

**GALLIUM NITRIDE HIGH ELECTRON MOBILITY TRANSISTORS (HEMTs)
HAVING REDUCED CURRENT COLLAPSE AND POWER ADDED
EFFICIENCY ENHANCEMENT**

TECHNICAL FIELD

5 This disclosure relates generally to High Electron Mobility Transistors (HEMTs) and more particularly to Gallium Nitride (GaN) HEMTs having reduced current collapse and power added efficiency enhancement.

BACKGROUND OF THE INVENTION

10 As is known in the art, current collapse (or dispersion) in pulsed IV measurement is a leading indicator of RF performance and power added efficiency (PAE) of a high frequency HEMT transistor. Gallium nitride (GaN) based HEMTs are prone to high levels of current collapse (CC). The geometry of the device structure, surface passivation, and the epitaxial structure of HEMTs all contribute to the CC. In terms of the epitaxial
15 structure, the doping schemes used in the GaN buffer layer and/or barrier, the density and location of defects (such as impurity atoms or dislocations), and the quality of layer interfaces have particular impact on the CC. One such HEMT epitaxial structure is shown in FIG. 1. Here the structure includes:

A Substrate, such as Si, Al_2O_3 , or SiC;

20 A Nucleation layer, such as AlN or Graphene, may not be present;

A High-Resistivity (typically greater than $1 \times 10^5 \text{ ohm} \cdot \text{cm}$) GaN Buffer, typically doped such as to render GaN insulating (dopants such as carbon, magnesium, iron) with thickness 200 nm to several microns;

An Unintentionally Doped (UID) GaN Channel, no intentional dopants, typical
25 thickness 50-500nm, 2D electron gas (2DEG) resides near UID GaN Channel to barrier interface;

A Barrier layer, such as AlGa_xN_{1-x}, InAlN, InAlGa_xN_{1-x} (traditional III-Nitrides), or ScAlN (rare earth-Nitrides); and

A Cap Layer, such as GaN, AlN, or SiN_x, may not be present.

30 While CC reduction is critical, for highest performance, it should be simultaneously accompanied with low levels of gate leakage and drain leakage in the “off” state of the transistor, which has made the task of designing a low CC structure more elusive.

Gallium nitride and its related Group III-Nitride ternary and quaternary compounds have a high density of dislocations and other point defects due to the epitaxy of the material and lack of well suited lattice matched substrates. These defects induce current pathways through the buffer that are detrimental to both DC leakage and RF performance. Typically, in GaN HEMT structures, the buffer is heavily doped with carbon and/or iron impurities to mitigate the leakage in the epitaxial buffer. However, due to their close proximity to the 2DEG GaN channel, the carbon and iron impurity dopants also act as long lived traps, which may have lifetimes of microseconds, or longer, for charge carrier electrons in the 2DEG channel, significantly increasing the CC in the final HEMT device and negatively impacting performance.

As is also known in the art, theoretical calculations of the ionization energy of substitutional beryllium in GaN have estimated the ionization energy to be between 60 meV (see Bernardini et al., *Theoretical evidence for efficient p-type doping of GaN using beryllium*, arXiv:cond-mat/9610108v2 (1997)) and 550 meV (see J.L. Lyons et al., *Impact of Group-II Acceptors on the Electrical and Optical Properties of GaN*, Jpn. J. Appl. Phys. 52, 08JJ04 (2013)). In addition, interstitial beryllium has been calculated to have a low formation energy and to act as a double donor (see C. G. Van de Walle et al., *First-principles studies of beryllium doping of GaN*, Phys. Rev. B, 63, 245205 (2001)) that has the potential to lead to the compensation of substitutional beryllium acceptors. In practice, beryllium doped GaN material exhibits insulating behavior (see K. Lee et al., *Compensation in Be-doped Gallium Nitride Grown Using Molecular Beam Epitaxy*, Material Research Society Symposium, Proc. Vol. 892 (2006)) and has been used to mitigate the effects of conductive buffer layers in GaN HEMTs (see D.F. Storm et al., *Reduction of buffer layer conduction near plasma-assisted molecular-beam epitaxy grown GaN/AlN interfaces by beryllium doping*, Appl. Phys. Lett., 81, 3819 (2002)). While suitable as a buffer dopant, beryllium doping at 1×10^{19} atoms/cm³ has been shown to have deleterious effects on the 2DEG mobility, 2DEG sheet density, and transistor performance when the UID GaN layer is less than 200 nm thick (see D.F. Storm et al., *Proximity effects of beryllium-doped GaN buffer layers on the electronic properties of epitaxial AlGaIn/GaN heterostructures*, Solid-State Electronics., 54, 1470-1473 (2010)). Beryllium doping levels up to 3×10^{19} atoms/cm³ have been shown to cause no significant degradation of the GaN crystal quality (see D.F. Storm et al., *Growth and characterization of plasma-assisted molecular beam epitaxial-grown AlGaIn/GaN heterostructures on free-standing hydride*

vapor phase epitaxy GaN substrates, J. Vac. Sci. Technol. B., 23, 1190 (2005)), however, it is expected that higher levels of beryllium doping impurities will eventually cause a deterioration of the GaN crystal quality.

SUMMARY OF THE INVENTION

5 In accordance with the present disclosure, a High Electron Mobility Transistor structure is provided, comprising: a GaN buffer layer disposed on the substrate; a doped GaN layer disposed on, and in direct contact with, the buffer layer, such doped GaN layer being doped with more than one different dopants, where one of the dopants is beryllium; an unintentionally doped (UID) GaN channel layer on, and in direct contact with, the
10 doped GaN layer, such UID GaN channel layer having a two-dimensional electron gas (2DEG) channel therein.

In one embodiment, a barrier layer is disposed on, and in direct contact with, the UID GaN channel layer.

In one embodiment, one of the dopants is beryllium.

15 In one embodiment, one of the dopants is beryllium and another one of the dopants is carbon.

In one embodiment, the UID GaN channel layer has a thickness less than 200 nm.

In one embodiment, a High Electron Mobility Transistor structure is provided comprising: a substrate; a high-resistivity GaN buffer layer disposed on the substrate; a
20 doped GaN layer disposed on, and in direct contact with, the buffer layer, such doped GaN layer being doped with beryllium and carbon; an unintentionally doped (UID) GaN channel layer disposed on, and in direct contact with, the doped GaN layer, such UID GaN channel layer having a 2DEG channel therein; and an AlGaN barrier layer disposed on, and in direct contact with, the UID GaN channel layer.

25 In one embodiment, the UID GaN layer has a thickness less than 200 nm.

In one embodiment, the doped GaN layer has a thickness of 10-300 nm.

In one embodiment, the beryllium doping is 5×10^{16} to 3×10^{19} atoms/cm³ and the carbon doping is less than or equal to the beryllium doping.

30 In one embodiment, the buffer layer has a resistivity of greater than 2.2×10^3 ohm*cm.

In molecular beam epitaxy (MBE) methods, while carbon is a highly-effective compensating dopant with a number of near-mid-gap states that can drastically reduce DC

leakage when used on its own as a dopant in close proximity to a 2DEG channel, it also generates additional trap sites that increase CC and reduce RF performance. The inventors recognized that moderate levels of beryllium doping ranging from 5×10^{16} to 3×10^{19} atoms/cm³ in close proximity to a 2DEG channel is sufficient to shift the band structure of gallium nitride and its related group III-nitride ternary and quaternary compounds in the buffer layer. The inventors further recognized that by adding a reduced level of carbon impurities along with the beryllium impurities (carbon impurities < beryllium impurities) low levels of off state leakage can be obtained while simultaneously shifting the band structure of the buffer layer to reduce CC and enhance the PAE of the HEMT transistor in RF operation.

The inventors have recognized the epitaxial elements responsible for one source of CC in GaN HEMT structures and have an effective solution for overcoming it without adversely affecting the DC leakage of the device: exact placement of beryllium and carbon doped layers relative to the conductive 2DEG channel, accurately controlled thickness of the doped layers, and accurately controlled doping levels immediately below the 2DEG layer. The disclosure describes concurrently doping the GaN buffer immediately below the UID GaN channel with carbon and beryllium at various levels to overcome the electrically active carriers, without allowing the dopants in the buffer to act as high levels of active long lived traps, thus reducing the CC and keeping the off state leakages at low and manageable levels.

The details of one or more embodiments of the disclosure are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the disclosure will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagrammatical, cross-sectional sketch of a Group III-Nitride HEMT structure according to the PRIOR ART;

FIG. 2 is a diagrammatical, cross-sectional sketch of a Group III-Nitride HEMT structure according to the disclosure;

FIG. 3A is a diagrammatical, cross-sectional sketch of a Group III-Nitride HEMT structure without an additional doped layer between the UID GaN channel and the high resistivity GaN buffer, useful as comparison to the HEMT structure of FIG. 2;

FIG. 3B is a diagrammatical, cross-sectional sketch of a Group III-Nitride HEMT structure utilizing only carbon as a dopant in the doped layer between the UID GaN channel and high resistivity GaN buffer, useful as comparison to the HEMT structure of FIG. 2;

5 FIG. 3C is a diagrammatical, cross-sectional sketch of a Group III-Nitride HEMT structure utilizing both carbon and beryllium as dopants in the doped layer between the UID GaN channel and high resistivity GaN buffer, one embodiment of the HEMT structure of FIG. 2;

10 FIG. 4A is a plot of normalized drain leakage and gate leakage current versus drain-to-source voltage for the structure of FIG. 3A, without an additional doped layer, useful for understanding the benefits of the structure of FIG. 2;

FIG. 4B is a plot of normalized drain leakage and gate leakage current versus drain-to-source voltage for the structure of FIG. 3B, utilizing only carbon doping in the doped layer, useful for understanding the benefits of the structure of FIG. 2;

15 FIG. 4C is a plot of normalized drain leakage and gate leakage current versus drain-to-source voltage for the structure of FIG. 3C, utilizing both carbon and beryllium as dopants in the doped layer in one embodiment of the HEMT structure of FIG. 2;

20 FIG. 5A is a plot of normalized drain current versus drain-to-source voltage for a quasi-static configuration and a 28V pulsed configuration highlighting the impact of current collapse for the structure of FIG. 3A, without an additional doped layer, useful for understanding the benefits of the structure of FIG. 2;

25 FIG. 5B is a plot of normalized drain current versus drain-to-source voltage for a quasi-static configuration and a 28V pulsed configuration highlighting the impact of current collapse for the structure of FIG. 3B, utilizing only carbon in the doped layer, useful for understanding the benefits of the structure of FIG. 2;

FIG. 5C is a plot of normalized drain current versus drain-to-source voltage for a quasi-static configuration and a 28V pulsed configuration highlighting the impact of current collapse for the structure of FIG. 3C, utilizing both carbon and beryllium as dopants in the doped layer in one embodiment of the HEMT structure of FIG. 2.

30 Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

Referring now to FIG. 2, a HEMT structure is shown having: a single crystal substrate, here, for example, Silicon, Sapphire, or Silicon Carbide; a nucleation layer, here, for example, AlN or Graphene formed epitaxially on the substrate; a doped high resistivity GaN buffer layer formed epitaxially on the nucleation layer, here such buffer layer being doped with, for example, beryllium doped GaN to have a resistivity of $2.2 \times 10^3 \text{ ohm*cm}$ (for $5 \times 10^{18} \text{ atoms/cm}^3$ doping), iron doped GaN to have a resistivity of $3 \times 10^5 \text{ ohm*cm}$ (see R.P. Vaudo et al., *Characteristics of semi-insulating, Fe-doped GaN substrates*, Physical Status Solidi 200, 18 (2003)), carbon doped GaN to have a resistivity of $1 \times 10^8 \text{ ohm*cm}$, or combination of dopants that result in high resistivity GaN; a doped GaN layer, having a thickness of 10-300 nm and having more than one dopant, here having: a beryllium dopant having a doping concentration in a range of 5×10^{16} to $3 \times 10^{19} \text{ atoms/cm}^3$; and, a carbon dopant having a doping concentration less than the doping concentration of the beryllium, but higher than $1 \times 10^{16} \text{ atoms/cm}^3$. The doping levels result from the co-deposition of beryllium and carbon impurities during the epitaxial growth of the doped GaN layer. Formed epitaxially on the doped GaN layer is an unintentionally doped (UID) GaN channel layer having a thickness of 50-200 nm and having a two-dimensional electron gas (2DEG) within. Formed epitaxially on the UID GaN layer is a barrier layer, such as AlGa_N, InAlGa_N, or ScAlN. The optimal doping density, within the ranges provided, is dependent on the thickness of the UID GaN channel layer and the charge density in the channel as controlled by the barrier material composition and thickness.

Referring now to FIGS. 3A, 3B and 3C, three HEMT structures are shown for purposes of comparison. All three structures utilize identical substrate, nucleation layer, and high resistivity GaN buffer layer structures, here SiC, AlN, and carbon and beryllium doped GaN, respectively. The structure shown in FIG. 3A has no doped layer between the UID GaN channel and high resistivity GaN buffer, achieved via a 300 nm UID channel thickness on, and in direct contact with, the high resistivity buffer layer. The structure shown in FIG. 3B has only carbon doping in the doped layer, here with a thickness of 165 nm and doped with a carbon density of $1.2 \times 10^{17} \text{ atoms/cm}^3$, between the UID GaN channel, here with a thickness of 110 nm, and high resistivity GaN buffer. The structure shown in FIG. 3C has both carbon and beryllium doping in the doped layer, here with a thickness of 165 nm and carbon doping density of $1.4 \times 10^{17} \text{ atoms/cm}^3$ and beryllium doping density of $1.2 \times 10^{18} \text{ atoms/cm}^3$, between the UID GaN channel, here with a

thickness of 110 nm, and high resistivity GaN buffer. Here, the structures in FIGS. 3A, 3B, and 3C are grown by molecular beam epitaxy (MBE). The doped GaN layers in this particular example are formed under nitrogen-rich conditions with predetermined flux ratios of gallium, nitrogen, and dopants and predetermined growth temperatures, here 660-780°C as measured by an optical pyrometer, that result in the desired dopant concentrations. While nitrogen-rich conditions are used here, gallium-rich conditions may also be used, although with different predetermined flux ratios and/or growth temperature. Here, beryllium is doped via thermal evaporation from a solid elemental beryllium source and carbon is doped via a CBr₄ gas source.

Referring now to FIGS. 4A, 4B and 4C, normalized drain and gate leakages are shown for three terminal source-gate-drain lateral transistors, with ohmic source and drain contacts and a Schottky gate contact, fabricated from the epitaxial structures shown in FIGS. 3A, 3B and 3C, respectively. More particularly, DC measurements of three terminal source-gate-drain lateral transistors of the drain current and gate current with the gate pinched off at -6V on the gate for varying drain-to-source voltages are shown. The “ideal” is for both the drain and gate leakage current to be as low as possible. Data is normalized to the drain leakage current at 100V for the structure shown in FIG. 3C. The structure shown in FIG. 3A, without a doped layer between the UID GaN and high resistivity buffer, shows high leakage current (~3-10x the leakage current of the structure shown in FIG. 3C). The structure shown in FIG. 3B with only carbon doping in the doped layer, shows a leakage current that is low and similar to the leakage current of the structure shown in FIG. 3C; the structure in FIG. 3C having both carbon and beryllium dopants in the doped layer.

Referring to FIGS. 5A, 5B and 5C, pulsed IV measurements are shown for the transistors fabricated from the epitaxial structures shown in FIGS. 3A, 3B and 3C, respectively. For the quasi-static curve, the quiescent bias point is $V_{DQ} = V_{GQ} = 0$ V. For the 28 V_{DQ} curve, the quiescent bias point is $V_{DQ} = 28$ V, $I_{DQ} = 110$ mA. “Ideal” is to minimize the shaded area, a measure of current collapse (or dispersion), to zero. The data is normalized to the quasi-static drain current at 15 V for the structure shown in FIG. 3C. The structure shown in FIG. 3A, without a doped layer between the UID GaN and high resistivity buffer, shows the current collapse is low (but this is the result of high leakage as shown in FIG. 4A). The structure shown in FIG. 3B, which has only carbon doping in the doped layer, shows relatively high current collapse as compared with the current collapse

of the structure shown in FIG. 3C, which has both carbon and beryllium doping in the doped layer, as shown in FIG. 5C. Thus, the structure shown in FIG. 3C, with both carbon and beryllium doping in the doped layer, has both a very low current collapse and low leakage.

5 It should now be appreciated a high electron mobility transistor structure according to the disclosure includes: a GaN buffer layer disposed on the substrate; a doped GaN layer disposed on, and in direct contact with, the buffer layer, such doped GaN layer being doped with multiple different dopants where one of the dopants is beryllium; an unintentionally doped (UID) GaN channel layer on, and in direct contact with, the doped
10 GaN layer, such UID GaN channel layer having a 2DEG channel therein. The high electron mobility transistor structure may include one or more of the following features, both individually or in combination, to include: a barrier layer on, and in direct contact with, the UID GaN channel layer; wherein the UID GaN channel layer has a thickness less than 200 nm; wherein one of the dopants is carbon; or a nucleation layer disposed on the
15 substrate.

 It should now also be appreciated a high electron mobility transistor structure according to the disclosure includes: a substrate; a GaN buffer layer disposed on the substrate; a doped GaN layer disposed on, and in direct contact with, the buffer layer, such doped GaN layer being doped with beryllium and carbon; and an unintentionally
20 doped (UID) GaN channel layer on, and in direct contact with, the doped GaN layer, such UID GaN channel layer having a 2DEG channel therein. The high electron mobility transistor structure may include one or more of the following features, both individually or in combination, to include: wherein the UID GaN layer has a thickness less than 200 nm; wherein the doped GaN layer has a thickness of 10-300 nm; wherein the beryllium doping
25 is 5×10^{16} to 3×10^{19} atoms/cm³ and the carbon doping is less than or equal to the beryllium doping; or a barrier layer on, and in direct contact with, the UID GaN channel layer.

 A number of embodiments of the disclosure have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the disclosure. For example, one may utilize a stepped or graded doping
30 profile within the doped GaN layer. Also, for example, while doped GaN has been described, it should be understood that other group III-N doped materials may be used such as doped AlGaIn. Similarly, the use of different group III-N barrier, channel, or buffer layer materials than GaN and AlGaIn may be used, including, for example, composite

barriers with more than one material or composition of barrier material (such as AlGa_N/InAl_N or InAlGa_N. Additionally, alternate doping sources such as solid source carbon may be used. Further, the disclosure does not depend on the use of any specific substrate, nucleation layer, or high-resistivity buffer dopant. Accordingly, other

5 embodiments are within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A High Electron Mobility Transistor structure, comprising:
 - a GaN buffer layer disposed on the substrate;
 - 5 a doped GaN layer disposed on, and in direct contact with, the buffer layer, such doped GaN layer being doped with multiple different dopants where one of the dopants is beryllium; and
 - an unintentionally doped (UID) GaN channel layer on, and in direct contact with, the doped GaN layer, such UID GaN channel layer having a 2DEG channel
 - 10 therein.
2. The structure recited in claim 1 including a barrier layer on, and in direct contact with, the UID GaN channel layer.
- 15 3. The structure recited in claim 2 wherein the UID GaN channel layer has a thickness less than 200 nm.
4. The structure recited in claim 1 wherein one of the dopants is carbon.
- 20 5. The structure recited in claim 1 including a nucleation layer disposed on the substrate.
6. A High Electron Mobility Transistor structure, comprising:
 - a substrate;
 - 25 a GaN buffer layer disposed on the substrate;
 - a doped GaN layer disposed on, and in direct contact with, the buffer layer, such doped GaN layer being doped with beryllium and carbon; and
 - an unintentionally doped (UID) GaN channel layer on, and in direct contact with, the doped GaN layer, such UID GaN channel layer having a 2DEG channel
 - 30 therein..
7. The structure recited in claim 6 wherein the UID GaN layer has a thickness less than 200 nm.

8. The structure recited in claim 6 wherein the doped GaN layer has a thickness of 10-300 nm.

5 9. The structure recited in claim 6 wherein the beryllium doping is 5×10^{16} to 3×10^{19} atoms/cm³ and the carbon doping is less than or equal to the beryllium doping.

10 10. The structure recited in claim 6 including a barrier layer on, and in direct contact with, the UID GaN channel layer.