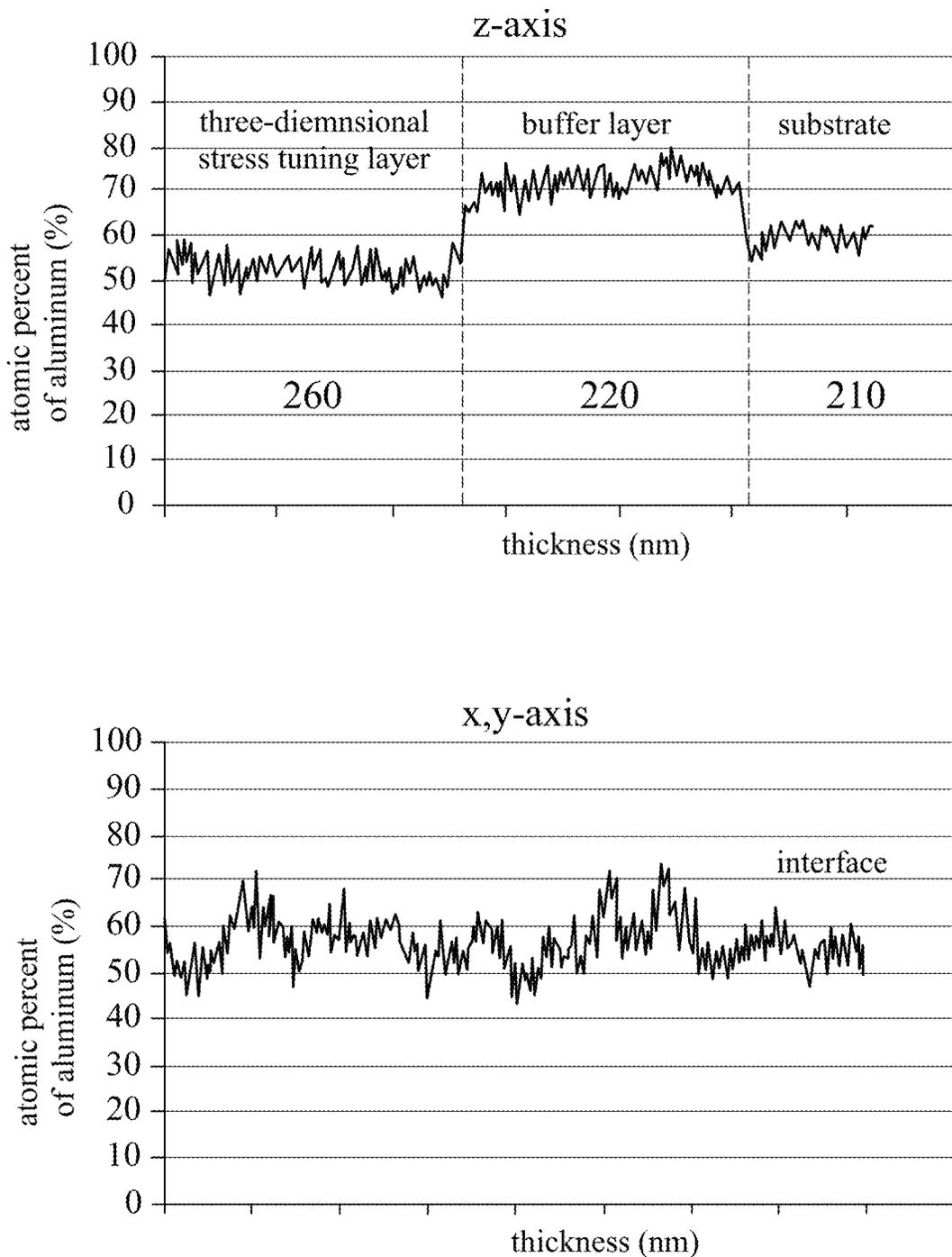


FIG.4

1

## NITRIDE BASED SEMICONDUCTOR DEVICE WITH IMPROVED LATTICE QUALITY

### CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part (CIP) of International Application No. PCT/CN2018/078652, filed on Mar. 12, 2018, which claims priority to Chinese Invention Patent Application No. 201710827123.6, filed Sep. 14, 2017.

### FIELD

The disclosure relates to a semiconductor device, more particularly to a nitride based semiconductor device.

### BACKGROUND

In recent years, with improvements in technology and efficiency, ultraviolet light emitting diodes (UV LEDs), with their longer lifespan and smaller volume, have been slowly replacing mercury lamps of lower efficiency. With the Minamata Convention on Mercury coming into effect in 2020, the global ban on mercury would further expedite the rise of application of the UV LEDs.

A conventional deep UV LED has an aluminum nitride (AlN)-based buffer layer. FIG. 1 shows an epitaxial structure of the conventional deep UV LED. An n-type nitride semiconductor layer **130**, a quantum well light emitting layer **140** and a p-type nitride semiconductor layer **150** are formed sequentially on the AlN-based buffer layer **120** grown on a substrate **110**. In particular, because there is lattice mismatch between the n-type nitride semiconductor layer and the AlN-based buffer layer, high compressive stress is experienced by the latter-grown aluminum gallium nitride (AlGaIn)-based layers such as the quantum well light emitting layer and the p-type nitride semiconductor layer. This causes an increase in the dislocation density and affects the lattice quality as well as the luminous efficiency of the deep UV LED.

### SUMMARY

Therefore, the object of the disclosure is to provide a semiconductor device that can alleviate at least one of the drawbacks of the prior art.

According to the disclosure, a nitride based semiconductor device includes a buffer layer, a three-dimensional stress tuning layer formed on the buffer layer, a first-type semiconductor layer formed on the three-dimensional stress tuning layer, an active layer formed on the first-type semiconductor layer, and a second-type semiconductor layer formed on the active layer.

The three-dimensional stress tuning layer and the buffer layer cooperatively define an interface therebetween. The interface has a three-dimensional composition distribution.

### BRIEF DESCRIPTION OF THE DRAWINGS

Other features and advantages of the disclosure will become apparent in the following detailed description of the embodiment with reference to the accompanying drawings, of which:

FIG. 1 is a sectional schematic view of a conventional deep ultraviolet light emitting diode;

2

FIG. 2 is a sectional schematic view of an embodiment of a nitride based semiconductor device according to the disclosure;

FIG. 3 is a transmission electron microscope image illustrating a three-dimensional stress tuning layer of the embodiment; and

FIG. 4 is a graph of an aluminum content distribution of the embodiment measured using energy dispersive x-ray spectroscopy.

### DETAILED DESCRIPTION

Referring to FIG. 2, a first embodiment of a nitride based semiconductor device according to the disclosure includes a substrate **210** for epitaxial growth thereon, a buffer layer **220** formed on the substrate **210**, a three-dimensional stress tuning layer **260** formed on the buffer layer **220**, a first-type semiconductor layer **230** formed on the three-dimensional stress tuning layer **260**, an active layer **240** formed on the first-type semiconductor layer **230**, and a second-type semiconductor layer **250** formed on the active layer **240**. In this embodiment, the buffer layer **220** is made from aluminum nitride (AlN). The first-type semiconductor layer **230** is an n-type semiconductor layer. The second-type semiconductor layer **250** is a p-type semiconductor layer. The nitride based semiconductor device may further include an anode formed on the first-type semiconductor layer **230** and a cathode formed on the second-type semiconductor layer **250**.

In this embodiment, epitaxial growth of the buffer layer **220**, the three-dimensional stress tuning layer **260**, the first-type semiconductor layer **230**, the active layer **240** and the second-type semiconductor layer **250** in sequence on the substrate **210** is exemplified to be performed using metal organic chemical-vapor deposition (MOCVD) technique, and the substrate **210** is exemplified to be a sapphire substrate.

The buffer layer **220** formed on the substrate **210** has a thickness greater than 100 nanometers. In certain embodiments, the thickness is between 1000 nanometers and 3000 nanometers. The three-dimensional stress tuning layer **260** and the buffer layer **220** cooperatively define an interface **270** therebetween. The buffer layer **220** has an irregular top surface that is connected to the three-dimensional stress tuning layer **260** and that cooperates with the three-dimensional stress tuning layer **260** to define the interface **270**. The irregular top surface of the buffer layer **220** includes a base portion **221** and a plurality of protruding portions **222** protruding from the base portion **221**, each of the protruding portions **222** having a height larger than 10 nanometers from the base portion **221**. In certain embodiments, the width of each protruding portion **222** is larger than 100 nanometers. The irregular top surface of the buffer layer **220** may be formed under growth conditions including a relatively low growth temperature and a relatively high ratio of Group V/III, where the growth temperature is between 1000° C. and 1350° C. and the ratio of Group V/III is larger than 1500. An excess of ammonia gas may cause pre-reaction problems for organic metal sources for forming the buffer layer **220**. In this embodiment, the growth temperature is exemplified to be at 1200° C. and the ratio of Group V/III is exemplified to be between 2000 and 3000.

The three-dimensional stress tuning layer **260** grown on the buffer layer **220** has a growth temperature between 1000° C. and 1300° C., a thickness between 100 nanometers and 5000 nanometers, and has a lattice constant larger than that of the buffer layer **220**. The three-dimensional stress tuning layer **260** may have a structure formula of  $Al_xGa_y$ ,

$\text{In}_{1-x-y}\text{N}$ , where  $x \geq 0$ ,  $y > 0$ , and  $x+y \leq 1$ . The flux of aluminum and gallium may be controlled to modify the lattice constant of the three-dimensional stress tuning layer **260**. In this embodiment,  $x$  is between 0.2 and 0.9. In certain embodiments,  $x$  is between 0.5 and 0.9.

The n-type semiconductor layer for the first-type semiconductor layer may have a structure formula of  $\text{Al}_{x_1}\text{Ga}_{1-x_1}\text{N}$  where  $x_1$  is between 0.5 and 1.

The active layer **240** has a quantum well structure with a structural formula of  $\text{Al}_{x_2}\text{Ga}_{1-x_2}\text{N}/\text{Al}_{x_3}\text{Ga}_{1-x_3}\text{N}$ , wherein  $x_2 < x_3$ ,  $x_2$  is between 0.3 and 0.9, and  $x_3$  is between 0.6 and 1. In certain embodiments,  $x_2$  is 0.4 and  $x_3$  is 0.6.

The second-type semiconductor layer **250** may include a p-type aluminum gallium nitride (AlGaN) barrier layer having a structural formula of  $\text{Al}_{x_4}\text{Ga}_{1-x_4}\text{N}$ , where  $x_4$  is between 0.3 and 0.9, a magnesium-doped p-type AlGaN layer also having a structural formula of  $\text{Al}_{x_4}\text{Ga}_{1-x_4}\text{N}$ , and a magnesium-doped p-type gallium nitride (GaN) layer.

In this embodiment, the interface **270** has a three-dimensional composition distribution. FIG. **3** shows a transmission electron microscope image of the three-dimensional stress tuning layer **260** and FIG. **4** shows an aluminum content measured using energy-dispersive x-ray (EDX) spectroscopy. As can be seen from FIG. **4**, the aluminum content distribution decreases along a growth direction from the buffer layer **220** of AlN to the three-dimensional stress tuning layer **260**, and is irregular on the interface **270**, which allows stress to be released three-dimensionally.

In this embodiment, the lattice constant of the stress tuning layer **260** is between that of the buffer layer **220** of AlN and the first-type semiconductor layer **230** of  $\text{Al}_{x_1}\text{Ga}_{1-x_1}\text{N}$ . If the stress tuning layer **260** is grown at a relatively high temperature, the adjustment of the aluminum content may be based on a growth parameter of the first-type semiconductor layer **230**. For example, a flux of trimethyl aluminum (TMAI) may be fixed while a flux of trimethyl gallium (TMGa) is varied. For example, when the flux of TMGa for growing the first-type semiconductor layer **230** is designated by  $f_1$  and the flux of TMGa for growing the three-dimensional stress tuning layer **260** is designated by  $f_2$ , the  $f_1$  and  $f_2$  may satisfy the relation of  $0 < f_2 < f_1$ . Alternatively, the  $f_1$  and  $f_2$  may satisfy an equation of  $f_2 = f_1/2$ . The flux of TMGa may be fixed while varying the flux of the TMAI in a similar manner.

In this embodiment, the aluminum content may also be controlled by controlling the respective growth temperatures of the buffer layer **220** of AlN, three-dimensional stress tuning layer **260** of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  and the first-type semiconductor layer **230** of  $\text{Al}_{x_1}\text{Ga}_{1-x_1}\text{N}$ . For example, when the growth temperature of the stress tuning layer **260** is designated to be  $T_1$ , the growth temperature of the buffer layer **220** is designated to be  $T_2$ , and the growth temperature of the first-type semiconductor layer **230** is designated to be  $T_3$ , the  $T_1$ ,  $T_2$  and  $T_3$  may satisfy a relation of  $T_3 < T_1 < T_2$ . Alternatively, the  $T_1$ ,  $T_2$  and  $T_3$  may satisfy an equation of  $T_1 = (T_2 + T_3)/2$ .

In the description above, for the purposes of explanation, numerous specific details have been set forth in order to provide a thorough understanding of the embodiment. It will be apparent, however, to one skilled in the art, that one or more other embodiments may be practiced without some of these specific details. It should also be appreciated that reference throughout this specification to "one embodiment," "an embodiment," an embodiment with an indication of an ordinal number and so forth means that a particular feature, structure, or characteristic may be included in the practice of the disclosure. It should be further appreciated

that in the description, various features are sometimes grouped together in a single embodiment, figure, or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of various inventive aspects, and that one or more features or specific details from one embodiment may be practiced together with one or more features or specific details from another embodiment, where appropriate, in the practice of the disclosure.

While the disclosure has been described in connection with what is considered the exemplary embodiment, it is understood that this disclosure is not limited to the disclosed embodiment but is intended to cover various arrangements included within the spirit and scope of the broadest interpretation so as to encompass all such modifications and equivalent arrangements.

What is claimed is:

1. A nitride based semiconductor device, comprising a buffer layer made from aluminum nitride (AlN); a three-dimensional stress tuning layer formed on said buffer layer and having a structure formula of  $\text{Al}_x\text{In}_{1-x-y}\text{N}$ , where  $x \geq 0$ ,  $y > 0$ ,  $x+y \leq 1$ ; a first-type semiconductor layer directly formed on said three-dimensional stress tuning layer and having a structure formula of  $\text{Al}_{x_1}\text{Ga}_{1-x_1}\text{N}$ , where  $x_1$  is between 0.5 and 1; an active layer formed on said first-type semiconductor layer; and a second-type semiconductor layer formed on said active layer, wherein said buffer layer has an irregular top surface disposed in contact with said three-dimensional stress tuning layer, said buffer layer cooperating with said three-dimensional stress tuning layer to define an interface therebetween, said interface having a three-dimensional composition distribution, wherein a lattice constant of said three-dimensional stress tuning layer ranges between a lattice constant of said buffer layer and a lattice constant of said first-type semiconductor layer.
2. The nitride based semiconductor device as claimed in claim 1, wherein said first-type semiconductor layer is an n-type semiconductor layer, and said second-type semiconductor layer is a p-type semiconductor layer.
3. The nitride based semiconductor device as claimed in claim 1, wherein said three-dimensional stress tuning layer has an aluminum content that is smaller than an aluminum content of said buffer layer said aluminum content of said three-dimensional stress tuning layer being irregular on the interface.
4. The nitride based semiconductor device as claimed in claim 1, wherein said three-dimensional stress tuning layer has a lattice constant larger than that of said buffer layer.
5. The nitride based semiconductor device as claimed in claim 1, wherein  $x$  ranges between 0.2 and 0.9.
6. The nitride based semiconductor device as claimed in claim 1, wherein said three-dimensional stress tuning layer has a growth temperature between  $1000^\circ\text{C}$ . and  $1300^\circ\text{C}$ .
7. The nitride based semiconductor device as claimed in claim 1, wherein said three-dimensional stress tuning layer has a thickness between 100 nanometers and 5000 nanometers.
8. The nitride based semiconductor device as claimed in claim 1, wherein said irregular top surface of said buffer layer includes a base portion and a plurality of extending portions protruding from said base portion, each of said protruding portions having a height larger than 10 nanometers from said base portion.

9. The nitride based semiconductor device as claimed in claim 1, wherein said buffer layer has a thickness greater than 100 nanometers.

\* \* \* \* \*