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### HEMT and method of fabricating the same

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#### Abstract

A high electron mobility transistor includes a substrate. A channel layer is disposed on the substrate. An active layer is disposed on the channel layer. The active layer includes a P-type aluminum gallium nitride layer. A P-type gallium nitride gate is disposed on the active layer. A source electrode and a drain electrode are disposed on the active layer.

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## Background/Summary

CROSS REFERENCE TO RELATED APPLICATIONS (1) This application is a division of U.S. application Ser. No. 17/335,049, filed on May 31, 2021. The content of the application is incorporated herein by reference.

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

(1) The present invention relates to a high electron mobility transistor (HEMT) which has P-type dopants in an active layer to increase a threshold voltage.

### 2. Description of the Prior Art

(2) Due to their semiconductor characteristics, III-V semiconductor compounds may be applied in many kinds of integrated circuit devices, such as high power field effect transistors, high frequency transistors, or HEMTs. In the high electron mobility transistor, two semiconductor materials with different band-gaps are combined and a heterojunction is formed at the junction between the semiconductor materials as a channel for carriers. In recent years, gallium nitride (GaN) based materials have been applied in high power and high frequency products because of their properties of wider band-gap and high saturation velocity.

(3) A two-dimensional electron gas (2DEG) may be generated by the piezoelectric property of the GaN-based materials, and the switching velocity may be enhanced because of the higher electron velocity and the higher electron density of the 2DEG.

(4) A normally-off HEMT often uses a P-type gallium nitride gate to form a depletion region within a channel layer to increase a threshold voltage. However, when a concentration of P-type dopants within the P-type gallium nitride gate is too high, current leakage occurs and flows from a gate electrode to the channel layer.

## SUMMARY OF THE INVENTION

(5) In light of above, a new structure of an HEMT is provided to solve the above-mentioned problem.

(6) According to a preferred embodiment of the present invention, an HEMT includes a substrate. A channel layer is disposed on the substrate. An active layer is disposed on the channel layer, wherein the active layer includes a P-type aluminum gallium nitride layer. A P-type gallium nitride gate is disposed on the active layer and a source electrode and a drain electrode are disposed on the active layer.

(7) According to another preferred embodiment of the present invention, a fabricating method of an HEMT includes providing a substrate. Later, a channel layer is formed to be disposed on the substrate. After that, an active layer is formed to be disposed on the channel layer, wherein the active layer includes a P-type aluminum gallium nitride layer. Next, a p-type gallium nitride gate is formed to be disposed on the active layer. Finally, a source electrode and a drain electrode are formed to be disposed on the active layer.

(8) These and other objectives of the present invention will no doubt become obvious to those of ordinary skill in the art after reading the following detailed description of the preferred embodiment that is illustrated in the various figures and drawings.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIG. 1 depicts an HEMT according to a preferred embodiment of the present invention.

(2) FIG. 2 depicts a concentration profile of P-type dopants within a P-type gallium nitride gate, an active layer and a channel layer taken along line AA' in FIG. 1 according to a preferred embodiment of the present invention.

(3) FIG. 3 depicts a concentration profile of P-type dopants within a P-type gallium nitride gate, an

active layer and a channel layer taken along line AA' in FIG. 1 according to another preferred embodiment of the present invention.

(4) FIG. 4 depicts a concentration profile of P-type dopants within a P-type gallium nitride gate, an active layer and a channel layer taken along line AA' in FIG. 1 according to yet another preferred embodiment of the present invention.

(5) FIG. 5 depicts an HEMT according to a second preferred embodiment of the present invention.

(6) FIG. 6 depicts a concentration profile of P-type dopants within a P-type gallium nitride gate, an active layer and a channel layer taken along line BB' in FIG. 5 according to a preferred embodiment of the present invention.

(7) FIG. 7 depicts a concentration profile of P-type dopants within a P-type gallium nitride gate, an active layer and a channel layer taken along line BB' in FIG. 5 according to another preferred embodiment of the present invention.

(8) FIG. 8 depicts a fabricating method of an HEMT according to a preferred embodiment of the present invention.

(9) FIG. 9 depicts a fabricating method of an HEMT according to another preferred embodiment of the present invention.

#### DETAILED DESCRIPTION

(10) FIG. 1 depicts a high electron mobility transistor (HEMT) according to a preferred embodiment of the present invention.

(11) As shown in FIG. 1, a normally-off HEMT **100** includes a substrate **10**. A nucleation layer **12** is disposed on the substrate **10**. A channel layer **14** is disposed on the nucleation layer **12**. An active layer **16** is disposed on the channel layer **14** and contacts the channel layer **14**. A second surface **S2** is defined as a surface where the active layer **16** contacts the channel layer **14**. The active layer **16** is a P-type aluminum gallium nitride layer. The P-type aluminum gallium nitride layer refers to an aluminum gallium nitride layer with P-type dopants. The P-type dopants include C, Mg, Zn or Fe. In this embodiment, the P-type dopants are preferably Mg. A P-type gallium nitride gate **18** is disposed on the active layer **16**. A first surface **S1** is defined as a surface where the P-type gallium nitride gate **18** contacts the active layer **16**. A protective layer **17** is disposed on the active layer **16** at two sides of the P-type gallium nitride gate **18**. A source electrode **20** and a drain electrode **22** are disposed on the active layer **16**. Two-dimensional electron gas (2DEG) **24** generates within the channel layer **14** which is not covered by the P-type gallium nitride gate **18**. The channel layer **14** includes gallium nitride, aluminum nitride, indium nitride, aluminum gallium nitride, indium gallium nitride or aluminum indium nitride. In this preferred embodiment, the channel layer **14** is preferably gallium nitride.

(12) FIG. 2 depicts a concentration profile of P-type dopants within a P-type gallium nitride gate, an active layer and a channel layer taken along line AA' in FIG. 1 according to a preferred embodiment of the present invention. FIG. 3 depicts a concentration profile of P-type dopants within a P-type gallium nitride gate, an active layer and a channel layer taken along line AA' in FIG. 1 according to another preferred embodiment of the present invention. FIG. 4 depicts a concentration profile of P-type dopants within a P-type gallium nitride gate, an active layer and a channel layer taken along line AA' in FIG. 1 according to yet another preferred embodiment of the present invention.

(13) As shown in FIG. 1 and FIG. 2, a gradient concentration of P-type dopants within the P-type aluminum gallium nitride layer decreases toward the channel layer **14**. That is, the concentration of P-type dopants within the P-type aluminum gallium nitride layer differs in different depths. The concentration of P-type dopants within the P-type gallium nitride gate **18** is higher than the concentration of P-type dopants within the active layer **16**. Moreover, P-type dopants within the P-type gallium nitride gate **18** are the same element as those within the active layer **16** such as Mg. There are no P-type dopants within the channel layer **14**. In other cases, there are small amount of P-type dopants diffused from the active layer **16**. Furthermore, a concentration of P-type dopants

within the active layer **16** is between  $1\text{E}16$  atoms/cm.sup.3 and  $1\text{E}19$  atoms/cm.sup.3. A concentration of P-type dopants within the active layer **16** is 5% to 20% of a concentration of P-type dopants within the P-type gallium nitride gate **18**. According to a preferred embodiment of the present invention, a concentration of P-type dopants within the active layer **16** is 6% to 12% of a concentration of P-type dopants within the P-type gallium nitride gate **18**.

(14) As shown in FIG. 3, a concentration of P-type dopants within the active layer **16** decreases in a stair step profile toward the channel layer **14**. In other words, the concentration of P-type dopants decreases from the P-type gallium nitride gate **18** toward the channel layer **14** in a stepwise manner, wherein the stepwise manner includes steps A1/A2, and the steps A1/A2 constitute a stair A going down from the P-type gallium nitride gate **18** to the channel layer **14**. In details, the concentration of P-type dopants within the active layer **16** is the same in all depths. Other element conditions such as the concentration of P-type dopants or types of P-type dopants are the same as those in the FIG. 2, and therefore descriptions are omitted here.

(15) As shown in FIG. 4, a concentration of P-type dopants within the active layer **16** decreases in a stair step profile toward the channel layer **14**. Depth in different ranges within the active layer **16** respectively corresponds to a concentration of P-type dopants in the active layer **16**. In details, there are two ranges of depth in this embodiment, and these two ranges respectively correspond to a fixed concentration of P-type dopants. Other element conditions such as the concentration of P-type dopants or types of P-type dopants are the same as those in the FIG. 2, and therefore description are omitted here.

(16) FIG. 5 depicts an HEMT according to a second preferred embodiment of the present invention, wherein elements which are substantially the same as those in the first preferred embodiment are denoted by the same reference numerals; an accompanying explanation is therefore omitted. As shown in FIG. 5, the difference between the HEMT **200** and the HEMT **100** is that an active layer **116** of the HEMT **200** includes a P-type aluminum gallium nitride layer **116a** and an undoped aluminum gallium nitride layer **116b**. On the other hand, the active layer **16** in the first preferred embodiment only includes a P-type aluminum gallium nitride layer. Please still refer to FIG. 5. The undoped aluminum gallium nitride layer **116b** is disposed between the P-type aluminum gallium nitride layer **116a** and the channel layer **14**. A width W2 of the undoped aluminum gallium nitride layer **116b** is the same as a width W1 of the P-type aluminum gallium nitride layer **116a**. Other elements are the same as those in the first preferred embodiment, and therefore description are omitted here.

(17) FIG. 6 depicts a concentration profile of P-type dopants within a P-type gallium nitride gate, an active layer and a channel layer taken along line BB' in FIG. 5 according to a preferred embodiment of the present invention. FIG. 7 depicts a concentration profile of P-type dopants within a P-type gallium nitride gate, an active layer and a channel layer taken along line BB' in FIG. 5 according to another preferred embodiment of the present invention.

(18) As shown in FIG. 6, a gradient concentration of P-type dopants within the P-type aluminum gallium nitride layer **116a** decreases toward the channel layer **14**. That is, the concentration of P-type dopants within the P-type aluminum gallium nitride layer **116a** differs in different depths. The concentration of P-type dopants within the P-type gallium nitride gate **18** is higher than the concentration of P-type dopants within the P-type aluminum gallium nitride layer **116a**. Moreover, a concentration of the P-type dopants within the undoped aluminum gallium nitride layer **116b** of the active layer **116** is 0. Moreover, P-type dopants within the P-type gallium nitride gate **18** are the same element as those within the P-type aluminum gallium nitride layer **116a** such as Mg. There are no P-type dopants within the channel layer **14**. Furthermore, a concentration of P-type dopants within the P-type aluminum gallium nitride layer **116a** is between  $1\text{E}16$  atoms/cm.sup.3 and  $1\text{E}19$  atoms/cm.sup.3. A concentration of P-type dopants within the P-type aluminum gallium nitride layer **116a** is 5% to 20% of a concentration of P-type dopants within the P-type gallium nitride gate **18**. According to a preferred embodiment of the present invention, a concentration of P-type

dopants within the P-type aluminum gallium nitride layer **116a** is 6% to 12% of a concentration of P-type dopants within the P-type gallium nitride gate **18**.

(19) As shown in FIG. 7, a concentration of P-type dopants within the P-type aluminum gallium nitride layer **116a** decreases in a stair step profile toward the channel layer **14**. The concentration of P-type dopants within the P-type aluminum gallium nitride layer **116a** is the same in all depths. A concentration of P-type dopants in the undoped aluminum gallium nitride layer **116b** is 0. Other element conditions such as concentration of P-type dopants or types of P-type dopants in the P-type aluminum gallium nitride layer **116a** are the same as those in the FIG. 6, and therefore description are omitted here.

(20) FIG. 8 depicts a fabricating method of an HEMT according to a preferred embodiment of the present invention, wherein elements which are substantially the same as those in the first and second preferred embodiments are denoted by the same reference numerals; an accompanying explanation is therefore omitted.

(21) As shown in FIG. 8, a fabricating method of an HEMT includes providing a substrate **10**. Then, a nucleation layer **12** is formed to cover the substrate **10**. Later, a channel layer **14** is formed on the substrate **10**. After that, an undoped aluminum gallium nitride layer **216** is formed on the channel layer **14**. Subsequently, a P-type gallium nitride layer **18a** is formed to cover the undoped aluminum gallium nitride layer **216**. Please refer to both FIG. 8 and FIG. 5. Some of P-type dopants within the P-type gallium nitride layer **18a** are diffused into the undoped aluminum gallium nitride layer **216** to transform the undoped aluminum gallium nitride layer **216** into a P-type aluminum gallium nitride layer **116a** while forming the P-type gallium nitride layer **18a**. P-type dopants can be merely diffused into part of the region along the depth of the undoped aluminum gallium nitride layer **216**. The region of the undoped aluminum gallium nitride layer **216** where P-type dopants not diffused into becomes an undoped aluminum gallium nitride layer **116b**. In this way, a concentration profile shown in FIG. 6 can be achieved. Alternatively, as shown in FIG. 1 and FIG. 8, P-type dopants can be diffused into an entirety of the undoped aluminum gallium nitride layer **216** to transform all the undoped aluminum gallium nitride layer **216** to the P-type aluminum gallium nitride layer, i.e. the active layer **16** in FIG. 1. In this way, a concentration profile shown in FIG. 2 can be achieved. According to a preferred embodiment of the present invention, P-type dopants are diffused under a fabricating temperature greater than 600° C., and preferably greater than 1000° C. After that, as shown in FIG. 1 or FIG. 5, the P-type gallium nitride layer **18a** is patterned to form a P-type gallium nitride gate **18**. Later, a source electrode **20** and a drain electrode **22** are formed to be disposed on the active layer **16**/active layer **116**.

(22) According to another preferred embodiment of the present invention, steps of diffusing P-type dopants can be performed after the P-type gallium nitride layer **18a** is completed. After forming the P-type gallium nitride layer **18a**, some P-type dopants within the P-type gallium nitride layer **18a** are diffused into the undoped aluminum gallium nitride layer **216** to transform the undoped aluminum gallium nitride layer **216** into the P-type aluminum gallium nitride layer. Similarly, P-type dopants can be merely diffused into part of the region along the depth of the undoped aluminum gallium nitride layer **216**. Alternatively, P-type dopants can be diffused into an entirety of the undoped aluminum gallium nitride layer **216**. P-type dopants are diffused under a fabricating temperature greater than 600° C. After the P-type aluminum gallium nitride layer is formed, a P-type gallium nitride gate **18**, a source electrode **20** and a drain electrode **22** are formed.

(23) FIG. 9 depicts a fabricating method of an HEMT according to another preferred embodiment of the present invention. The difference between FIG. 8 and FIG. 9 is that the P-type aluminum gallium nitride layer **316** is formed by a chemical vapor deposition process including providing P-type dopants and in-situ doping P-type dopants to form the P-type aluminum gallium nitride layer **316**, rather than diffusing P-type dopants within the P-type gallium nitride layer. In other words, the P-type gallium nitride layer is formed after forming the P-type aluminum gallium nitride layer **316**. In addition, an undoped aluminum gallium nitride layer (not shown) can be formed optionally

before forming the P-type aluminum gallium nitride layer **316**. By altering the timing to input P-type dopants and the flow rate of P-type dopants, a concentration profile of P-type dopants within the P-type aluminum gallium nitride layer **316** can be changed. For example, in the case of all of the P-type aluminum gallium nitride layer **316** containing P-type dopants, the P-type aluminum gallium nitride layer **316** can serve as the active layer **16** in FIG. **1**. In the case that an undoped aluminum gallium nitride layer (not shown) is below the P-type aluminum gallium nitride layer **316**, the P-type aluminum gallium nitride layer **316** and the undoped aluminum gallium nitride layer can respectively serve as the P-type aluminum gallium nitride layer **116a** and the undoped aluminum gallium nitride layer **116b** in FIG. **5**. In other words, a concentration profile in FIG. **2**, FIG. **3**, FIG. **4**, FIG. **6** and FIG. **7** can be reached by combining the P-type aluminum gallium nitride layer **316** with an optional undoped aluminum gallium nitride layer. In detail, by controlling flow rate of P-type dopants during the chemical vapor deposition process, the P-type aluminum gallium nitride layer **316** with an optional undoped aluminum gallium nitride layer can be formed. Later, as shown in FIG. **1** or FIG. **5**, the P-type gallium nitride layer is patterned to form the P-type gallium nitride gate **18**. Subsequently, a source electrode **20** and a drain electrode **22** are formed. (24) The present invention adds P-type dopants into the active layer of the HEMT. In this way, a threshold voltage of the HEMT can be increased. The depth of P-type dopants can be adjusted based on product requirements. The deeper P-type dopants are, i.e. the P-type dopants are closer to the channel layer, the higher threshold voltage of the HEMT becomes. However, when the depth of P-type dopants is deeper, the on-resistance of the HEMT is also raised. Therefore, the depth of P-type dopants can be adjusted to control the device function based on different product requirements.

(25) Those skilled in the art will readily observe that numerous modifications and alterations of the device and method may be made while retaining the teachings of the invention. Accordingly, the above disclosure should be construed as limited only by the metes and bounds of the appended claims.

## Claims

1. A high electron mobility transistor (HEMT), comprising: a substrate; a channel layer disposed on the substrate; an active layer disposed on the channel layer, wherein the active layer is a P-type aluminum gallium nitride layer; a P-type gallium nitride gate disposed on the active layer, wherein a concentration of P-type dopants within the P-type gallium nitride gate, within the active layer and within the channel layer decreases from the P-type gallium nitride gate toward the channel layer in a stepwise manner, and among an entirety of the P-type aluminum gallium nitride layer, a concentration of P-type dopants in the P-type aluminum gallium nitride layer which is closer to the channel layer is less than the concentration of P-type dopants in the P-type aluminum gallium nitride layer which is farther from the channel layer; and a source electrode and a drain electrode disposed on the active layer.
2. The HEMT of claim 1, wherein the P-type aluminum gallium nitride layer contacts the channel layer.
3. The HEMT of claim 1, wherein the concentration of P-type dopants within the P-type aluminum gallium nitride layer is between  $1\text{E}16$  atoms/cm.<sup>3</sup> and  $1\text{E}19$  atoms/cm.<sup>3</sup>.
4. The HEMT of claim 1, wherein the concentration of P-type dopants within the P-type aluminum gallium nitride layer is 6% to 12% of a concentration of P-type dopants within the P-type gallium nitride gate.
5. The HEMT of claim 1, wherein P-type dopants within the P-type aluminum gallium nitride layer comprise C, Mg, Zn or Fe.
6. The HEMT of claim 1, wherein the stepwise manner comprises a plurality of steps, and the steps constitute a stair going down from the P-type gallium nitride gate to the channel layer.

7. A high electron mobility transistor (HEMT), comprising: a substrate; a channel layer disposed on the substrate; an active layer disposed on the channel layer, wherein the active layer is a P-type aluminum gallium nitride layer; a P-type gallium nitride gate disposed on the active layer, wherein a concentration of P-type dopants within the P-type gallium nitride gate, within the active layer and within the channel layer decreases from the P-type gallium nitride gate toward the channel layer in a stepwise manner, and the channel layer, the active layer and the P-type gallium nitride gate are stacked from bottom to top in a listed sequence, and wherein among an entirety of the P-type aluminum gallium nitride layer, a concentration of P-type dopants in the P-type aluminum gallium nitride layer which is closer to the channel layer is less than the concentration of P-type dopants in the P-type aluminum gallium nitride layer which is farther from the channel layer; and a source electrode and a drain electrode disposed on the active layer.

8. The HEMT of claim 7, wherein the P-type aluminum gallium nitride layer contacts the channel layer.

9. The HEMT of claim 7, wherein the concentration of P-type dopants within the P-type aluminum gallium nitride layer is between  $1 \times 10^{16}$  atoms/cm.<sup>3</sup> and  $1 \times 10^{19}$  atoms/cm.<sup>3</sup>.

10. The HEMT of claim 7, wherein the concentration of P-type dopants within the P-type aluminum gallium nitride layer is 6% to 12% of a concentration of P-type dopants within the P-type gallium nitride gate.

11. The HEMT of claim 7, wherein P-type dopants within the P-type aluminum gallium nitride layer comprise C, Mg, Zn or Fe.

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