Title: ELECTRODE FOR P-TYPE GALLIUM NITRIDE-BASED SEMICONDUCTORS

Abstract: An improved electrode for a p-type gallium nitride based semiconductor material is disclosed that includes a layer of an oxidized metal and a first and a second layer of a metallic material. The electrode is formed by depositing three or more metallic layers over the p-type semiconductor layer such that at least one metallic layer is in contact with the p-type semiconductor layer. At least two of the metallic layers are then subjected to an annealing treatment in the presence of oxygen to oxidize at least one of the metallic layers to form a metal oxide. The electrodes provide good ohmic contacts to p-type gallium nitride-based semiconductor materials and, thus, lower the operating voltage of gallium nitride-based semiconductor devices.
ELECTRODE FOR P-TYPE GALLIUM NITRIDE-BASED SEMICONDUCTORS

RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/389,750, filed June 17, 2002 and U.S. Provisional Application No. 60/393,008, filed June 28, 2002. This application is a continuation of U.S. Application No. 10/187,465, filed June 28, 2002. This application is a continuation-in-part of U.S. Application No. 10/187,466, filed June 28, 2002 and U.S. Application No. 10/187,468, filed June 28, 2002. This application is related to U.S. Provisional Application: Domain Epitaxy for Thin Film Growth, by Jagdish Narayan, filed concurrently herewith under Attorney Docket No. 0717.2033-001. The entire teachings of the above applications are incorporated herein by reference.

BACKGROUND OF THE INVENTION

Recently, much attention has been focused on GaN-based compound semiconductors (e.g., In_{x}Al_{y}Ga_{1-x-y}N, wherein x + y ≤ 1, 0 ≤ x ≤ 1, and 0 ≤ y ≤ 1) for blue, green, and ultraviolet light emitting diode (LED) applications. One important reason is that GaN-based LEDs have been found to exhibit efficient light emission at room temperature.

In general, GaN-based LEDs comprise a multilayer structure in which n-type and p-type GaN-based semiconductor layers are stacked on a substrate (most commonly on a sapphire substrate with the n-type GaN-based semiconductor layer in contact with the substrate), and In_{x}Ga_{1-x}N/GaN multiple quantum well layers are sandwiched between the p-type and n-type GaN layers. A number of methods for growing the multilayer structure are known in the art, including metalorganic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE) and hydride vapor phase epitaxy (HVPE).

In general, p-type GaN-based semiconductor layers formed by growth methods, such as MOCVD, behave like a semi-insulating or high-resistive material.
This is thought to result from hydrogen passivation caused by hydrogen that is present in the reaction chamber complexing with the p-type dopant and thus preventing the dopant from behaving as an active carrier. Typically, p-type GaN-based semiconductor materials are thermally annealed to activate the p-type carriers. However, even after thermal annealing, the resistivity of p-type GaN-based semiconductor materials remains relatively high making it difficult to form a satisfactory ohmic contact with the material. In addition, there are few metals with a high work function comparable to the band gap and electron affinity of gallium nitride and that will form a low resistance interface with gallium nitride. A good ohmic contact to gallium nitride is desirable because the performance of gallium nitride-based devices, such as the operating voltage is strongly influenced by the contact resistance.

Sapphire is generally used as the substrate for GaN-based LEDs because it is inexpensive and GaN-based semiconductor layers grown on a sapphire substrate are reasonably free of defects. However, sapphire is electrically insulative. Thus, electrodes cannot be mounted on the sapphire substrate, but must be formed directly on the n-type and p-type GaN-based semiconductor layers. In addition, since p-type GaN-based semiconductor layers have only moderate conductivity, a p-electrode typically is formed to cover substantially the entire surface of the p-type GaN-based semiconductor layer in a GaN-based LED in order to ensure uniform application of current to the entire layer and obtaining uniform light emission from the LED. However, this geometry requires that the light emitted by the LED be observed through the sapphire substrate or through a transparent p-electrode. Typically, light-transmitting electrodes transmit only 20 to 40% of the light emitted from the LED. Although sapphire has a high transmission coefficient, observation of the light emitted from the LED through the sapphire substrate requires a complicated packaging step. Thus, in order to decrease the cost of manufacture and increase the efficiency of GaN-based LEDs, it is desirable to develop p-electrodes that have improved light transmission.
SUMMARY OF THE INVENTION

The invention is an improved electrode for a p-type gallium nitride based semiconductor material that includes a layer of an oxidized metal and a first and a second layer of a metallic material. The first metallic layer has a first surface in contact with a p-type gallium nitride based semiconductor material and a second surface in contact with a first surface of the oxidized metal layer. The oxidized metal layer has a second surface in contact with a surface of the second metallic layer. Preferably, the electrode is light transmissive. In one embodiment, the oxidized metal layer is nickel oxide and the first and second metallic layers are gold.

The electrode of the invention can be used to form a semiconductor device, such as a light-emitting diode (LED) or a laser diode (LD). The semiconductor device includes a substrate having a first major surface. Over the first major surface of the substrate is a semiconductor device structure that includes an n-type gallium nitride-based semiconductor layer, and a p-type gallium nitride-based semiconductor layer over the n-type semiconductor layer. A first electrode is in electrical contact with the n-type semiconductor layer, and a second electrode in contact with the p-type semiconductor layer. The second electrode includes a layer of an oxidized metal and a first and a second layer of a metallic material. The first metallic layer has a first surface in contact with a p-type gallium nitride based semiconductor material and a second surface in contact with a first surface of the oxidized metal layer. The oxidized metal layer has a second surface in contact with a surface of the second metallic layer. Preferably, the second electrode is light transmissive and forms an ohmic contact with the p-type semiconductor layer. The oxidized metal layer includes metal oxides such as nickel oxide and zinc oxide. The oxidized metal layer is preferably nickel oxide. Typically, the layer of metallic material includes metals such as gold, nickel, palladium, platinum, silver, and combinations thereof. In one embodiment, the first and second metallic layers are substantially the same. Preferably, the first and second metallic layers are gold.

To prepare semiconductor devices utilizing the electrode of the invention, a substrate having a first major surface is provided, and a semiconductor device structure is provided over the first major surface of the substrate. The
semiconductor device structure includes an n-type gallium nitride-based semiconductor layer and a p-type gallium nitride-based semiconductor layer over the n-type semiconductor layer. An electrode is formed that is in electrical contact with the n-type gallium nitride-based semiconductor layer. Three or more metallic layers are formed over the p-type semiconductor layer such that at least one metallic layer is in contact with the p-type semiconductor layer. At least two of the metallic layers are then subjected to an annealing treatment in the presence of oxygen to form an electrode in contact with the p-type gallium nitride-based semiconductor layer. Generally, the annealing treatment is conducted at a temperature that is about 400°C or more but below the decomposition temperature of the GaN-based semiconductor layers. Preferably the annealing temperature is in the range of between about 400 °C and about 550 °C. In one embodiment, the annealing treatment is preformed in an environment that includes oxygen and nitrogen. After the annealing treatment, the electrode formed is typically light transmissive. In one embodiment, prior to the annealing treatment, the electrode has a first metallic layer having a first surface is formed in contact with the p-type semiconductor layer, and a second metallic layer having a first surface is formed in contact with a second surface of the first metallic layer. After annealing the second metallic layer is substantially oxidized to a metal oxide. A third metallic layer is then formed in contact with a second surface of the metal oxide layer. Preferably, prior to the annealing treatment, the first metallic layer includes gold and the second metallic layer includes nickel. After annealing the second metallic layer is substantially oxidized to nickel oxide, and a third metallic layer is formed over the metal oxide. Preferably, the third metallic layer is gold. In another embodiment, prior to the annealing treatment, three metallic layers are formed over the p-type semiconductor material. The first metallic layer has a first surface in contact with the p-type semiconductor layer; the second metallic layer has a first surface in contact with a second surface of the first material; and the third metallic layer has a surface in contact with a second surface of the second metallic material. In one embodiment, the third metallic layer is substantially the same metallic material as the first metallic layer. In a preferred embodiment, the first and
third layers include gold and the second layer includes nickel which is substantially oxidized to nickel oxide during the annealing treatment.

The electrodes of the invention form ohmic contacts with p-type GaN-based semiconductor materials and typically are more light transmissive than prior art electrodes used to form ohmic contacts with p-type GaN-based semiconductor materials which do not contain metal oxides.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a current-voltage curve for an electrode formed by the method described in Example 1.

Fig. 2 is a current-voltage curve for an electrode formed by the method described in Example 2.

DETAILED DESCRIPTION OF THE INVENTION

As used herein, a gallium nitride-based semiconductor material is a material having the formula In$_x$Al$_y$Ga$_{1-x-y}$N, wherein $x + y \leq 1$, $0 \leq x \leq 1$, and $0 \leq y \leq 1$. Gallium nitride-based semiconductor material are usually grown by a vapor phase growth method such as metalorganic chemical vapor deposition (MOCVD or MOVPE), hydride chemical vapor deposition (HDCVD), or molecular beam epitaxy (MBE). Generally, a gallium nitride-based semiconductor material is an n-type material even when no n-type dopant is included in the material since nitrogen lattice vacancies are created during crystal growth. Thus, an n-type gallium nitride-based semiconductor material may not include an n-type dopant. However, an n-type gallium nitride-based semiconductor typically exhibits better conductivity when the material includes an n-type dopant. n-Type dopants for gallium nitride-based semiconductor materials include Group IV elements such as silicon, germanium and tin, and Group VI elements such as selenium, tellurium and sulfur.

A p-type gallium nitride-based semiconductor material is a gallium nitride-based semiconductor material that includes a p-type dopant. The p-type dopants (also called an acceptor) for gallium nitride-based semiconductor materials include Group II elements such as cadmium, zinc, beryllium, magnesium, calcium,
strontium, and barium. Preferred p-type dopants are magnesium and zinc. Typically, during growth of the gallium nitride-based semiconductor material gaseous compounds containing hydrogen atoms are thermally decomposed to form the semiconductor material. The released hydrogen atoms, which are present mainly as protons, become trapped in the growing semiconductor material, and combine with p-type dopant inhibiting their acceptor function. To improve the conductivity of a p-type gallium nitride-based semiconductor material, the material may be placed in a high electric field, typically above 10,000 volts/cm for about 10 minutes or more. The protons trapped in the semiconductor material are drawn out of the material to the negative electrode, thereby activating the function of the p-type dopants (see U.S. Patent Application No. 10/127,345, the entire teachings of which are incorporated herein by reference). Alternatively, the conductivity of the p-type gallium nitride-based semiconductor material can be improved by annealing the material at a temperature above 600°C in a nitrogen environment for 10 minutes or more (see U.S. Patent No. 5,306,662, the entire teachings of which are incorporated herein by reference).

As described above, a gallium nitride-based semiconductor structure includes an p-type gallium nitride-based semiconductor layer and n-type gallium nitride-based semiconductor layer. The p-type gallium nitride-based semiconductor layer is generally grown over the n-type gallium nitride-based semiconductor layer. The n-type and p-type semiconductor layers can be in direct contact with each other or, alternatively, an active region can be sandwiched between the n-type and p-type gallium nitride-based semiconductor layers. An active region can have a single quantum-well structure or a multiple quantum-well structure. An active region having a single quantum-well structure has a single layer (i.e., the well layer) formed of a gallium nitride-based semiconductor material having a lower band-gap than the n-type and p-type gallium nitride-based semiconductor layers sandwiching it. An active region having a multiple quantum-well structure includes multiple well layers alternately stacked with multiple layers that have a higher band-gap than the well layers (i.e., barrier layers). The outer most layer of the active region closest to the n-type gallium nitride-based semiconductor layer is a well layer and has a smaller
band-gap than the n-type gallium nitride-based semiconductor layer. The outer most
layer of the active region closest to the p-type gallium nitride-based semiconductor
layer may be a well layer or a barrier layer and may have a band-gap that is larger or
smaller than the p-type gallium nitride-based semiconductor layer. Typically, the
thickness of a well layer in a quantum-well structure is about 70 Å or less, and the
barrier layers are about 150 Å or less. Generally, the well layers and barrier layers in
a quantum-well structure are not intentionally doped.

The phrase “substantially light transmissive,” as used herein, with respect to
an electrode means that the electrode transmits at least 1% of the light emitted from
the gallium nitride-based semiconductor device therethrough. A light-transmitting
electrode typically transmits at least about 40% of the light emitted from the gallium
nitride-based semiconductor device. Preferably, a light-transmitting electrode
transmits about 60% or more of the light emitted from the gallium nitride-based
semiconductor device.

The phrase “substantially oxidized,” as used herein when referring to a
metallic layer, means that at least about 60% of the metal forming the metallic layer
has been oxidized to a metal oxide. In one embodiment, at least about 80% of the
metal in the metallic layer is oxidized to a metal oxide. In another embodiment, at
least about 95% of the metal in the metallic layer is oxidized to a metal oxide. In yet
another embodiment, at least about 99% of the metal in the metallic layer is oxidized
to a metal oxide.

The phrase “ohmic contact,” as used herein, refers to a region where two
materials are in contact, which has the property that the current flowing through the
region is proportional to the potential difference across the region.

To prepare electrodes of the invention, a first, second and third layer of a
metallic material are deposited on a p-type gallium nitride-based material, such as p-
type gallium nitride (p-GaN), by evaporation sublimation or other techniques known
to those skilled in the art. The first metallic layer is deposited on the p-type gallium
nitride-based material such that a first surface of the first metallic layer is in contact
with the p-type gallium nitride-based material. Typically, the thickness of the first
metallic layer is in the range of between about 5 Å and about 100 Å. The first
metallic layer is a metal such as gold, platinum, palladium, silver or combination thereof. In a preferred embodiment, the first metallic layer is gold. A second metallic layer is deposited on the first metallic layer such that a first surface of the second metallic layer is in contact with a second surface of the first metallic layer.

The thickness of the second metallic layer is in the range of between about 30 Å and about 500 Å. The second metallic layer is a metal such as nickel or zinc. Preferably, the second metallic layer is nickel. A third metallic layer is deposited on the second metallic layer such that a first surface of the third metallic layer is in contact with a second surface of the second metallic layer. The thickness of the third metallic layer is in the range of between about 10 Å and about 500 Å. The third metallic layer is a metal such as gold, platinum, palladium, silver or combination thereof. Preferably, the second metallic layer is gold.

In one embodiment, the first and the second layers are deposited on the p-type gallium nitride-based material and are annealed in the presence of oxygen before the third layer is deposited on the second layer. In another embodiment, the annealing step is done after deposition of the third layer. In either case, the second metallic layer is substantially oxidized to a metal oxide, such as nickel oxide or zinc oxide, during the annealing step. The metal oxide formed behaves as a p-type semiconductor (p-NiO or p-ZnO). During the annealing step, the metallic layers are heated to a temperature in the range of between about 400 °C and about 550°C for about 30 seconds to about 1 hour. The amount of oxygen present in the annealing environment is greater than about 1% and may be as high as 100%. The annealing environment can be air or a controlled environment such as 65% oxygen/35% nitrogen. The annealing step may be performed in a furnace, rapid thermal annealing, or on a hot plate.

It is believed that during the annealing process epitaxial layers, such as Au/p-NiO/Au/p-GaN layers, are formed by domain matching epitaxy where integral multiples of lattice planes match across the film-substrate interface. For example, epitaxial gold, which has a lattice constant of 0.408 nm, grown on top of p-type gallium nitride provides a template for the growth of nickel oxide, which has a lattice constant 0.417 nm, via lattice matching epitaxy. Nickel oxide can grow over
the top of gold as well as laterally to contact p-type gallium nitride semiconductor layer, providing an ohmic contact to p-type gallium nitride.

EXAMPLE 1

An electrode was prepared by depositing a 25 Å thick layer of gold on a p-type gallium nitride semiconductor material. An 80 Å thick layer of nickel was deposited on the gold layer, then a 40 Å thick gold layer was deposited on the nickel layer. The metal layers were annealed at a temperature of 470 °C in a furnace in an environment that containing 65% oxygen and 35% nitrogen for 30 min.

A current-voltage (I-V) curve was plotted in Fig. 1. The inset in Fig. 1 shows the configuration used to measure the voltage between two metal pads. As can be seen from Fig. 1, the current-voltage curve is linear indicating that the electrode formed an ohmic contact with the p-type gallium nitride semiconductor material.

EXAMPLE 2

An electrode was prepared by depositing a 10 Å thick layer of gold on a p-type gallium nitride semiconductor material. An 50 Å thick layer of nickel was deposited on the gold layer, then a 50 Å thick gold layer was deposited on the nickel layer. The metal layers were annealed at a temperature of 520 °C in a furnace in an environment that containing 100 % oxygen for 15 min.

A current-voltage (I-V) curve was plotted in Fig. 2. The voltage was measured between two metal pads using the same configuration as shown in the inset in Fig. 1. As can be seen from Fig. 2, the current-voltage curve is linear indicating that the electrode formed an ohmic contact with the p-type gallium nitride semiconductor material.

EQUIVALENTS

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.
CLAIMS

What is claimed is:

1. A semiconductor device comprising:
   a) a substrate having a first major surface;
   b) a semiconductor device structure over the first major surface of the substrate, the device structure comprising an n-type gallium nitride-based semiconductor layer, and a p-type gallium nitride-based semiconductor layer over the n-type semiconductor layer;
   c) a first electrode in electrical contact with the n-type semiconductor layer; and
   d) a second electrode in contact with the p-type semiconductor layer, the second electrode comprising:
      i) a layer of an oxidized metal having a first and a second surface;
      ii) a first layer of a metallic material having a first surface in contact with the p-type semiconductor layer and a second surface in contact with the first surface of the oxidized metal layer;
      iii) a second layer of a metallic material having a surface in contact with the second surface of the oxidized metallic material.

2. The device of Claim 1, wherein the second electrode is substantially light transmissive.

3. The device of Claim 1, wherein the oxidized metal includes nickel oxide or zinc oxides.

4. The device of Claim 3, wherein the oxidized metal is nickel oxide.
5. The device of Claim 3, wherein the first and the second layers of metallic material are, independently, selected from the group consisting of gold, palladium, nickel, platinum, silver and combinations thereof.

6. The device of Claim 5, wherein the first layer of metallic material includes gold.

7. The device of Claim 6, wherein the second layer of metallic material includes gold.

8. The device of Claim 1, wherein the p-type semiconductor layer includes a planar surface, and the second electrode substantially covers the surface of the p-type semiconductor layer.

9. The device of Claim 1, further comprising an active region of a semiconductor material between the n-type semiconductor layer and the p-type semiconductor layer.

10. The device of Claim 9, wherein the active region is a single quantum-well layer.

11. The device of Claim 9, wherein the active region has multiple quantum-well structure.

12. A method for producing a semiconductor device comprising:
   providing a substrate having a first major surface;
   providing a semiconductor device structure over the first major surface of the substrate, the device structure comprising an n-type gallium nitride-based semiconductor layer, and a p-type gallium nitride-based semiconductor layer over the n-type semiconductor layer;
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forming an electrode in electrical contact with the n-type gallium nitride-based semiconductor layer;

forming three or more metallic layers over the p-type semiconductor layer, wherein at least one of the metallic layers is in contact with the p-type semiconductor layer; and

subjecting at least two of the metallic layers to an annealing treatment in the presence of oxygen to form an electrode in contact with the p-type gallium nitride-based semiconductor layer.

13. The method of Claim 12, wherein the annealing treatment is conducted at a temperature of about 400°C or more.

14. The method of Claim 12, wherein prior to the annealing treatment, a first metallic layer having a first surface is in contact with the p-type semiconductor layer, and a second metallic layer having a first surface is in contact with a second surface of the first metallic layer.

15. The method of Claim 14, wherein prior to the annealing treatment, a surface of a third metallic layer is in contact with a second surface of the second metallic material.

16. The method of Claim 15, wherein the second metallic layer is nickel or zinc and the first and third metallic layers are, independently, selected from the group consisting of gold, palladium, nickel, platinum, silver and combinations thereof.

17. The method of Claim 16, wherein the second metallic layer is nickel which is substantially oxidized to nickel oxide during the annealing treatment.

18. The method of Claim 17, wherein the first and third metallic layers are the same material.
19. The method of Claim 18, wherein the first and third metallic materials are gold.

20. The method of Claim 14, wherein the annealing treatment oxidizes the second metallic layer to form a metal oxide.

21. The method of Claim 20, wherein after the annealing treatment, a surface of a third metallic layer is formed in contact with a second surface of the second metallic material which has been substantially oxidized to a metal oxide.

22. The method of Claim 21, wherein the second metallic layer is nickel and the metal oxide formed is nickel oxide.

23. The method of Claim 22, wherein the first and the third metallic layers are, independently, selected from the group consisting of gold, palladium, nickel, platinum, silver and combinations thereof.

24. The method of Claim 23, wherein the third metallic layer comprises substantially the same metallic material as the first metallic layer.

25. The method of Claim 24, wherein the first metallic layer and the third metallic layer comprises gold.

26. The method of Claim 12, wherein the electrode formed is substantially light transmissive.

27. The method of Claim 12, wherein the annealing treatment is performed in an environment that includes nitrogen.

28. An electrode for a p-type gallium nitride based semiconductor material,
comprising:
a) a layer of an oxidized metal having a first and a second surface;
b) a layer of a first metallic material having a first surface in contact with the p-type gallium nitride based semiconductor material and a second surface in contact with the first surface of the oxidized metal layer; and
c) a layer of a second metallic material having a surface in contact with the second surface of the oxidized metal layer.

29. The electrode of Claim 28, wherein the electrode is substantially light transmissive.

30. The electrode of Claim 28, wherein the oxidized metal layer includes nickel oxide or zinc oxide.

31. The electrode of Claim 30, wherein the first and the second metallic layers are, independently, selected from the group consisting of gold, palladium, nickel, platinum, silver and combinations thereof.

32. The electrode of Claim 31, wherein the first and the second metallic layers are the same.

33. The electrode of Claim 32, wherein the first and the second metallic layers comprise gold.