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(19) **United States**(12) **Patent Application Publication****Guo et al.**(10) **Pub. No.: US 2004/0119063 A1**(43) **Pub. Date: Jun. 24, 2004**(54) **GALLIUM NITRIDE-BASED DEVICES AND
MANUFACTURING PROCESS**

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(73) Assignee: **Emcore Corporation**, Somerset, NJ(21) Appl. No.: **10/721,488**(22) Filed: **Nov. 25, 2003****Related U.S. Application Data**

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Publication Classification(51) **Int. Cl.⁷ H01L 29/06**(52) **U.S. Cl. 257/13**(57) **ABSTRACT**

A nitride semiconductor is grown on a silicon substrate by depositing a few mono-layers of aluminum to protect the silicon substrate from ammonia used during the growth process, and then forming a nucleation layer from aluminum nitride and a buffer structure including multiple superlattices of $\text{Al}_R\text{Ga}_{(1-R)}\text{N}$ semiconductors having different compositions and an intermediate layer of GaN or other Ga-rich nitride semiconductor. The resulting structure has superior crystal quality. The silicon substrate used in epitaxial growth is removed before completion of the device so as to provide superior electrical properties in devices such as high-electron mobility transistors.

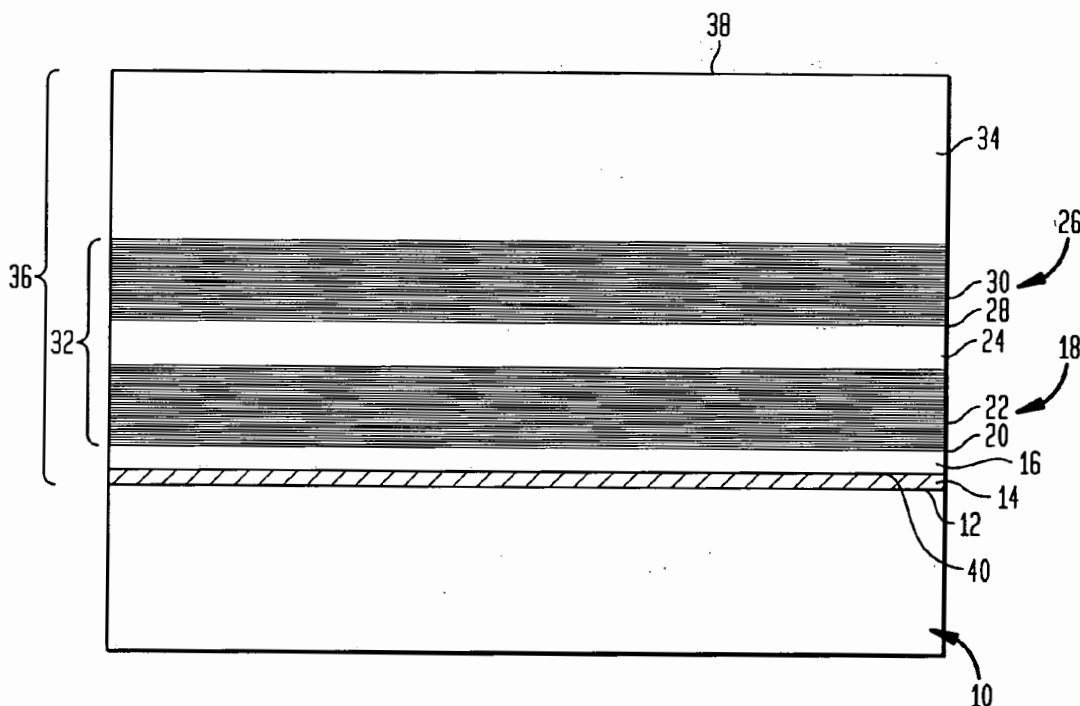


FIG. 1

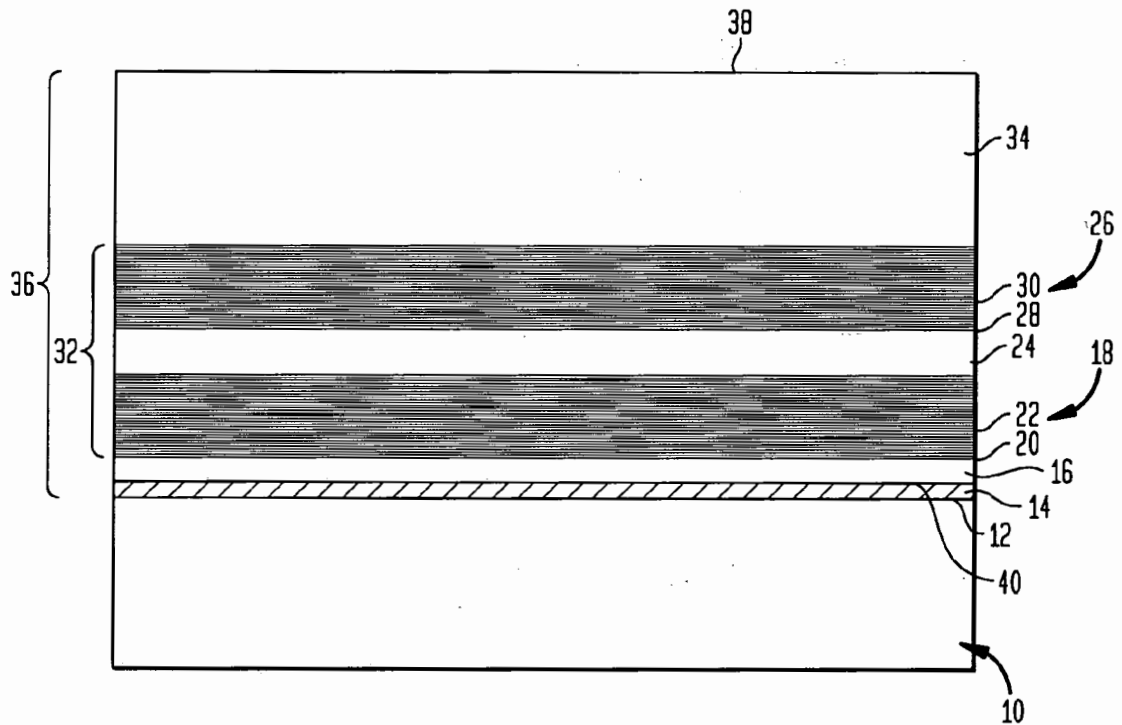


FIG. 2A

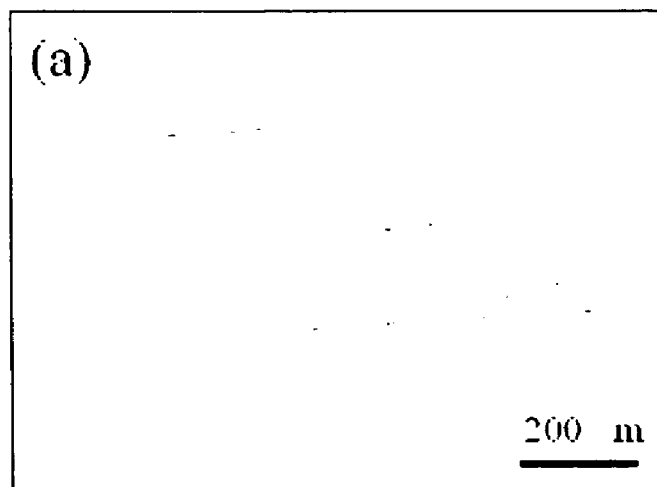


FIG. 2B

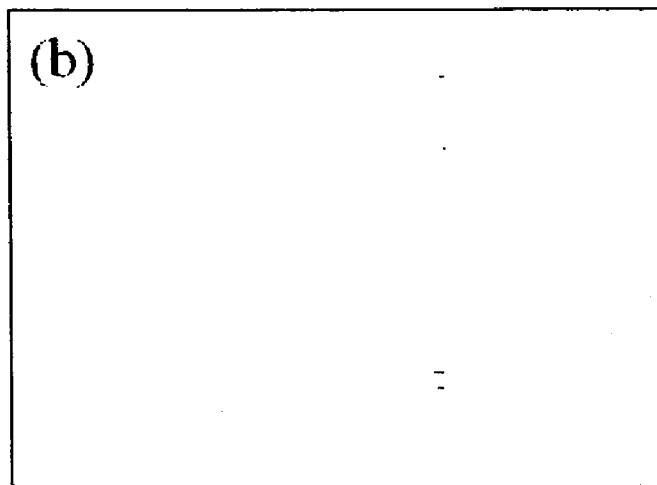


FIG. 3

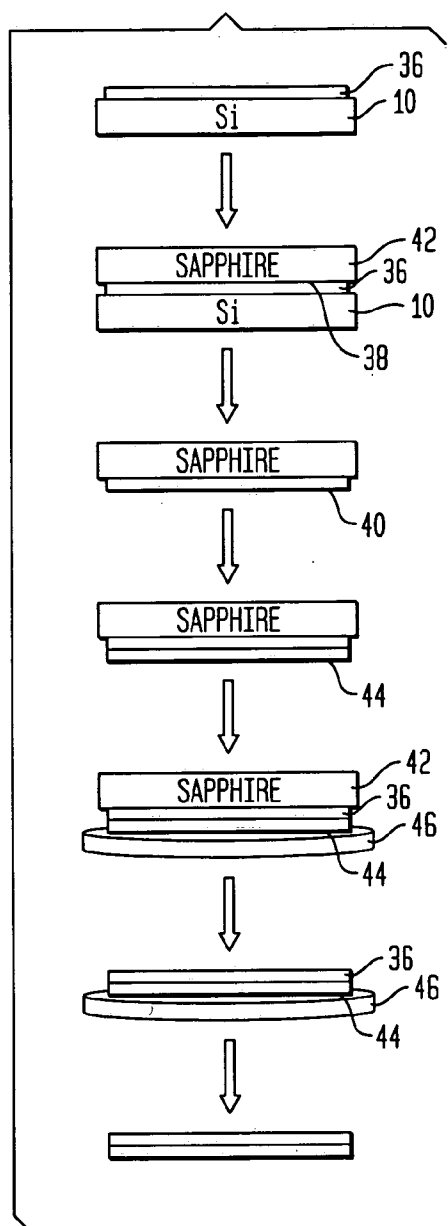


FIG. 4

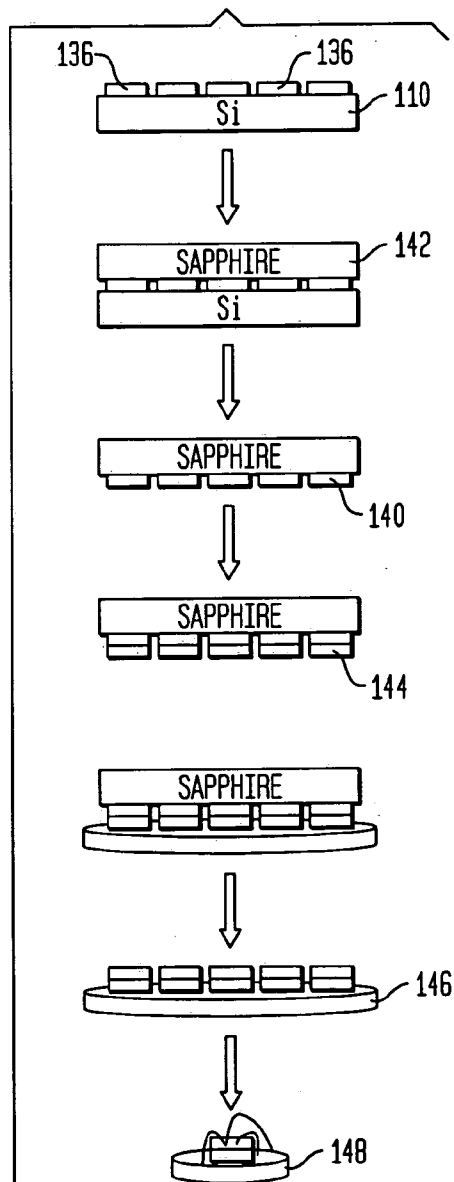


FIG. 5

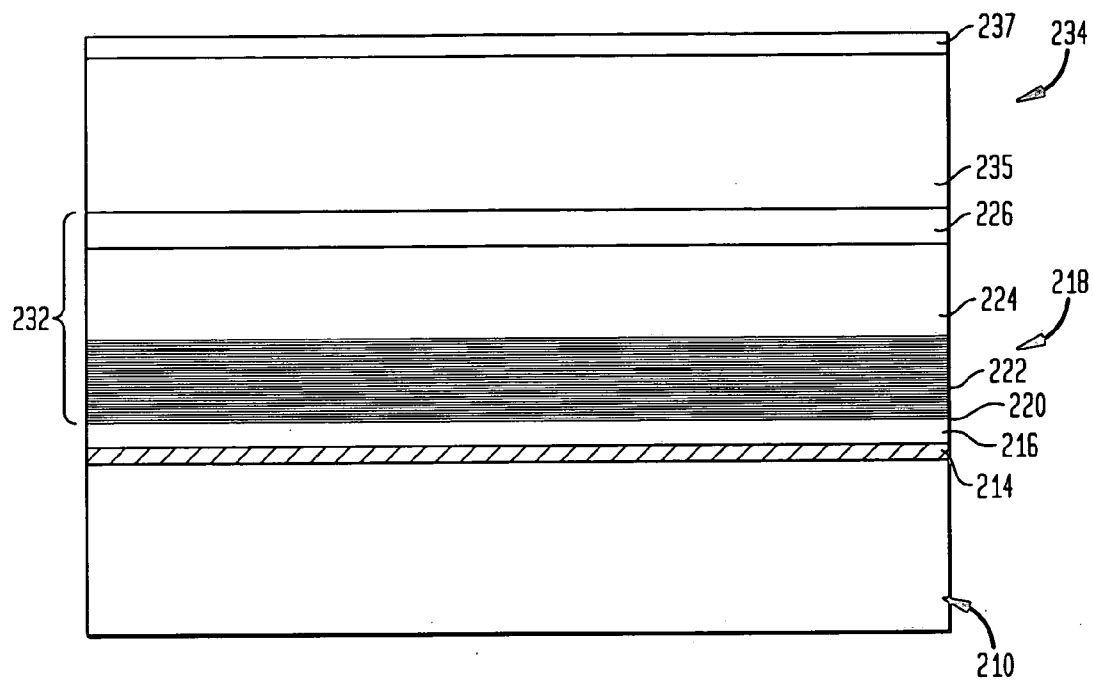


FIG. 6

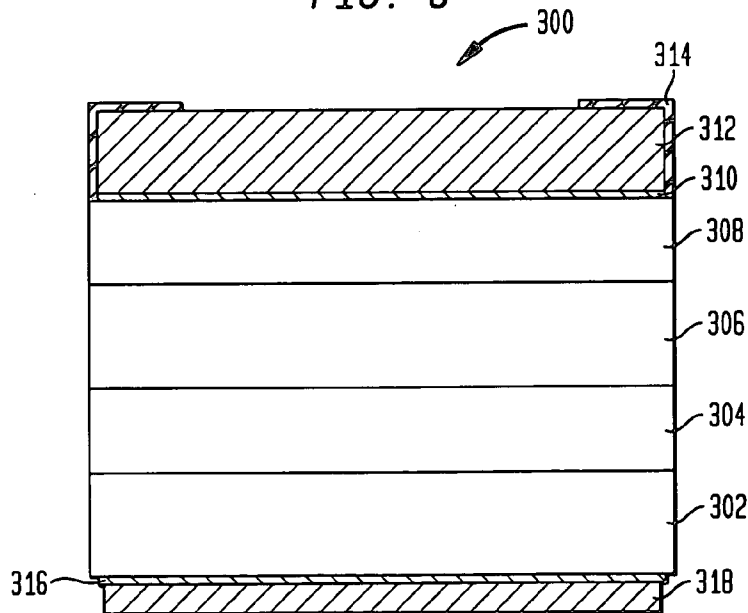
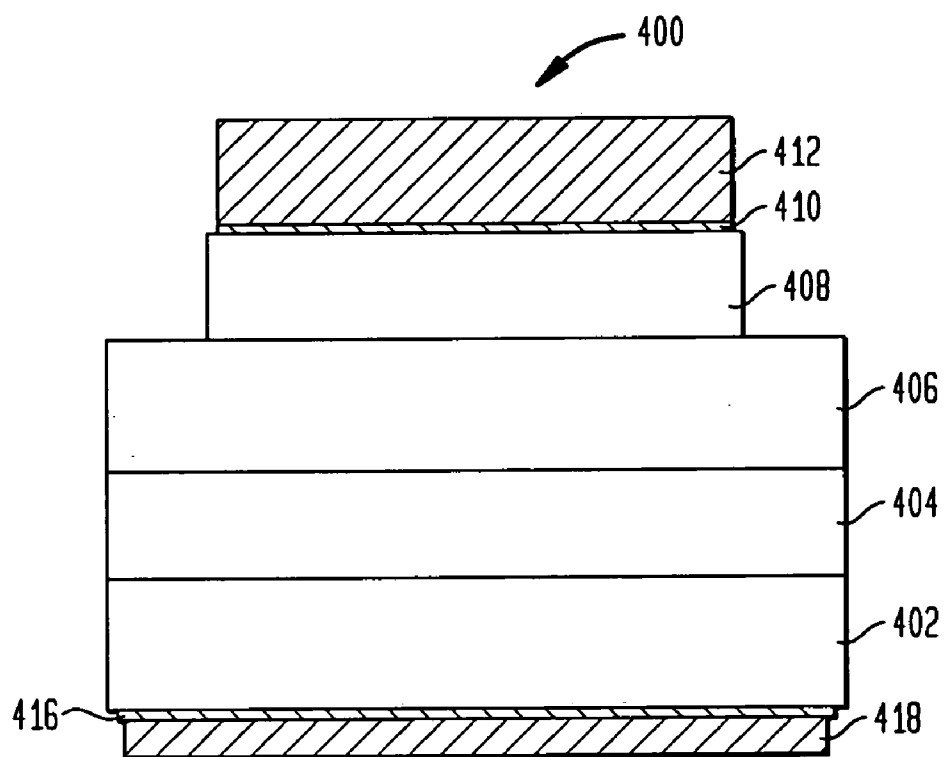


FIG. 7



GALLIUM NITRIDE-BASED DEVICES AND MANUFACTURING PROCESS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit of U.S. Provisional Patent Application Serial No. 60/430,837, filed Dec. 4, 2002, the disclosure of which is incorporated by reference herein.

BACKGROUND OF THE INVENTION

[0002] The present invention relates to nitride semiconductor structures and devices and to processes for making the same.

[0003] Nitride semiconductors such as gallium nitride and related semiconductors are widely regarded as desirable wide bandgap compound semiconductors. These materials have been adopted in optoelectronic devices such as light-emitting diodes ("LEDs"), laser diodes and photodiodes, and have also been employed in non-optical electronic devices such as field effect transistors ("FETs") and field emitters. In optoelectronic devices, the wide bandgap of the material allows for emission or absorption of light in the visible-ultraviolet range. In electronic devices, gallium nitride and related materials provide high electron mobility and allow for operation at very high signal frequencies.

[0004] Nitride semiconductors typically are formed by epitaxial growth on a substrate. In an epitaxial growth process, the constituents of the semiconductor film to be formed are deposited on a crystalline substrate so that the deposited semiconductor material has a crystal structure patterned on the crystal structure of the substrate. Various epitaxial growth processes use different techniques for delivering the materials to the surface of the substrate. For example, in reactive sputtering, the metallic constituent of the semiconductor as, for example, gallium, aluminum or indium, is dislodged from a metallic sputtering target in proximity to the substrate in an atmosphere which includes nitrogen. In a process known as metal organic chemical vapor deposition (MOCVD), the substrate is exposed to an atmosphere containing organic compounds of the metals and a reactive, nitrogen-containing gas, most commonly ammonia, while the substrate is at an elevated temperature, typically on the order of 700-1100° C. Under these conditions, the compounds decompose, leaving the metal nitride semiconductor as a thin film of crystalline material on the surface. After growth of the film, the substrate and grown film are cooled and further processed to form the finished devices.

[0005] To provide a high quality nitride semiconductor film, with relatively few crystal defects, the substrate used for crystal growth should ideally have a lattice spacing (spacing between adjacent atoms in its crystal lattice) equal to that of the nitride semiconductor to be grown. If the lattice spacing of the substrate is substantially different than that of the grown film, the grown film will have defects such as dislocations in the crystal lattice. Also, the substrate should have a coefficient of thermal expansion equal to or greater than that of the nitride semiconductor to be grown, so that when the substrate and nitride semiconductor are cooled to room temperature after growth, the substrate contracts to a greater degree than the film, placing the film in compression. If the coefficient of thermal expansion of the substrate is

substantially smaller than that of the grown film, the film will tend to contract more than the substrate, placing the film in tension when the film and substrate are cooled. This can cause cracks in the film.

[0006] Gallium nitride based semiconductors are most commonly grown on crystalline sapphire wafers. Satisfactory results can be achieved on sapphire, despite a relatively large lattice mismatch between sapphire and gallium nitride. Silicon carbide, in theory, is a more desirable material for growth of high-quality gallium nitride, inasmuch as it has a smaller lattice mismatch. Moreover, silicon carbide has higher thermal conductivity than sapphire, which aids in dissipating heat from the finished device. However, high-quality, crystalline silicon carbide wafers are very expensive and, at the present time, are not available in large sizes greater than about 100 mm (4 inches) in diameter.

[0007] High-quality silicon substrates are widely available at reasonable cost. However, the lattice spacing of silicon is not well matched to that of gallium nitride. Moreover, silicon has a lower coefficient of thermal expansion than gallium nitride, so that gallium nitride films grown on silicon tend to crack when the film and substrate are cooled to room temperature. Moreover, silicon substrates are relatively poor electrical insulators. Where the deposited nitride semiconductor is used in certain electronic devices, such as FET's, the substrate causes significant electrical losses in the device and limits the performance of the device. For all of these reasons, silicon has not been widely adopted as a substrate for growing nitride semiconductors.

[0008] Various proposals have been advanced to compensate for the lattice mismatch and thermal expansion mismatch between the nitride semiconductors and silicon. For example, Nitronics, International Publication No. WO 02/48434, suggests using a "compositionally graded transition layer" formed on a silicon substrate and depositing a gallium nitride material over the transitionally graded layer. The transition layer may contain aluminum indium gallium nitride, indium gallium nitride or aluminum gallium nitride, with proportions of aluminum, indium and gallium varying from a back surface adjacent the substrate to a front surface upon which the semiconductor is to be grown. The compositionally graded layer may include a "superlattice," i.e., a crystalline structure having a periodic variation in composition as, for example, different amounts of aluminum, indium and gallium.

[0009] Another approach taught in Feltn et al., "Stress Control In GaN Grown On Silicon (111) By Metal Organic Vapor Phase Epitaxy," Applied Physics Letters, Vol. 79, No. 20, pp. 3230-3232 (Nov. 12, 2001), utilizes an aluminum nitride buffer layer in direct contact with the silicon substrate. A layer of gallium nitride is deposited over the aluminum nitride buffer layer, followed by a superlattice including alternating layers of aluminum nitride and gallium nitride, followed by further gallium nitride layers and superlattices and, finally, by a layer of gallium nitride at the top of the structure which constitutes the active semiconductor layer to be grown. According to the Feltn et al. article, this approach yields a high-quality, active layer.

[0010] Despite these and other efforts in the prior art, however, it has been difficult to grow high-quality gallium nitride-based semiconductors on silicon substrates. Moreover, devices such as FETs fabricated from gallium nitride-

based semiconductors on silicon substrates have suffered from performance problems caused by the silicon substrate itself.

SUMMARY OF THE INVENTION

[0011] One aspect of the present invention provides a method of making a semiconductor structure including the steps of depositing a small amount of aluminum directly on a silicon substrate to provide an aluminum protected substrate, and then depositing a nucleation layer of a nitride semiconductor on the aluminum protected substrate. Most preferably, the nucleation layer is formed from a nitride semiconductor having a metal content consisting predominantly of aluminum, most preferably substantially pure aluminum nitride. The method according to this aspect of the invention preferably further includes the step of epitaxially growing a buffer structure including one or more superlattices of nitride semiconductor on the nucleation layer, and then epitaxially growing an operative structure including one or more gallium nitride-based semiconductors on the buffer structure.

[0012] A further aspect of the present invention provides methods of making a semiconductor structure including the steps of depositing a nucleation layer of a nitride semiconductor on a silicon substrate and epitaxially growing a buffer structure including one or more superlattices of nitride semiconductors on the nucleation layer such that the first superlattice of nitride semiconductors is grown directly on the nucleation layer, without an intervening layer. Here again, the method includes the step of epitaxially growing an operative structure including one or more gallium nitride-based semiconductors on the buffer structure. Most desirably, the step of growing the buffer structure includes growing an intermediate layer of a gallium nitride-based semiconductor over the first superlattice of the buffer structure and growing a second superlattice of nitride semiconductors over the intermediate layer. The most preferred methods according to the invention combine both of the foregoing aspects. Thus, the nucleation layer is formed by first depositing some aluminum on the substrate and then depositing the nitride semiconductor to form the nucleation layer, and the buffer structure includes a first superlattice directly in contact with the nucleation layer.

[0013] Methods according to the foregoing aspects of the present invention can provide high-quality gallium nitride-based semiconductors in the operative structure. Although the present invention is not limited by any theory of operation, it is believed that the superlattices introduce compressive strain into the gallium nitride-based semiconductor materials in the structure and, hence, prevent cracking of the gallium nitride based semiconductor layers. Further, it is also believed that the superlattices serve as "filters" which limit propagation of crystalline defects such as those referred to as threading dislocations from the lower layers of the structure upwardly into the operative structure at the top. These factors are believed to contribute to the high crystal quality of the gallium nitride-based semiconductors in the operative structure. Further, it is believed that the superlattices tend to limit diffusion of silicon into the gallium nitride-based semiconductors. As further discussed below, this prevents incidental, unwanted doping of the semiconductors in the operative structure with silicon from the substrate. It is also believed that placing the first superlattice

of the buffer structure on the nucleation layer, without an intervening layer of gallium nitride between the nucleation layer and the first superlattice, further suppresses formation of crystal defects and hence improves crystal quality. It is additionally believed that pretreatment of the substrate with aluminum, prior to deposition of the nucleation layer, protects the substrate from etching by ammonia. Regardless of the mechanism of operation, however, the preferred methods according to this aspect of the invention can form high-quality nitride semiconductor films, on silicon substrates.

[0014] Related aspects of the present invention provide semiconductor structures incorporating a silicon substrate, a layer of aluminum directly overlying the substrate, and a nucleation layer of a nitride semiconductor directly overlying the aluminum layer, together with a buffer structure including one or more superlattices overlying the nucleating layer, and an operative structure including one or more gallium nitride based semiconductors overlying the buffer structure.

[0015] Semiconductor structures according to a further aspect of the invention incorporate a silicon substrate, a nucleation layer of a nitride semiconductor overlying the substrate, and buffer structure incorporating a first superlattice directly overlying the nucleation layer, together with an operative structure including one or more gallium nitride-based semiconductors overlying the buffer structure. Here again, the most preferred structures incorporate both aspects of the invention and, hence, include a first superlattice directly overlying the nucleation layer and an aluminum layer between the nucleation layer and the substrate. Most preferably, the buffer structure includes the first superlattice, an intermediate layer of a gallium nitride-based semiconductor, most preferably pure gallium nitride overlying the first superlattice, and a second superlattice overlying the intermediate layer. The superlattices desirably are formed from multiple layers of semiconductor compounds according to the formula $\text{Al}_R\text{Ga}_{(1-R)}\text{N}$, where R is from 0 to 1 inclusive. Preferably, each superlattice is formed from two different such compounds, i.e., two compounds having different values of R.

[0016] A further aspect of the present invention provides a method of making a semiconductor element including the steps of epitaxially growing a nitride semiconductor structure on a silicon substrate, then bonding a carrier to the nitride semiconductor structure, and then removing the silicon substrate from the nitride semiconductor structure. Most preferably, the method according to this aspect of the invention further includes the steps of applying a base material other than silicon on the nitride semiconductor structure after removing the silicon substrate and then removing the carrier, so as to leave the nitride semiconductor structure on the base material. Methods according to this aspect of the present invention provide finished structures without the silicon wafer used as a substrate during epitaxial growth. The base material may be essentially high-quality insulator which can be applied conveniently to the nitride semiconductor structure. Merely by way of example, the base material may include aluminum nitride or diamond-like carbon deposited on the exposed surface of the nitride semiconductor structure after removal of the substrate. A related aspect of the present invention provides a semiconductor element including a nitride semiconductor structure having one or more epitaxially grown layers and a base

supporting the nitride semiconductor structure, the base being a structure other than a substrate used in epitaxially growth of the nitride semiconductor structure. Most preferably, the element according to this aspect of the invention does not include the substrate used in epitaxial growth of the nitride semiconductor structure.

[0017] These aspects of the present invention incorporate the realization that the electrical performance limitations associated with a silicon substrate can be resolved readily by removing the substrate after growth and substituting a different base material which typically would be unsuitable for epitaxial growth.

[0018] According to another aspect of the invention, a vertical current conduction Schottky diode includes a silicon substrate. At least one layer of nitride semiconductor overlies a surface of the silicon substrate. At least one first metal layer overlies the layer of nitride semiconductor and forms a Schottky contact therewith. At least one further metal layer overlies another surface of the silicon substrate and forms an ohmic contact therewith.

[0019] The layer of nitride semiconductor may include GaN or another gallium nitride-based semiconductor. A further layer of nitride semiconductor may be disposed between the silicon substrate and the first layer of nitride semiconductor, and the further layer of nitride semiconductor may have a higher doping concentration than that of the first layer of nitride semiconductor. The further layer may include GaN or another gallium nitride based semiconductor. The first layer of nitride semiconductor and the first metal layer may overlay an entire width of the layer of nitride semiconductor. Alternatively, the first layer of nitride semiconductor and the first metal layer overlay a portion of the silicon substrate.

[0020] A vertical current conduction Schottky diode is made in accordance with a still further aspect of the invention. At least one layer of nitride semiconductor is formed on the surface of the silicon substrate. At least one first metal layer is deposited on the layer of nitride semiconductor to form a Schottky contact therewith. At least one further metal layer is deposited on another surface of the silicon substrate to form an ohmic contact therewith.

[0021] The layer of nitride semiconductor may include GaN or another gallium nitride-based semiconductor. A further layer of nitride semiconductor may be formed prior to forming the first layer of nitride semiconductor and has a higher doping concentration than that of the first layer of nitride semiconductor. The further layer may include GaN or another gallium nitride based semiconductor. A portion of the first layer of nitride semiconductor may be removed such that the layer of nitride semiconductor forms a mesa structure.

[0022] These and other objects, features and advantages of the present invention will be more readily apparent from the detailed description of the preferred embodiments set forth below, taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] FIG. 1 is a fragmentary, diagrammatic sectional view on an enlarged scale of a semiconductor structure according to one embodiment of the present invention.

[0024] FIG. 2 is a comparative Nomarski image depicting a portion of a semiconductor structure in accordance with one embodiment of the present invention and another structure, not in accordance with the present invention, for comparison purposes.

[0025] FIG. 3 is a process flow diagram depicting a process in accordance with a further embodiment of the invention.

[0026] FIG. 4 is another process flow diagram depicting a process in accordance with yet another embodiment of the invention.

[0027] FIG. 5 is a view similar to that of FIG. 1 depicting a semiconductor structure according to a further embodiment of the invention.

[0028] FIG. 6 is a fragmentary, diagrammatic sectional view on an enlarged scale of a Schottky diode according to a still further embodiment of the invention.

[0029] FIG. 7 is a view similar to that of FIG. 6 depicting a Schottky diode according to an additional embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0030] As used in the present disclosure, the term "III-V semiconductor" refers to a compound semiconductor material according to the stoichiometric formula $\text{AlIn}_b\text{Ga}_c\text{N}_d\text{As}_e\text{P}_f$ where $(a+b+c)$ is about 1 and $(d+e+f)$ is also about 1. The term "nitride semiconductor" or "nitride-based semiconductor" refers to a III-V semiconductor in which d is 0.5 or more, most typically about 0.8 or more. Most preferably, the semiconductor materials are pure nitride semiconductors, i.e., nitride semiconductors in which d is about 1.0. The term "gallium nitride based semiconductor" as used herein refers to a nitride semiconductor including gallium, and most preferably including gallium as the principal metal present, i.e., having $c \geq 0.5$ and most preferably ≥ 0.8 . The semiconductors may have p-type or n-type conductivity, which may be imparted by conventional dopants and may also result from the inherent conductivity type of the particular semiconductor material. For example, gallium nitride-based semiconductors having defects typically are inherently n-type even when undoped. Conventional electron donor dopants such as Si, Ge, S, and O, can be used to impart n-type conductivity to nitride semiconductors, whereas p-type nitride semiconductors may include conventional electron acceptor dopants such as Mg and Zn.

[0031] A process according to one embodiment of the present invention begins with a doped silicon substrate 10. The silicon substrate most preferably is a substantially mono-crystalline silicon wafer having a polished, flat top surface 12. The top surface desirably is the (1,1,1) crystal plane of the silicon. In the first stage of the process, the wafer is brought to a temperature of about 600-900° C. in a conventional chemical vapor deposition apparatus and exposed to an organo-aluminum compound, most preferably a lower alkyl aluminum compound such as trimethyl aluminum ("TMA") in vapor form for a few seconds. The aluminum compound decomposes to deposit a thin aluminum layer 14 on the top surface 12 of the wafer. FIG. 1 is not drawn to scale. The thickness of aluminum layer 14 is greatly exaggerated for clarity of illustration. In practice, the

aluminum layer includes only about 1-10 mono-layers of aluminum atoms and has a thickness less than about 100 Å, more preferably less than about 50 Å. Also, although the aluminum layer is depicted as a discrete, separate layer for clarity of illustration, it is believed that there is some diffusion of silicon into the aluminum layer **14** from substrate **10**, and also some diffusion of nitrogen into the aluminum layer from the overlying layers discussed below. Thus, it is believed that in the finished article the aluminum layer will take the form of either a thin aluminum-rich zone at the upper surface of wafer **10**. It is believed that the aluminum layer serves to protect the silicon substrate from etching during exposure to ammonia in subsequent process steps, and accordingly the substrate, with the aluminum layer, is referred to herein as an "aluminum-protected" silicon substrate.

[0032] Following deposition of the aluminum layer, the aluminum-protected substrate is exposed to a mixture of an organo-metallic compound, most preferably an organo-aluminum compound, and ammonia, together with a carrier gas, so as to deposit a thin layer **16** of a nitride semiconductor, most preferably AlN. The AlN is deposited at substrate temperature on the order of 600-900° C., i.e., a temperature low enough to promote deposition of the nitride semiconductor, such as AlN, in a substantially polycrystalline form resulting from nucleation of the nitride semiconductor at numerous sites on the substrate. Nucleation layer **16** desirably is about 20-50 nm thick; here again, its thickness is greatly exaggerated in **FIG. 1** for clarity of illustration.

[0033] Following deposition of nucleation layer **16**, a first superlattice **18** is deposited directly on the top of the nucleation layer. As used in this disclosure, the "top" surface of a grown semiconductor structure should be understood as the surface most remote from the substrate used in forming the structure, i.e., the surface facing upwardly in **FIG. 1**. Also, a statement that one structure is deposited "directly on" an other structure should be understood as meaning that the one structure directly abuts the top surface of the other structure, without intervening layers. By contrast, a statement that one structure is "over" an other structure should be understood as meaning that the one structure is more remote from the substrate than the other structure, but does not exclude the presence of intervening layers.

[0034] The first superlattice includes a plurality of layers **20** and **22** of nitride semiconductors having differing compositions. In a superlattice, the layers have thicknesses on the order of 10 nm or less, typically 5 nm or less and most commonly 3 nm or less, so that the overall structure is more in the nature of a composite crystal lattice than a set of discrete, individual layers. Preferably, each of layers **20** and **22** is formed from a pure nitride semiconductor selected from the group consisting of gallium nitride, aluminum nitride and aluminum gallium nitride, i.e., the group of semiconductors defined by the stoichiometric formula $\text{Al}_R\text{Ga}_{(1-R)}\text{N}$, with the layers having unequal values of R. That is, layer **20** has the formula $\text{Al}_X\text{Ga}_{(1-X)}\text{N}$, whereas layer **22** has the formula $\text{Al}_Y\text{Ga}_{(1-Y)}\text{N}$, where $X \neq Y$. Superlattice **18**, as a whole, desirably includes about 5-15 repetitions of layers **20** and **22**, most preferably about 10 repetitions. For example, layer **20** may be pure AlN, whereas layer **22** may be $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$. A pure AlN layer is deposited by exposing the substrate to an organo-aluminum compound ammonia

and carrier gas as discussed above, whereas an AlGaIn layer is deposited by exposing the substrate to a similar gas mixture also incorporating an organo-gallium compound, desirably a lower alkyl organogallium compound such as trimethylgallium. The thicknesses of the aluminum gallium nitride layers **22** and aluminum nitride layers **20** desirably are substantially constant throughout the thickness of superlattice **18**. However, this is not essential. The compositions and thicknesses of the layers can be varied within the superlattice to provide compositional grading within the superlattice, i.e., so that the overall proportion of gallium and aluminum within the superlattice varies in the upward direction, away from substrate **10**. Also, the individual layers in the superlattice may include some indium in the metallic component.

[0035] Following deposition of the first superlattice **18**, a thin intermediate layer **24** of a gallium nitride based semiconductor, most preferably GaN, is deposited by exposing the substrate to a mixture of an organo-gallium compound, ammonia and a carrier gas, at a temperature of about 950 to about 1100° C. Layer **24** most preferably is about 200 to about 400 nm thick.

[0036] A second superlattice **26** is formed over intermediate layer **24**, desirably directly on the intermediate layer. The second superlattice is generally similar to the first superlattice **18** and incorporates alternating layers of an aluminum-rich nitride semiconductor such as AlN **28** and a gallium enriched nitride semiconductor such as $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$. More generally, layers **28** have the stoichiometric formula $\text{Al}_P\text{Ga}_{(1-P)}\text{N}$ and layers **30** have the stoichiometric formula $\text{Al}_Q\text{Ga}_{(1-Q)}\text{N}$, where $P \neq Q$. The thicknesses and layer compositions in the second superlattice may be the same as or different from the thicknesses and layer compositions in the first superlattice. The period of the second superlattice **26** may be less than that of the first superlattice. The second superlattice may be superlattice composed of about 5-10 repetitions of layers **28** and **30**.

[0037] The first superlattice **18**, intermediate layer **24** and second superlattice **26** cooperatively constitute a buffer structure **32**. After deposition of the buffer structure, an operative structure **34** is deposited over the buffer structure, and most preferably directly on the top surface of the second superlattice in the buffer structure. Operative structure **34** includes one or more gallium nitride based semiconductors and may include other semiconductors as well. In its simplest form, operative structure **34** may include one a single relatively thick layer of a gallium nitride based semiconductor such as pure GaN. In more complex forms, the operative structure may include plural layers having differing compositions and/or dopings as used, for example, to make conventional devices such as optical electronic devices such as light-emitting diodes, laser diodes and the like, or electronic devices such as field effect transistors and Schottky diodes. The gallium nitride based semiconductors in the operative structure may be deposited at conventional growth temperatures using MOCVD techniques. The resulting semiconductor structure incorporates a nitride structure **36** incorporating the nucleation layer **16**, buffer structure **32** and operative structure **34**. The nitride structure has a top surface **38** remote from substrate **10** and a bottom surface **40** adjacent substrate **10**.

[0038] The gallium nitride based semiconductors in the operative structure have excellent crystal quality. After

deposition, the structure can be cooled to room temperature and then removed from the reactor, without appreciable cracking of the gallium nitride based semiconductors in the operative structure. Although the present invention is not limited by any theory of operation, it is believed that the combination of the compressive stress induced by the superlattices in the operative structure and in the intermediate layer **24** serves to suppress formation of defects and, moreover, placement of the first superlattice below the lowest gallium nitride layer in the structure (below intermediate layer **24**) serves to further limit the formation of crystal defects. It is also believed that the aluminum layer **14** serves to protect the silicon substrate from etching by the ammonia used to deposit the nitride semiconductors and, thus, serves to further limit formation of defects in the crystal. It is also believed that the compressive stress applied by the superlattices and, hence, by the buffer structure as a whole to the operative structure **34** serves to prevent cracking when the substrate and nitride structure are cooled to room temperature.

[0039] Conventional techniques used in high-quality chemical vapor deposition should be followed. Optionally, between deposition of layers having differing compositions as, for example, between deposition of the aluminum layer **14** and the buffer layer **16**, and both before and after deposition of each superlattice, the chamber can be purged of metals from the preceding layer by flushing it with a mixture of the hydrogen or nitrogen carrier gas and ammonia for a prolonged period.

[0040] The quality of the structure depicted in **FIG. 1** is evidenced by the Nomarski images of **FIG. 2**. The imaged marked (a) is a Nomarski image of a structure which is not in accordance with the present invention, formed by depositing gallium nitride directly on an aluminum nitride nucleation layer, whereas the structure marked (b) in **FIG. 2** shows comparable structure with the buffer structure as discussed above with reference to **FIG. 1** between the nucleation layer and the gallium nitride layer. Structure (a) shows numerous lines representing crystal defects due to surface cracking, whereas structure (b) is substantially free of such defects.

[0041] The structure resulting from the process discussed above with reference to **FIG. 1** can be further processed using conventional techniques to form individual devices as, for example, by subdividing the nitride structure **36** and the silicon substrate **10** to form individual units, each incorporating a portion of the nitride structure and a corresponding portion of substrate **10**, and applying contacts to the resulting units and packaging the same.

[0042] More preferably, however, the substrate **10** is removed. In a process according to a further embodiment of the invention (**FIG. 3**), a semiconductor structure incorporating a silicon substrate **10** and a nitride structure **36**, which may be the same as or different from the nitride structure discussed above with reference to **FIGS. 1 and 2**, is engaged with a temporary carrier **42** so that the top surface **38** of the nitride structure bears against the carrier, and the top surface of the nitride structure is bonded to the carrier, preferably by using a dielectric "glue" that promotes adhesion between the top nitride layer and the carrier. This dielectric can be, for example, benzocyclobutene (BCB), methylsilsequioxane (MSSQ), or a material such as those sold under the com-

mercial designations Flare™, SiLK™, Parylene-N and PETI **5**. The surfaces of, the nitride structure, the carrier, or both, is or are coated with the glue and then the surfaces are brought into contact under a relatively low temperature, below 400° C. If the subsequent processing steps do not need to go above 100° C., other polymers such as HMDS or photoresist can be used. Additionally, if solvents such as acetone are not in future processing steps, such soluble adhesives such as wax or Crystalbond™ may be used.

[0043] Carrier **42** is illustrated in **FIG. 3** as a sapphire element, but the carrier can be formed from other materials which are inert to the other reagents used in the processes to follow and which can survive at the temperatures used in the process. Most preferably, the carrier also has a coefficient of thermal expansion close to that of the nitride structure, and also does not contaminate the nitride structure. Thus, the carrier desirably is substantially free of materials which tend to diffuse into the nitride structure.

[0044] Following the carrier-bonding step, the substrate **10** is removed as by etching it away from the nitride structure **36**, preferably by using an etchant such as a potassium hydroxide solution as, for example, 20% KOH by weight aqueous solution at 70° C., which attacks the silicon substrate but which does not appreciably attack the nitride structure. In this process, the nitride structure acts as a "etch stop"; the etching continues until the nitride structure is reached. An additional etch stop may be provided at or adjacent the nitride structure. For example, a layer of SiO₂ will effectively stop etching by KOH. Following removal of the substrate, the bottom surface **40** of the nitride structure is exposed. A base **44** is applied onto bottom surface **40**, as by chemical vapor deposition or sputtering of a base material on the bottom surface. The base material desirably is a material having good electrical insulating properties such as aluminum nitride or a carbonaceous, diamond-like material. Base material **44** desirably also has relatively high thermal conductivity. Base material **44** may be grown on the exposed bottom surface of the nitride structure, even if there is a substantial crystal lattice mismatch between the nitride structure and the base material. The base material need not form as a mono-crystalline, defect-free structure, provided that the poly-crystalline or defect-laden base material retains the desired insulating properties. Merely by way of example, aluminum nitride or carbon can be deposited by chemical vapor deposition.

[0045] Following deposition of the base **44**, a tape or other temporary handling element **46** is applied onto the exposed surface of base **44** and the carrier **42** is removed, leaving the nitride structure **36** on base **44** and physically supported by the base and by the tape or other temporary handling element **46**, and leaving the nitride structure with its bottom surface **40** confronting the base **44**. The resulting structure is devoid of the silicon substrate used during epitaxial growth of the nitride structure. The resulting structure can be subjected to conventional semiconductor processing techniques such as subdividing, application of contacts and mounting to a package to form one or more usable devices. In a further variant, the base material deposition step can be omitted.

[0046] In a process according to a further embodiment of the invention (**FIG. 4**), a nitride structure on a silicon growth substrate **110** is subjected to post-growth processing as, for example, application of contacts, subdivision and etching so

as to form a plurality of semi-finished gallium nitride devices **136** on the silicon growth substrate **110**, each such semi-finished device incorporating a gallium nitride structure. The semi-finished devices are subjected to process steps similar to those discussed above with reference to **FIG. 3**, including application of a temporary carrier **142** overlying the top surfaces of the gallium nitride structures and removal of the substrate to expose the bottom surfaces **140** of these structures. Following removal of the substrate, again, a base material is applied so as to form a base **144** on each gallium nitride structure **140**. Following application of the bases, a temporary handling element such as a tape **146** may be applied and the devices may be subjected to procedures such as lead-bonding and mounting on a package element **148**.

[0047] The finished devices prepared according to the methods discussed above with reference to **FIGS. 3 and 4** can provide superior electrical properties because the silicon substrate used in epitaxial growth of the nitride structure is not present in the finished device. Although relatively expensive materials as, for example, sapphire wafers are employed as temporary carriers, these can be recycled and reused, and form no part of the finished device.

[0048] Numerous variations and combinations of the features set forth above can be utilized without departing from the present invention as defined by the claims. For example, the aluminum layer and aluminum-protected silicon substrate discussed above can be utilized in growth of other nitride semiconductor structures and other III-V semiconductor structures. Also, the III-V semiconductors used in the preferred embodiments can be varied by addition of other group V elements as, for example, As and P. The buffer structure incorporated in the nitride structure may include more than two superlattices. Conversely, the intermediate layer and second superlattice can be omitted. In one such variant, depicted in **FIG. 5**, the second superlattice is omitted and replaced by a further polycrystalline nucleation layer as, for example, a layer of AlN deposited at a low temperature. This structure includes a substrate **210** and aluminum layer **214** identical to the corresponding structures discussed above with reference to **FIG. 1**. The nucleation layer **214** consists of 30 nm thick AlN. The buffer structure **232** includes a first superlattice **218** having 10 repetitions of a basic unit, each unit including a layer **220** of AlN 2 nm thick and a layer **222** of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$, also 2 nm thick. The buffer structure **232** further includes an intermediate layer **224** of GaN 0.4 μm thick, and a nucleation layer **226** of 13 nm thick polycrystalline AlN. The operative structure **235** includes a layer **235** of GaN 0.6 μm thick and a top layer **237** of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ 23 nm thick. Layers **237** and **235** cooperatively provide a two-dimensional electron gas and contribute to operation of the device as a high electron mobility transistor.

[0049] **FIG. 6** illustrates a cross-sectional view of a nitride semiconductor Schottky diode **300** formed in accordance with a further embodiment of the invention. The Schottky diode **300** includes a doped silicon substrate **302** upon which is formed a buffer structure **304** which may be the buffer structure **32** shown in **FIG. 1** or the buffer structure **232** shown in **FIG. 5**. The buffer structure typically has a thickness of between 0.1 to 10 microns. A highly doped n-type nitride semiconductor layer **306**, such as a layer of GaN or other gallium nitride-based semiconductor, is formed atop the buffer structure **302** and has a doping

concentration of between 10^{18} to 10^{19} cm^{-3} with a thickness of between 0.1 to 10 microns. A lower doped n-type nitride semiconductor layer **308** is formed atop the highly doped nitride semiconductor layer and may also be comprised of GaN or another gallium nitride-based semiconductor. The concentration of dopants in the lower doped layer is between 10^{15} to 10^{16} cm^{-3} , and the layer has a thickness of between 0.1 to 10 microns. Alternatively, the more highly doped layer **306** is omitted, and the lower doped layer **308** is formed directly atop the buffer structure **304**.

[0050] A Schottky contact layer **310** is deposited atop the lower doped layer **308** and preferably covers the complete width of the lower doped layer. A thick metal layer **312** is disposed atop the Schottky contact layer **310**.

[0051] At the bottom of the device, a thin ohmic metal contact layer **316** is formed on the backside of the silicon substrate **302**, and another metal stack **318** is deposited atop the ohmic metal layer **316**. An optional passivation layer **314** may be formed atop all of or part of the Schottky contact metal layer **310** and the thick metal layer **312**.

[0052] The structure of the Schottky diode **300** provides a forward direction, vertical current conduction path from the Schottky contact metal and through the low doped layer **308**, the highly doped layer **306**, the buffer structure **304** and the silicon substrate **302** to the ohmic metal layer **316** and metal stack **318**. Additionally, the width of the Schottky contact metal layer **310** and the metal stack **312** provide a vertical conduction path that utilizes the full width of the Schottky diode structure.

[0053] Advantageously, the vertical conduction path minimizes the resistance of the device while under forward bias but maintains a high breakdown voltage while under reverse bias. The turn-on voltage of the device is typically between 0.5V and 1.5V while the breakdown voltage is greater than -100V. Additionally, the on-resistance of the device is less than 10-20 milliohm-cm², whereas known devices in the industry typically have resistances greater than this value.

[0054] The vertical conduction path of the Schottky diode is particularly useful in achieving a low on-resistance in a gallium nitride based diode even though the GaN and other nitride-based semiconductors used typically have relatively high resistances. Known GaN-based semiconductor devices grown on an insulating substrate, such as sapphire, typically use lateral conduction in the nitride-based layers to carry the forward current. The forward current must travel over a relatively long path as well as along relatively thin layers of highly resistive material that have small cross-sectional areas in the direction transverse to the direction of current flow. In such a lateral conduction structure, the path length is determined by the horizontal dimensions of the die (e.g., a millimeter or more) and the cross-sectional area is determined by the thickness of the GaN layers (e.g., a few microns). By contrast, in the vertical conduction structure of **FIG. 6**, the path length between the silicon substrate and the Schottky contact has a miniscule length, equal to the thickness of the GaN layers (a few microns), and has a substantial cross-sectional area, corresponding to the surface area of the die structure, thereby substantially reducing the resistance of the device.

[0055] Moreover, the reduction in on-resistance due to the vertical conducting structure is achieved using a relatively

inexpensive, highly conductive silicon substrate. Using the preferred interfacial structures discussed above, this low on-resistance can be achieved while maintaining high crystal quality in the nitride-based semiconductors. Additionally, the doping levels in the nitride-based semiconductors can be relatively low, which aids in maintaining a high breakdown voltage, without incurring excessive on-resistance.

[0056] FIG. 7 illustrates another embodiment of a vertical conduction Schottky diode **400** formed in accordance with the invention but having a mesa structure. A buffer structure **404** is formed on the top surface of a silicon substrate **402** in accordance with one of the methods described above with a structure corresponding to one of the above-described structures. A highly doped, n-type nitride semiconductor layer **406** is disposed atop the buffer structure **404** and has a composition, doping concentration and thickness similar to the corresponding region of the device shown in FIG. 6. A lower doped, n-type nitride semiconductor layer **408** is formed atop the highly doped layer **406** and likewise has a composition, doping concentration and thickness similar to the corresponding region shown in FIG. 6. However, the width of the lower doped layer **408** is less than the width of the more highly doped layer. Additionally, the Schottky contact metal layer **410** and the upper thick metal stack **412** are similar in structure and thickness to the corresponding layers shown in FIG. 6 but have a width similar to the lower doped layer **408**. An edge termination structure (not shown) may be formed to counter any edge effects resulting from the Schottky contact metal. A passivation layer may also be included. An ohmic contact metal layer **416** and a metal stack **418** are formed on the backside of the silicon substrate.

[0057] As these and other variations and combinations can be employed, the foregoing description of the preferred embodiments should be taken by way of illustration rather than by way of limitation of the invention as defined by the claims.

1. A semiconductor structure comprising:
 - (a) a silicon substrate;
 - (b) a layer of aluminum directly overlying a first surface of said substrate;
 - (c) a polycrystalline nucleation layer of a nitride semiconductor directly overlying said aluminum layer;
 - (d) a buffer structure including one or more superlattices overlying said nucleation layer, each said superlattice including a plurality of nitride-based semiconductors of different compositions; and
 - (e) an operative structure of one or more gallium nitride-based semiconductors overlying said buffer structure.
2. A structure as claimed in claim 1 wherein said buffer structure includes a first superlattice, an intermediate layer of a nitride-based semiconductor overlying the first superlattice, and a second superlattice overlying the intermediate layer.
3. A structure as claimed in claim 2 wherein each of said first and second superlattices consists essentially of semiconductors according to the formula $\text{Al}_r\text{Ga}_{(1-r)}\text{N}$ where $0 \leq r \leq 1$.
4. A structure as claimed in claim 3 wherein each of said first and second superlattices consists of only two semiconductors having different values of r .

5. A structure as claimed in claim 4 wherein the semiconductors included in said first superlattice are the same as the semiconductors included in said second superlattice.

6. A structure as claimed in claim 3 wherein said first superlattice directly overlies said nucleation layer.

7. A structure as claimed in claim 6 wherein said nucleation layer consists essentially of aluminum nitride.

8. A structure as claimed in claim 1 wherein said buffer structure includes a first superlattice directly overlying said nucleation layer.

9. A structure as claimed in claim 6 wherein said nucleation layer consists essentially of aluminum nitride.

10. A structure as claimed in claim 1 wherein said operative structure includes a first layer of nitride semiconductor; said structure further comprising at least one first metal layer overlying said first layer of nitride semiconductor and forming a Schottky contact therewith.

11. A structure as claimed in claim 10 wherein said first layer of nitride semiconductor includes a gallium-nitride-based semiconductor.

12. A structure as claimed in claim 10 wherein said first layer of nitride semiconductor includes GaN.

13. A structure as claimed in claim 10 further comprising at least one further metal layer overlying a second surface of said silicon substrate and forming an ohmic contact therewith.

14. A structure as claimed in claim 10 wherein said operative structure includes a further layer of nitride semiconductor disposed between said first layer of nitride semiconductor and said buffer structure; said further layer of nitride semiconductor having a higher doping concentration than that of said first layer of nitride semiconductor.

15. A structure as claimed in claim 14 wherein said further layer of nitride semiconductor includes a gallium nitride-based semiconductor.

16. A structure as claimed in claim 14 wherein said further layer of nitride semiconductor includes GaN.

17. A structure as claimed in claim 10 wherein said first layer of nitride semiconductor overlays an entire width of said buffer structure, and said first metal layer overlays an entire width of said first layer of nitride semiconductor.

18. A structure as claimed in claim 10 wherein said first layer of nitride semiconductor overlays a portion of said buffer structure, and said first metal layer overlays an entire width of said first layer of nitride semiconductor.

19. A semiconductor structure comprising:

- (a) a silicon substrate;
- (b) a polycrystalline nucleation layer of a nitride semiconductor overlying a surface of said substrate;
- (c) a buffer structure including a first superlattice directly overlying said nucleation layer, said first superlattice including a plurality of nitride-based semiconductors of different compositions; and
- (e) an operative structure of one or more gallium nitride-based semiconductors overlying said buffer structure.

20. A structure as claimed in claim 19 wherein said nucleation layer consists essentially of aluminum nitride and said first superlattice consists essentially of semiconductors according to the formula $\text{Al}_r\text{Ga}_{(1-r)}\text{N}$ where $0 \leq r \leq 1$.

21. A structure as claimed in claim 19 wherein said buffer structure includes an intermediate layer of a nitride-based semiconductor overlying said first superlattice, and a second

superlattice including a plurality of nitride-based semiconductors overlying the intermediate layer.

22. A structure as claimed in claim 21 wherein each of said first and second superlattices consists essentially of semiconductors according to the formula $\text{Al}_r\text{Ga}_{(1-r)}\text{N}$ where $0 < r < 1$.

23. A structure as claimed in claim 22 wherein each of said first and second superlattices consists of only two semiconductors having different values of r .

24. A structure as claimed in claim 23 wherein the semiconductors included in said first superlattice are the same as the semiconductors included in said second superlattice.

25. A structure as claimed in claim 19 wherein said operative structure includes a first layer of nitride semiconductor; said structure further comprising at least one first metal layer overlying said first layer of nitride semiconductor and forming a Schottky contact therewith.

26. A structure as claimed in claim 25 wherein said first layer of nitride semiconductor includes a gallium nitride-based semiconductor.

27. A structure as claimed in claim 25 wherein said first layer of nitride semiconductor includes GaN.

28. A structure as claimed in claim 25 further comprising at least one further metal layer overlying another surface of said silicon substrate and forming an ohmic contact therewith.

29. A structure as claimed in claim 25 wherein said operative structure includes a further layer of nitride semiconductor disposed between said first layer of nitride semiconductor and said buffer structure; said further layer of nitride semiconductor having a higher doping concentration than that of said first layer of nitride semiconductor.

30. A structure as claimed in claim 29 wherein said further layer of nitride semiconductor includes a gallium nitride-based semiconductor.

31. A structure as claimed in claim 29 wherein said further layer of nitride semiconductor includes GaN.

32. A structure as claimed in claim 25 wherein said first layer of nitride semiconductor overlays an entire width of said buffer structure, and said first metal layer overlays an entire width of said first layer of nitride semiconductor.

33. A structure as claimed in claim 25 wherein said first layer of nitride semiconductor overlays a portion of said buffer structure, and said first metal layer overlays an entire width of said first layer of nitride semiconductor.

34. A method of making a semiconductor structure comprising the steps of:

- (a) depositing aluminum directly on a surface of a silicon substrate to provide an aluminum-protected substrate; then
- (b) depositing a nucleation layer of a nitride semiconductor on said aluminum-protected substrate; then
- (c) epitaxially growing a buffer structure including one or more superlattices of nitride semiconductors on said nucleation layer; and then
- (d) epitaxially growing an operative structure including one or more gallium nitride-based semiconductors on said buffer structure.

35. A method as claimed in claim 34 wherein said step of depositing said nucleation layer of said nitride semiconduc-

tor includes using NH_3 as a reactant in contact with said aluminum-protected substrate.

36. A method as claimed in claim 35 wherein said step of depositing said nucleation layer includes metal organic chemical vapor deposition.

37. A method as claimed in claim 34 wherein said step of growing said buffer structure includes growing a first superlattice of nitride semiconductors directly on said nucleation layer.

38. A method as claimed in claim 34 wherein said step of epitaxially growing said operative structure includes growing a first layer of nitride semiconductor; said method further comprising depositing at least one first metal layer on said first layer of nitride semiconductor to form a Schottky contact therewith.

39. A method as claimed in claim 38 wherein said first layer of nitride semiconductor includes a gallium nitride-based semiconductor.

40. A method as claimed in claim 38 wherein said first layer of nitride semiconductor includes GaN.

41. A method as claimed in claim 38 further comprising depositing at least one further metal layer on another surface of said silicon substrate to form an ohmic contact therewith.

42. A method as claimed in claim 38 wherein said step of epitaxially growing said operative structure includes growing a further layer of nitride semiconductor atop said buffer structure prior to growing said first layer of nitride semiconductor such that said further layer of nitride semiconductor has a higher doping concentration than that of said first layer of nitride semiconductor.

43. A method as claimed in claim 42 wherein said further layer of nitride semiconductor includes a gallium nitride-based semiconductor.

44. A method as claimed in claim 42 wherein said further layer of nitride semiconductor includes GaN.

45. A method as claimed in claim 38 further comprising removing a portion of said first layer of nitride semiconductor such that said first layer of nitride semiconductor forms a mesa structure.

46. A method of making a semiconductor structure comprising the steps of:

- (a) depositing a nucleation layer of a nitride semiconductor on a silicon substrate; then
- (b) epitaxially growing a buffer structure including one or more superlattices of nitride semiconductors on said nucleation layer, said step of growing said buffer structure including growing a first superlattice of nitride semiconductors directly on said nucleation layer; and then
- (c) epitaxially growing an operative structure including one or more gallium nitride-based semiconductors on said buffer structure.

47. A method as claimed in claim 46 wherein said step of growing said buffer structure includes growing an intermediate layer of a gallium-nitride semiconductor over said first superlattice and growing a second superlattice of nitride semiconductors over said intermediate layer.

48. A method as claimed in claim 46 wherein said step of epitaxially growing said operative structure includes growing a first layer of nitride semiconductor; said method further comprising depositing at least one first metal layer on said first layer of nitride semiconductor to form a Schottky contact therewith.

49. A method as claimed in claim 48 wherein said first layer of nitride semiconductor includes a gallium nitride-based semiconductor.

50. A method as claimed in claim 48 wherein said first layer of nitride semiconductor includes GaN.

51. A method as claimed in claim 48 further comprising depositing at least one further metal layer on another surface of said silicon substrate to form an ohmic contact therewith.

52. A method as claimed in claim 48 wherein said step of epitaxially growing said operative structure includes growing a further layer of nitride semiconductor atop said buffer structure prior to growing said first layer of nitride semiconductor such that said further layer of nitride semiconductor has a higher doping concentration than that of said first layer of nitride semiconductor.

53. A method as claimed in claim 51 wherein said further layer of nitride semiconductor includes a gallium nitride-based semiconductor.

54. A method as claimed in claim 51 wherein said further layer of nitride semiconductor includes GaN.

55. A method as claimed in claim 48 further comprising removing a portion of said first layer of nitride semiconductor such that said first layer of nitride semiconductor forms a mesa structure.

56. A method of making a semiconductor element comprising the steps of:

- (a) epitaxially growing a nitride semiconductor structure on a silicon substrate; then
- (b) bonding a carrier to said nitride semiconductor structure; then
- (c) removing said silicon substrate from said nitride semiconductor structure.

57. A method as claimed in claim 56 further comprising the step of applying a base material other than silicon on said nitride semiconductor structure after removing said silicon substrate.

58. A method as claimed in claim 57 further comprising the step of removing said carrier after applying said base material.

59. A method as claimed in claim 58 further comprising the step of treating said nitride semiconductor structure before said step of bonding the carrier to form one or more devices in said structure.

60. A method as claimed in claim 58 further comprising the step of treating said nitride semiconductor structure to form one or more devices in said structure after said step of removing the carrier.

61. A method as claimed in claim 58 wherein said step of applying a base material includes depositing said base material on said nitride semiconductor structure to form a film of said base material on a bottom surface of the nitride semiconductor structure, remote from said carrier.

62. A method as claimed in claim 61 wherein said step of depositing said base material includes depositing a base material selected from the group consisting of aluminum nitride and diamond.

63. A semiconductor element including a nitride semiconductor structure having one or more epitaxially-grown layers and a base supporting said nitride semiconductor structure, said base being a structure other than a substrate used in epitaxial growth of said nitride semiconductor structure, the element not including the substrate used in epitaxial growth of said nitride semiconductor structure.

64. A semiconductor element as claimed in claim 63 wherein said base is formed from a material selected from the group consisting of nitride semiconductors and diamond.

65. A method of making a semiconductor structure on a silicon substrate comprising the steps of:

- (a) depositing a layer of aluminum less than about 10 atomic monolayers thick on the top surface of the substrate to form an aluminum-protected substrate; and then
- (b) depositing at least one nitride semiconductor on the aluminum-protected substrate.

66. A method as claimed in claim 65 wherein said step of depositing a nitride semiconductor includes exposing the aluminum-protected substrate to an atmosphere which includes one or more organometallic compounds and ammonia.

67. A semiconductor structure made by a process as claimed in claim 65.

68. A vertical current conduction Schottky diode comprising:

- a silicon substrate;
- at least one layer of nitride semiconductor overlying a surface of said silicon substrate;
- at least one first metal layer overlying said layer of nitride semiconductor and forming a Schottky contact therewith; and
- at least one further metal layer overlying another surface of said silicon substrate and forming an ohmic contact therewith.

69. A structure as claimed in claim 68 wherein said at least one layer of nitride semiconductor includes a gallium nitride-based semiconductor.

70. A Schottky diode as claimed in claim 68 wherein said at least one layer of nitride semiconductor includes GaN.

71. A Schottky diode as claimed in claim 68 further comprising a buffer structure disposed between said silicon substrate and said layer of nitride semiconductor.

72. A Schottky diode as claimed in claim 71 wherein said buffer structure includes at least one superlattice disposed between said silicon substrate and said layer of nitride semiconductor that includes a plurality of nitride semiconductors of different compositions.

73. A Schottky diode as claimed in claim 71 wherein said buffer structure includes a first superlattice, an intermediate layer of nitride semiconductor overlying said first superlattice, and a second superlattice overlying said intermediate layer.

74. A Schottky diode as claimed in claim 68 further comprising a layer of aluminum that directly overlays said silicon substrate.

75. A Schottky diode as claimed in claim 74 further comprising a polycrystalline nucleation layer that includes a nitride semiconductor and which directly overlays said aluminum layer.

76. A Schottky diode as claimed in claim 68 further comprising a further layer of nitride semiconductor disposed between said silicon substrate and said first layer of nitride semiconductor; said further layer of nitride semiconductor having a higher doping concentration than that of said first layer of nitride semiconductor.

77. A Schottky diode as claimed in claim 76 wherein said further layer of nitride semiconductor includes a gallium nitride-based semiconductor.

78. A Schottky diode structure as claimed in claim 76 wherein said further layer of nitride semiconductor includes GaN.

79. A Schottky diode as claimed in claim 68 wherein said layer of nitride semiconductor overlays an entire width of said silicon substrate, and said first metal layer overlays an entire width of said first layer of nitride semiconductor.

80. A Schottky diode as claimed in claim 68 wherein said layer of nitride semiconductor overlays a portion of said silicon substrate, and said first metal layer overlays an entire width of said layer of nitride semiconductor.

81. A method of making a vertical current conduction Schottky diode comprising:

forming at least one layer of nitride semiconductor on a surface of a silicon substrate;

depositing at least one first metal layer on said layer of nitride semiconductor to form a Schottky contact therewith; and

depositing at least one further metal layer on another surface of said silicon substrate to form an ohmic contact therewith.

82. A method as claimed in claim 81 wherein said one layer of nitride semiconductor includes a gallium nitride-based semiconductor.

83. A method as claimed in claim 81 wherein said one layer of nitride semiconductor includes GaN.

84. A method as claimed in claim 81 further comprising forming a buffer structure on said surface of said silicon substrate prior to forming said layer of nitride semiconductor.

85. A method as claimed in claim 84 wherein said step of forming said buffer structure includes growing at least one superlattice that includes a plurality of nitride semiconductors of different compositions.

86. A method as claimed in claim 84 wherein said step of forming said buffer structure includes growing a first superlattice, growing an intermediate layer of nitride semiconductor overlying said first superlattice, and growing a second superlattice overlying said intermediate layer.

87. A method as claimed in claim 81 further comprising depositing a layer of aluminum directly on said silicon substrate.

88. A method as claimed in claim 87 further comprising forming a polycrystalline nucleation layer that includes a nitride semiconductor directly on said aluminum layer.

89. A method as claimed in claim 81 further comprising forming a further layer of nitride semiconductor prior to forming said first layer of nitride semiconductor; said further layer of nitride semiconductor having a higher doping concentration than that of said first layer of nitride semiconductor.

90. A method as claimed in claim 89 wherein said further layer of nitride semiconductor includes a gallium nitride-based semiconductor.

91. A method as claimed in claim 89 wherein said further layer of nitride semiconductor includes GaN.

92. A method as claimed in claim 81 further comprising removing a portion of said layer of gallium nitride such that said layer of gallium nitride forms a mesa structure.

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