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III-N diodes with n-doped wells and capping layers

Abstract

Disclosed herein are IC devices, packages, and device assemblies that include III-N diodes with n-doped wells and capping layers. An example IC device includes a support structure and a III-N layer, provided over a portion of the support structure, the III-N layer including an n-doped well of a III-N semiconductor material having n-type dopants with a dopant concentration of at least 5×10^{17} dopants per cubic centimeter. The IC device further includes a first and a second electrodes and at least one capping layer. The first electrode interfaces a first portion of the n-doped well. The capping layer interfaces a second portion of the n-doped well and includes a semiconductor material with a dopant concentration below 10^{17} dopants per cubic centimeter. The second electrode is provided so that the capping layer is between the second portion of the n-doped well and the second electrode.

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Background/Summary

BACKGROUND

(1) Solid-state devices that can be used in high voltage and/or high frequency applications are of great importance in modern semiconductor technologies. For example, radio frequency (RF) integrated circuits (RFIC) and power management integrated circuits (PMIC) may be critical functional blocks in system on a chip (SoC) implementations. Such SoC implementations may be found in mobile computing platforms such as smartphones, tablets, laptops, netbooks, and the like. In such implementations, the RFIC and PMIC are important factors for power efficiency and form factor and can be equally or even more important than logic and memory circuits.

(2) Due, in part, to their large band gap and high mobility, III-N material based devices, such as gallium nitride (GaN) based diodes and transistors, may be particularly advantageous for high voltage and/or high frequency applications.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) Embodiments will be readily understood by the following detailed description in conjunction with the accompanying drawings. To facilitate this description, like reference numerals designate like structural elements. Embodiments are illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings.

(2) FIG. 1 provides a cross-sectional side view illustrating an integrated circuit (IC) device that includes a III-N diode with an n-doped well and one or more capping layers, according to some embodiments of the present disclosure.

(3) FIG. 2 is a flow diagram of an example method of manufacturing an IC device that includes a III-N diode with an n-doped well and one or more capping layers, in accordance with various embodiments of the present disclosure.

(4) FIGS. 3A-3F are various views illustrating different example stages in the manufacture of an IC device that includes a III-N diode with an n-doped well and one or more capping layers using the method of FIG. 2, according to some embodiments of the present disclosure.

(5) FIG. 4 provides a cross-sectional side view illustrating an IC device that includes a III-N diode with an n-doped well and one or more capping layers integrated with a III-N transistor, according to some embodiments of the present disclosure.

(6) FIGS. 5A-5B are top views of a wafer and dies that may include one or more IC devices having one or more III-N diodes with n-doped wells and capping layers in accordance with any of the embodiments of the present disclosure.

(7) FIG. 6 is a cross-sectional side view of an IC package that may include one or more IC devices having one or more III-N diodes with n-doped wells and capping layers in accordance with any of the embodiments of the present disclosure.

(8) FIG. 7 is a cross-sectional side view of an IC device assembly that may include one or more IC devices having one or more III-N diodes with n-doped wells and capping layers in accordance with any of the embodiments of the present disclosure.

(9) FIG. 8 is a block diagram of an example computing device that may include one or more IC devices having one or more III-N diodes with n-doped wells and capping layers in accordance with any of the embodiments of the present disclosure.

DETAILED DESCRIPTION

(10) Overview

(11) The systems, methods and devices of this disclosure each have several innovative aspects, no

single one of which is solely responsible for all desirable attributes disclosed herein. Details of one or more implementations of the subject matter described in this specification are set forth in the description below and the accompanying drawings.

(12) For purposes of illustrating III-N diodes with n-doped wells and capping layers as described herein it might be useful to first understand phenomena that may come into play in III-N technology. The following foundational information may be viewed as a basis from which the present disclosure may be properly explained. Such information is offered for purposes of explanation only and, accordingly, should not be construed in any way to limit the broad scope of the present disclosure and its potential applications.

(13) As mentioned above, III-N material based devices have properties that make them particularly advantageous for certain applications. For example, because GaN has a larger band gap (about 3.4 electron-volts (eV)) than silicon (Si; band gap of about 1.1 eV), a GaN transistor is expected to withstand a larger electric field (resulting, e.g., from applying a large voltage to the drain, V_{dd}) before suffering breakdown, compared to a Si transistor of similar dimensions. Furthermore, GaN devices may advantageously employ a 2D electron gas (2 DEG) (i.e., a group of electrons, an electron gas, free to move in two dimensions but tightly confined in the third dimension, e.g., a 2D sheet charge) as their transport channels, enabling high mobilities without using impurity dopants. For example, the 2D sheet charge may be formed at an abrupt heterojunction interface formed by deposition (e.g., epitaxial deposition), on GaN, of a charge-inducing film of a material having larger spontaneous and piezoelectric polarization, compared to GaN (such a film is generally referred to as a “polarization layer”). Providing a polarization layer on a III-N material such as GaN, thus forming a heterostructure layer stack, allows forming very high charge densities without intentionally added impurity dopants, which, in turn, enables high mobilities.

(14) Despite the advantages, there are some challenges associated with III-N devices which hinder their large-scale implementation. One such challenge resides in the absence of viable p-type doping available due to the complexity of activating p-type dopants in GaN and other III-N semiconductors. This leads to the lack of p-n junction diodes in III-N technology. However, p-n junctions are essential building blocks widely used for rectification (e.g., in diodes), variable capacitances (e.g., in varactors), or voltage reference circuits (e.g., in bipolar transistors), to name a few. One prominent example illustrating the necessity of p-n junction diodes is electrostatic discharge (ESD) protection circuitry, which is indispensable for any technology. Therefore, there is the strong need to enable rectifying devices in III-N technology which could fulfil the requirements of ESD protective diodes, particularly the ability to handle large currents under forward bias.

(15) In state-of-the-art solutions for GaN transistor technologies, a diode is formed by establishing an ohmic contact for the cathode and, for the anode, a Schottky contact to the 2 DEG of a heterostructure layer stack, where the anode is fully recessed so that the anode material contacts the edge (including the sidewall) of the III-N material stack, e.g., as described in “Current transport mechanism of AlGaIn/GaN Schottky barrier diode with fully recessed Schottky anode” by Yao Yao et. al., published in Japanese Journal of Applied Physics 54, 011001, in 2015). Inventors of the present disclosure realized that such a design is limited in its current carrying capabilities due to the low injection efficiency of electrons into the 2 DEG channel. This injection occurs at the anode either by tunneling through the thick, large-band gap polarization layer, or by tunneling through the recessed GaN edge. Owing to the thinner electronic barrier at the anode/GaN edge, the injection of electrons from the recessed edge is dominant. However, this perimeter-type injection cannot be scaled with anode area and, thus, high currents as required for ESD protection cannot be achieved.

(16) Disclosed herein are IC devices, packages, and device assemblies that include III-N diodes with n-doped wells and capping layers. An example IC device may include a support structure and a III-N layer, provided over a portion of the support structure, the III-N layer including a III-N semiconductor material (in the following, also referred to simply as an “III-N material”) having n-type dopants with a dopant concentration of at least 5×10^{17} dopants per cubic centimeter. The

III-N material with such n-type dopants may be referred to as an “n-doped well.” The example IC device may further include a first and a second electrodes and at least one capping layer. The first electrode (e.g., a cathode) may interface (e.g., be in contact with) a first portion of the n-doped well. The capping layer may interface (e.g., be in contact with) a second portion of the n-doped well and may include a semiconductor material with a dopant concentration below 10^{17} dopants per cubic centimeter (e.g., the capping layer may include an intrinsic or a low-doped semiconductor material). The second electrode (e.g., an anode) may be provided so that the capping layer is between the second portion of the n-doped well and the second electrode. Embodiments of the present disclosure are based on recognition that forming a Schottky diode based on an n-doped well of a M-N material may be used to address the problem of limited injection into the 2 DEG, present in state-of-the-art designs as described above. One or more additional capping layers provided on top of the n-doped well may be used to achieve a sufficiently large Schottky barrier below the anode. No capping layers need to be provided between the n-doped well and the cathode. In diode structures with n-doped wells and capping layers as described herein, the current path is not limited to the narrow 2 DEG channel. Instead, the current will flow towards the cathode through the entire depth/volume of the n-doped well. Therefore, the resistivity may be significantly reduced, and much larger currents can be achieved despite a reduction in carrier mobility due to ionized impurity scattering caused by the presence of the n-type dopants in the n-doped well of the III-N material. Consequently, the maximum reachable currents can be easily improved by scaling the geometrical parameters of the n-doped well.

(17) In the present descriptions, various aspects of the illustrative implementations are described using terms commonly employed by those skilled in the art to convey the substance of their work to others skilled in the art. For example, the term “III-N material” refers to a compound semiconductor material with a first sub-lattice of at least one element from group III of the periodic table (e.g., Al, Ga, In) and a second sub-lattice of nitrogen (N), while the term “III-N device” (e.g., a III-N diode or a III-N transistor) refers to a device that includes a III-N material (which may include one or more different III-N materials, e.g., a plurality of different III-N materials stacked over one another) as an active material. In another example, the terms “oxide,” “carbide,” “nitride,” etc. refer to compounds containing, respectively, oxygen, carbon, nitrogen. Similarly, the terms naming various compounds refer to materials having any combination of the individual elements within a compound (e.g., the terms “gallium nitride” or “GaN” refer to a material that includes gallium and nitrogen, the terms “aluminum indium gallium nitride” or “AlInGaN” refer to a material that includes aluminum, indium, gallium and nitrogen, and so on). In yet another example, the term “high-k dielectric” refers to a material having a higher dielectric constant than silicon oxide, while the term “low-k dielectric” refers to a material having a lower dielectric constant than silicon oxide. The terms “substantially,” “close,” “approximately,” “near,” and “about,” generally refer to being within $\pm 10\%$ of a target value, e.g., within $\pm 5\%$ of a target value, based on the context of a particular value as described herein or as known in the art. Similarly, terms indicating orientation of various elements, e.g., “coplanar,” “perpendicular,” “orthogonal,” “parallel,” or any other angle between the elements, generally refer to being within $\pm 5\text{--}20\%$ of a target value based on the context of a particular value as described herein or as known in the art.

(18) IC devices as described herein, in particular IC devices that include III-N diodes with n-doped wells and capping layers, may be implemented in one or more components associated with an IC or/and between various such components. In various embodiments, components associated with an IC include, for example, transistors, diodes, power sources, resistors, capacitors, inductors, sensors, transceivers, receivers, antennas, etc. Components associated with an IC may include those that are mounted on IC or those connected to an IC. The IC may be either analog or digital and may be used in a number of applications, such as microprocessors, optoelectronics, logic blocks, audio amplifiers, etc., depending on the components associated with the IC. In some embodiments, IC devices as described herein may be included in an radio frequency IC (RFIC), which may, e.g., be

included in any component associated with an IC of an RF receiver, an RF transmitter, or an RF transceiver, e.g., as used in telecommunications within base stations (BS) or user equipment (UE). Such components may include, but are not limited to, power amplifiers, low-noise amplifiers, RF filters (including arrays of RF filters, or RF filter banks), switches, upconverters, downconverters, and duplexers. In some embodiments, IC devices as described herein may be included in ESD protection devices or circuits. In some embodiments, the IC devices as described herein may be employed as part of a chipset for executing one or more related functions in a computer.

(19) For purposes of explanation, specific numbers, materials and configurations are set forth in order to provide a thorough understanding of the illustrative implementations. However, it will be apparent to one skilled in the art that the present disclosure may be practiced without the specific details or/and that the present disclosure may be practiced with only some of the described aspects. In other instances, well-known features are omitted or simplified in order not to obscure the illustrative implementations.

(20) Further, references are made to the accompanying drawings that form a part hereof, and in which is shown, by way of illustration, embodiments that may be practiced. It is to be understood that other embodiments may be utilized, and structural or logical changes may be made without departing from the scope of the present disclosure. Therefore, the following detailed description is not to be taken in a limiting sense. For convenience, if a collection of drawings designated with different letters are present, e.g., FIGS. 3A-3F, such a collection may be referred to herein without the letters, e.g., as “FIG. 3.”

(21) In the drawings, some schematic illustrations of example structures of various devices and assemblies described herein may be shown with precise right angles and straight lines, this is simply for ease of illustration, and embodiments of these assemblies may be curved, rounded, or otherwise irregularly shaped as dictated by, and sometimes inevitable due to, the manufacturing processes used to fabricate semiconductor device assemblies. Therefore, it is to be understood that such schematic illustrations may not reflect real-life process limitations which may cause the features to not look so “ideal” when any of the structures described herein are examined using e.g., scanning electron microscopy (SEM) images or transmission electron microscope (TEM) images. In such images of real structures, possible processing defects could also be visible, e.g., not-perfectly straight edges of materials, tapered vias or other openings, inadvertent rounding of corners or variations in thicknesses of different material layers, occasional screw, edge, or combination dislocations within the crystalline region, and/or occasional dislocation defects of single atoms or clusters of atoms. There may be other defects not listed here but that are common within the field of device fabrication. Inspection of layout and mask data and reverse engineering of parts of a device to reconstruct the circuit using e.g., optical microscopy, TEM, or SEM, and/or inspection of a cross-section of a device to detect the shape and the location of various device elements described herein using e.g., Physical Failure Analysis (PFA) would allow determination of presence of one or more III-N diodes with n-doped wells and capping layers as described herein.

(22) Various operations may be described as multiple discrete actions or operations in turn, in a manner that is most helpful in understanding the claimed subject matter. However, the order of description should not be construed as to imply that these operations are necessarily order dependent. These operations may not be performed in the order of presentation. Operations described may be performed in a different order from the described embodiment. Various additional operations may be performed, and/or described operations may be omitted in additional embodiments.

(23) For the purposes of the present disclosure, the phrase “A and/or B” means (A), (B), or (A and B). For the purposes of the present disclosure, the phrase “A, B, and/or C” means (A), (B), (C), (A and B), (A and C), (B and C), or (A, B, and C). The term “between,” when used with reference to measurement ranges, is inclusive of the ends of the measurement ranges.

(24) The description uses the phrases “in an embodiment” or “in embodiments,” which may each

refer to one or more of the same or different embodiments. The terms “comprising,” “including,” “having,” and the like, as used with respect to embodiments of the present disclosure, are synonymous. The disclosure may use perspective-based descriptions such as “above,” “below,” “top,” “bottom,” and “side”; such descriptions are used to facilitate the discussion and are not intended to restrict the application of disclosed embodiments. The accompanying drawings are not necessarily drawn to scale. Unless otherwise specified, the use of the ordinal adjectives “first,” “second,” and “third,” etc., to describe a common object, merely indicate that different instances of like objects are being referred to and are not intended to imply that the objects so described must be in a given sequence, either temporally, spatially, in ranking or in any other manner.

(25) Example III-N Diode with an n-Doped Well and One or More Capping Layers

(26) FIG. 1 provides a cross-sectional side view illustrating an IC device **100** that includes a III-N diode **101** (an approximate boundary of which is illustrated in FIG. 1 with a dashed contour) with an n-doped well and one or more capping layers, according to some embodiments of the present disclosure. A legend provided within a dashed box at the bottom of FIG. 1 illustrates colors/patterns used to indicate some of the elements of the IC device **100** so that FIG. 1 is not cluttered by too many reference numerals. For example, FIG. 1 uses different colors/patterns to identify a support structure **102**, an n-doped well **106**, a buffer layer **118**, etc.

(27) As shown in FIG. 1, the IC device **100** may include a support structure **102**, and a III-N layer **104**, provided over the support structure **102**, the III-N layer **104** including an n-doped well **106**. Optionally, the III-N layer **104** may also include a further III-N material **108**, e.g., as shown in FIG. 1, where the further III-N material **108** may be a low-doped or undoped III-N material, while dopant concentration of the n-doped well **106** may be higher than that of the further III-N material **108**. The IC device **100** may further include one or more first electrodes **110** and one or more second electrodes **112** over various portions of the n-doped well **106** (e.g., the IC device **100** may include two first electrodes **110**, one on either side of the second electrode **112**, as shown in FIG. 1), as well as one or more capping layers **114** between the second electrodes **112** and the n-doped well **106** of the III-N layer **104**. In some embodiments, the IC device **100** may further include a buffer layer **118**, a passivation layer **120**, and an insulator **122**.

(28) The support structure **102** may be any suitable support structure, e.g., a substrate, a die, a wafer, or a chip, on which III-N diodes as described herein may be implemented. In some embodiments, the support structure **102** may include a semiconductor, such as silicon. In other implementations, the support structure **102** may include/be alternate materials, which may or may not be combined with silicon, that include but are not limited to germanium, indium antimonide, lead telluride, indium arsenide, indium phosphide, gallium arsenide, indium gallium arsenide, gallium antimonide, or other combinations of group III-N or group IV materials. In some embodiments, the support structure **102** may include a ceramic material, or any other non-semiconductor material. For example, in some embodiments, the support structure **102** may include glass, a combination of organic and inorganic materials, embedded portions having different materials, etc. Although a few examples of materials from which the support structure **102** may be formed are described here, any material that may serve as a foundation upon which at least one III-N diode with an n-doped well and one or more capping layers as described herein may be built falls within the spirit and scope of the present disclosure.

(29) Although not specifically shown in FIG. 1, in some embodiments, the support structure **102** of the IC device **100** may include an insulating layer, such as an oxide isolation layer, provided thereon. For example, in some embodiments, a layer of an insulator **122** may be provided over the support structure **102** (not shown in FIG. 1). The insulator **122** may include any suitable insulating material, e.g., any suitable interlayer dielectric (ILD), to electrically isolate the semiconductor material of the support structure **102** from other regions of or surrounding the III-N diode **101**. Providing such an insulating layer over the support structure **102** may help mitigate the likelihood that conductive pathways will form through the support structure **102**. Examples of the insulator

122 may include, in some embodiments, silicon oxide, silicon nitride, aluminum oxide, and/or silicon oxynitride. In general, the insulator **122** may be provided in various portions of the IC device **100**. In some embodiments, the insulator **122** may include a continuous insulator material encompassing at least portions of the III-N diode **101**, e.g., as shown in FIG. **1**. In various embodiments, the insulator **122** may include different insulating materials in different portions of the IC device **100**.

(30) The III-N layer **104** may be formed of a III-N semiconductor material, i.e., of a compound semiconductor with a first sub-lattice of at least one element from group III of the periodic table (e.g., Al, Ga, In), and a second sub-lattice of nitrogen (N). In some embodiments, the III-N material of the III-N layer **104** may be a binary, ternary, or quaternary III-N compound semiconductor that is an alloy of two, three, or even four elements from group III of the periodic table (e.g., boron, aluminum, indium, gallium) and nitrogen. For example, the III-N material of the III-N layer **104** may include nitrogen and gallium, and optionally, one or more of indium or aluminum (e.g., GaN, InGaN, or AlGaN). In some embodiments, the III-N material of the III-N layer **104** may advantageously be a M-N material having a high electron mobility, such as, but not limited to GaN, InGaAs, InP, InSb, and InAs. For some In.sub.xGa.sub.1-xAs embodiments, In content (x) may be between 0.6 and 0.9, and advantageously is at least 0.7 (e.g., In.sub.0.7Ga.sub.0.3As). For some such embodiments, the III-N material may be a ternary III-N alloy, such as InGaN, or a quaternary III-N alloy, such as AlInGaN. In some embodiments, the III-N material of the III-N layer **104** may be a semiconductor material having a band gap greater than a band gap of silicon (i.e., greater than about 1.1 eV), preferably greater than 1.5 eV, or greater than 2 eV. In some embodiments, the III-N material of the III-N layer **104** may be formed of a highly crystalline semiconductor, e.g., of substantially a monocrystalline semiconductor (possibly with some limited amount of defects, e.g., dislocations).

(31) In some embodiments, the III-N material of the n-doped well **106** may be substantially the same as the III-material of the further III-N material **108** (i.e., these materials may have substantially the same material compositions), except for the differences in the doping levels of the III-material of the n-doped well **106** and the further III-N material **108**. For example, in some embodiments, the n-doped well **106** may be formed by doping the upper layer of the III-N material of the III-N layer **104** with n-type dopants so that the upper layer forms the n-doped well **106** and the remaining portion of the III-N layer **104** is not substantially doped, thus forming the further III-N material **108**. However, in other embodiments, the III-N material of the n-doped well **106** and the further III-N material **108** may include different III-N materials. Regardless of the exact material compositions, the n-doped well **106** may include n-type dopants in dopant concentrations noticeably higher than those of the further III-N material **108** or other remaining portions of the III-N layer **104**. In particular, the n-doped well **106** may include the n-type dopants (e.g., silicon, germanium, selenium, oxygen, telluride, zinc, nitrogen, and so on) at a dopant concentration of at least about 5×10^{17} dopants per cubic centimeter, e.g., at least 1×10^{18} dopants per cubic centimeter. In contrast, the remaining portions of the III-N layer **104** (i.e., outside of the n-doped well **106**, e.g., the further III-N material **108**) may include low-doped or substantially intrinsic III-N material with dopant concentrations of n-type dopants being below 10^{17} dopants per cubic centimeter, e.g., below 10^{16} dopants per cubic centimeter. In some embodiments, the further III-N material **108** may be an intrinsic III-N semiconductor material or alloy, not intentionally doped with any electrically active impurities. In alternate embodiments, one or more a nominal impurity dopant level may be present within the III-N material of the III-N layer **104** outside of the n-doped well **106** (e.g., within the further III-N material **108**), for example to set a threshold voltage of a III-N transistor that may be provided in the IC device **100** along with the III-N diode **101** (such a III-N transistor not shown in FIG. **1** but shown, e.g., in FIG. **4**), or to provide halo pocket implants, etc. In such impurity-doped embodiments however, impurity dopant level within the III-N material of the III-N layer **104** outside of the n-doped well **106** may be relatively low, e.g.,

below 10.sup.15 dopants per cubic centimeter, or below 10.sup.13 dopants per cubic centimeter.

(32) FIG. 1 illustrates that, in some embodiments, the n-doped well **106** may be provided as an upper layer of at least a portion of the III-N layer **104**, i.e., at least a portion of the further III-N material **108** may be provided between the n-doped well **106** and the support structure **102**.

However, in other embodiments, all of the thickness of at least a portion of the III-N layer **104** may be doped with n-type dopants of sufficient dopant concentration so that all of the thickness of that portion of the III-N layer **104** is the n-doped well **106**. In various embodiments, a thickness of the n-doped well **106** may be between about 50 and 5000 nanometers, e.g., between about 50 and 2000 nanometers, or between about 100 and 1000 nanometers. In the embodiments where low-doped or intrinsic further III-N material **108** remains between the n-doped well **106** and the support structure **102**, a thickness of such a material may be between about 50 and 5000 nanometers, e.g., between about 50 and 2000 nanometers, or between about 100 and 1000 nanometers. Unless specified otherwise, all thicknesses described herein refer to a dimension measured in a direction perpendicular to the support structure **102**.

(33) In some embodiments, the IC device **100** may, optionally, include a buffer material **118** between the III-N material of the III-N layer **104** and the support structure **102**. In some embodiments, the buffer material **118** may be a layer of a semiconductor material that has a band gap larger than that of the III-N material of the III-N layer **104**, so that the buffer material **118** can serve to prevent current leakage from various III-N devices built based on the III-N layer **104** to the support structure **102**. A properly selected semiconductor for the buffer material **118** may also enable better epitaxy of the III-N material of the III-N layer **104** thereon, e.g., it may improve epitaxial growth of the III-N material of the III-N layer **104**, for instance in terms of a bridge lattice constant or amount of defects. For example, a semiconductor that includes aluminum, gallium, and nitrogen (e.g., AlGa_N) or a semiconductor that includes aluminum (Al) and nitrogen (N), e.g., AlN, may be used as the buffer material **118** when the III-N material of the III-N layer **104** is a semiconductor that includes gallium and nitrogen (e.g., GaN). Other examples of materials for the buffer material **118** may include materials typically used as ILD, described above, such as oxide isolation layers, e.g., silicon oxide, silicon nitride, aluminum oxide, and/or silicon oxynitride. When implemented in the IC device **100**, the buffer material **118** may have a thickness between about 100 and 5000 nm, including all values and ranges therein, e.g., between about 200 and 1000 nanometers, or between about 250 and 500 nanometers.

(34) FIG. 1 further illustrates a first portion **126-1** of the n-doped well **106** and a second portion **126-2** of the n-doped well **106** (an approximate boundary of each shown in FIG. 1 with a respective dotted contour). As shown in FIG. 1, an electrode **110-1** (e.g., a cathode) may interface (e.g., be in contact with) the first portion **126-1**, while an electrode **112** (e.g., an anode) may be provided over the second portion **126-2** but not be in contact with the second portion **126-2**. Instead, at least one capping layer **114** may be provided between the electrode **112** and the second portion **126-2**. FIG. 1 illustrates an embodiment of the IC device **100** where a first capping layer **114-1** and a second capping layer **114-2** are provided, but, in other embodiments of the IC device **100**, the second capping layer **114-2** may be absent, or additional capping layers may be present besides the capping layers **114-1** and **114-2**. Each of the electrodes **110** and **112** may include any suitable electrically conductive material, alloy, or a stack of multiple electrically conductive materials. In some embodiments, the electrically conductive materials of any of the electrodes **110** and **112** may include one or more metals or metal alloys, with metals such as copper, ruthenium, palladium, platinum, cobalt, nickel, hafnium, zirconium, titanium, tantalum, and aluminum, tantalum nitride, titanium nitride, tungsten, doped silicon, doped germanium, or alloys and mixtures of these. In some embodiments, the electrically conductive materials of the electrodes **110** and **112** may include one or more electrically conductive alloys, oxides, or carbides of one or more metals.

(35) Sufficiently high dopant concentration of the n-type dopants in the n-doped well **106** ensures a good ohmic contact (i.e., a contact with sufficiently low resistance) between the first portion **126-1**

and the electrode **110-1**. Because the rectification of the metal-semiconductor junction degrades with increasing n-doping density, one or more capping layers **114** are introduced between the electrode **112** and the second portion **126-2** to form a Schottky contact of a sufficient barrier height. In some embodiments, the one or more capping layers **114** may include one or more semiconductor materials typically used as polarization materials in III-N transistors, e.g., one or more semiconductor materials having stronger piezo-polarization behavior or properties than the III-N semiconductor material of the III-N layer **104**. For example, the capping layer(s) **114** may include semiconductor materials that include aluminum, gallium, and nitrogen (e.g., $\text{Al.sub.xGa.sub.1-xN}$), or semiconductor materials that include aluminum, indium, gallium, and nitrogen (e.g., $\text{Al.sub.xIn.sub.yGa.sub.zN}$). However, in general, the one or more capping layers **114** may include any semiconductor materials having a work function that is suitable to form a Schottky contact with a sufficient potential barrier difference (i.e., barrier height) between the metal material of the electrode **112** and the semiconductor material of the capping layer **114** that is in contact with the metal material of the electrode **112**. In some embodiments, the barrier height may be at least about 0.2 eV, e.g., at least about 0.5 eV or at least about 1 eV. The semiconductor materials of the capping layers **114** may have a dopant concentration below that of the n-doped well **106**, e.g., may be low-doped or intrinsic semiconductor materials. For example, in some embodiments, the dopant concentration of the semiconductor material(s) of the capping layer(s) **114** may be below about 10^{17} dopants per cubic centimeter, e.g., below about 10^{16} dopants per cubic centimeter or below about 10^{15} dopants per cubic centimeter. In some embodiments, a thickness of the capping layers **114** may be between about 2 and 50 nanometers, e.g., between about 2 and 20 nanometers, or between about 5 and 10 nanometers.

(36) When only one capping layer **114** is implemented in the IC device **100**, the capping layer **114** may be between the second portion **126-2** of the n-doped well **106** and the second electrode **112** so that one side of the capping layer **114** interfaces (e.g., is in contact with) the second portion **126-2** of the n-doped well **106** and the opposite side of the capping layer **114** interfaces (e.g., is in contact with) the second electrode **112**, forming a Schottky contact of a sufficient barrier height with the second electrode **112**. When two capping layers **114-1** and **114-2** are implemented in the IC device **100**, the first capping layer **114-1** may be between the second capping layer **114-2** and the second electrode **112** so that one side of the first capping layer **114-1** interfaces (e.g., is in contact with) the second capping layer **114-2** and the opposite side of the first capping layer **114-1** interfaces (e.g., is in contact with) the second electrode **112**, forming a Schottky contact of a sufficient barrier height with the second electrode **112**. The second capping layer **114-2** may be between the first capping layer **114-1** and the second portion **126-2** of the n-doped well **106** so that one side of the second capping layer **114-2** interfaces (e.g., is in contact with) the first capping layer **114-1** and the opposite side of the second capping layer **114-2** interfaces (e.g., is in contact with) the second portion **126-2** of the n-doped well **106**. In some embodiments, different ones of the capping layers **114** may have different material compositions, e.g., in order to help reduce epitaxy-induced stress. In other embodiments, different ones of the capping layers **114** may have substantially the same material composition.

(37) Compared to the 2 DEG-based III-N diodes, the current flow in the III-N diode **101** is not restricted to a narrow potential well region (i.e., the region where the 2 DEG is formed), but is spread over the entire depth of the n-doped well **106**. Moreover, in the III-N diode **101**, the electrons may be injected homogeneously over the full length of the anode (the electrode **112**). Consequently, the III-N diode **101** may allow achieving significantly increased on-current (e.g., greater than about 100 microampere per micrometer) compared to 2 DEG-based III-N diodes. Furthermore, the device current in the III-N diode **101** may advantageously scale with the area of the electrode **112**, such that the geometrical diode parameters can be adjusted according to the needs of the application, providing a significant improvement in terms of maximum currents for the case of the bulk diode.

(38) In some embodiments, the distance between the first portion **126-1** and the second portion **126-2** of the n-doped well **106** may be between about 2 and 50 nanometers, e.g., between about 2 and 20 nanometers, or between about 5 and 10 nanometers. In some embodiments, another cathode may be provided on the other side of the anode **112**, as shown in FIG. **1** with a further electrode **110-2** (e.g., a second cathode) provided on the other side of the electrode **112**. FIG. **1** further illustrates a passivation layer **120** that may be provided over portions of the n-doped well **106** in some embodiments, and the insulator **122** that may be provided over the III-N layer **104**. The passivation layer **120** may include any suitable material, e.g., a material that includes silicon and nitrogen (e.g., SiN), to reduce/suppress surface currents at the surface of the n-doped well **106**. The insulator **122** provided over the III-N layer **104** may serve to provide electrical isolation between various electrodes and other elements of the IC device **100**.

(39) Although not specifically shown in FIG. **1**, the IC device **100** may further include additional M-N diodes similar to the III-N diode **101**, described above.

(40) Manufacturing IC Devices with III-N Diodes with n-Doped Wells and Capping Layers

(41) The IC devices implementing one or more III-N diodes with n-doped wells and capping layers as described herein may be manufactured using any suitable techniques. FIG. **2** illustrates one example of such a method. However, other examples of manufacturing any of the IC devices described herein, as well as larger devices and assemblies that include such structures (e.g., as shown in FIGS. **6-8**) are also within the scope of the present disclosure.

(42) FIG. **2** is a flow diagram of an example method **200** of manufacturing an IC device that includes a III-N diode with an n-doped well and one or more capping layers, in accordance with various embodiments of the present disclosure. Although the operations of the method **200** are illustrated once each and in a particular order, the operations may be performed in any suitable order and repeated as desired. For example, one or more operations may be performed in parallel to manufacture, substantially simultaneously, multiple III-N diodes with n-doped wells and capping layers as described herein. In another example, the operations may be performed in a different order to reflect the structure of a particular device assembly in which one or more III-N diodes with n-doped wells and capping layers as described herein will be included. In addition, the example manufacturing method **200** may include other operations not specifically shown in FIG. **2**, such as various cleaning or planarization operations as known in the art. For example, in some embodiments, the support structure **102**, as well as layers of various other materials subsequently deposited thereon, may be cleaned prior to, after, or during any of the processes of the method **200** described herein, e.g., to remove oxides, surface-bound organic and metallic contaminants, as well as subsurface contamination. In some embodiments, cleaning may be carried out using e.g., a chemical solutions (such as peroxide), and/or with ultraviolet (UV) radiation combined with ozone, and/or oxidizing the surface (e.g., using thermal oxidation) then removing the oxide (e.g., using hydrofluoric acid (HF)). In another example, the IC devices/assemblies described herein may be planarized prior to, after, or during any of the processes of the method **200** described herein, e.g., to remove overburden or excess materials. In some embodiments, planarization may be carried out using either wet or dry planarization processes, e.g., planarization be a chemical mechanical planarization (CMP), which may be understood as a process that utilizes a polishing surface, an abrasive and a slurry to remove the overburden and planarize the surface.

(43) Various operations of the method **200** may be illustrated with reference to the example embodiments shown in FIGS. **3A-3F**, illustrating fabrication of an IC device as shown in FIG. **1**, but the method **200** may be used to manufacture any suitable IC devices having one or more III-N diodes with n-doped wells and capping layers according to any other embodiments of the present disclosure. FIGS. **3A-3F** illustrate cross-sectional side views similar to the view shown in FIG. **1**, in various example stages in the manufacture of an IC device using the method of FIG. **2** in accordance with some embodiments of the present disclosure.

(44) The method **200** may begin with providing a III-N layer with an n-doped well, and further

providing a diode stack over a support structure (a process **202** shown in FIG. 2, a result of which is illustrated with an IC device **302** shown in FIG. 3A). The IC device **302** illustrates that the support structure provided in the process **202** may be the support structure **102** as described above and that the III-N layer with the n-doped well provided in **202** may be the III-N layer **104** with the n-doped well **106** as described above. The IC device **302** further illustrates that the diode stack provided in **202** may be a diode stack **322** that includes one or more capping layers **114** as described above. In some embodiments, the process **202** may include epitaxially growing various layers shown in FIG. 3A, e.g., for forming the buffer layer **118**, the III-N material of the III-N layer **104**, and the one or more capping layers **114**. In this context, “epitaxial growth” refers to the deposition of crystalline overlayers in the form of the desired materials. The epitaxial growth of various layers of the process **202** may be carried out using any known gaseous or liquid precursors for forming the desired material layers.

(45) The method **200** may then proceed with patterning the diode stack provided in the process **202** (a process **204** shown in FIG. 2, a result of which is illustrated with an IC device **304** shown in FIG. 3B). The IC device **304** illustrates that the diode stack **322** may be patterned in **204** to form a patterned diode stack **324**, having a shape suitable for providing an interface between the anode and a portion of the n-doped well **106** in the final III-N diode as described above. In various embodiments, the process **204** may include any suitable patterning techniques for forming the patterned diode stack **324**. Examples patterning techniques which may be used in **204** may include, but are not limited to, photolithographic or electron-beam (e-beam) patterning, possibly in conjunction with a suitable etching technique, e.g., a dry etch, such as RF reactive ion etch (RIE) or inductively coupled plasma (ICP) RIE. In various embodiments, any of the etches performed in **204** may include an anisotropic etch, using etchants in a form of e.g., chemically active ionized gas (i.e., plasma) using e.g., bromine (Br) and chloride (Cl) based chemistries. In some embodiments, during any of the etches of the process **204**, the IC device may be heated to elevated temperatures, e.g., to temperatures between about room temperature and 200 degrees Celsius, including all values and ranges therein, to promote that byproducts of the etch are made sufficiently volatile to be removed from the surface.

(46) The method **200** may then, optionally, continue with providing a passivation layer over the IC device with a patterned diode stack that was formed in **204** (a process **206** shown in FIG. 2, a result of which is illustrated with an IC device **306** shown in FIG. 3C). The IC device **306** illustrates that the passivation layer provided in the process **206** may be the passivation layer **120** as described above. In various embodiments, process **206** may include any suitable deposition techniques for depositing the passivation layer **120**, possibly in combination with any suitable patterning techniques for patterning the passivation layer **120**. Example deposition techniques that may be used to deposit the passivation layer **120** in the process **206** may include, but are not limited to, spin-coating, dip-coating, atomic layer deposition (ALD), physical vapor deposition (PVD) (e.g., evaporative deposition, magnetron sputtering, or e-beam deposition), or chemical vapor deposition (CVD). Example patterning techniques that may be used to pattern the passivation layer **120** in the process **206** may include any of the patterning techniques described above with reference to the process **204**.

(47) The method **200** may then continue with providing an insulator over the IC device with a patterned diode stack that was formed in the process **204** (a process **208** shown in FIG. 2, a result of which is illustrated with an IC device **308** shown in FIG. 3D). The IC device **308** illustrates that the insulator provided in the process **208** may be the insulator **122** as described above. In various embodiments, the process **208** may include any suitable deposition techniques for depositing the insulator **122**, possibly in combination with any suitable patterning techniques for patterning the insulator **122**. Example deposition techniques that may be used to deposit the insulator **122** in the process **208** may include any of the deposition techniques described above with reference to the process **206**. Example patterning techniques that may be used to pattern the insulator **122** in the

process **208** may include any of the patterning techniques described above with reference to the process **204**.

(48) The method **200** may then continue with patterning the insulator deposited in the process **208** to provide an anode (a process **210** shown in FIG. 2, a result of which is illustrated with an IC device **310** shown in FIG. 3E) and to provide at least one cathode (a process **212** shown in FIG. 2, a result of which is illustrated with an IC device **312** shown in FIG. 3F). In some embodiments of the method **200**, the order of the processes **210** and **212** may be reversed compared to what is shown in FIGS. 2 and 3, while in some other embodiments, the processes **210** and **212** may be performed simultaneously, and/or in a time-overlapping manner. In various embodiments, the processes **210** and **212** may include any suitable deposition techniques for depositing the electrically conductive materials of the electrodes **110** and **112** as described herein, possibly in combination with any suitable patterning techniques for patterning the electrodes **110** and **112**. Example deposition techniques that may be used to deposit the electrically conductive materials of the electrodes **110** and **112** in the processes **210** and **212** may include any of the deposition techniques described above with reference to the process **206**, as well as electroplating. Example patterning techniques that may be used to pattern the electrically conductive materials of the electrodes **110** and **112** in the processes **210** and **212** may include any of the patterning techniques described above with reference to the process **204**.

(49) Additional Devices and Assemblies

(50) III-N diodes with n-doped wells and capping layers as described herein may be particularly advantageous because of ease of their integration with III-N transistors, which may be realized using conventional semiconductor processing with some additional processes to form the III-N diodes as described herein. FIG. 4 provides a cross-sectional side view illustrating an IC device **400** that includes a III-N diode with an n-doped well and one or more capping layers integrated with a III-N transistor, according to some embodiments of the present disclosure. In particular, the IC device **400** illustrates the III-diode **101** as shown in FIG. 1, and the right side of the IC device **400** is substantially the same as the IC device **100**, shown in FIG. 1. Descriptions provided with reference to FIG. 1 are applicable to the IC device **400** of FIG. 4 and, in the interests of brevity, are not repeated here. Instead, only the differences are described. Similar to FIG. 1 and FIG. 3, a legend provided within a dashed box at the bottom of FIG. 4 to illustrate colors/patterns used to indicate some classes of materials of some of the elements shown in FIG. 4.

(51) Besides having the III-N diode **101** as described above, the IC device **400** further includes a III-N transistor **401** (an approximate boundary of which is illustrated in FIG. 4 with a dash-dotted contour). As shown in FIG. 4, the III-N transistor **401** may include a polarization layer **434**, source and drain (S/D) regions **436**, S/D contacts **438**, a gate stack **440** that includes at least a gate electrode material **442** and, optionally, also a gate dielectric material **444**, and a gate contact **448**.

(52) FIG. 4 illustrates that, in some embodiments, the III-N transistor **401** and the III-N diode **101** may be implemented in substantially the same layer above the support structure **102**. In particular, in some embodiments, both the III-N transistor **401** and the III-N diode **101** may be built based on the III-N layer **104** as described above. In such embodiments, a portion of the III-N layer **104** in the III-N diode **101** of the IC device **400** may be doped with n-type dopants to form the n-doped well **106** as described herein, whereas a portion of the III-N layer **104** in the III-N transistor **401** of the IC device **400** may be left undoped or low-doped, i.e., the III-N layer **104** in the III-N transistor **401** may be formed of the further III-N material **108** as described above. Furthermore, the polarization layer **434** of the III-N transistor **401** may be substantially aligned with the one or more capping layers **114** of the III-N diode **101** of the IC device **400**, which may be advantageous if the polarization layer **434** and the one or more capping layers **114** are deposited in a single process so that the material of the polarization layer **434** may be substantially the same as the material of any of the one or more capping layers **114**. Thicknesses of the polarization layer **434** and the one or more capping layers **114** in the IC device **400** may be different. For example, in some

embodiments, the total thickness of the one or more capping layers **114** may be greater than that of the polarization layer **434**, e.g., at least about 5 nanometers greater, including all values and ranges therein, e.g., at least about 10 nanometers greater, or at least about 15 nanometers greater.

(53) In general, the polarization material **434** may be a layer of a charge-inducing film of a material having larger spontaneous and/or piezoelectric polarization than that of the bulk of the III-N layer material immediately below it (e.g., the further III-N material **108**), creating a heterojunction (i.e., an interface that occurs between two layers or regions of semiconductors having unequal band gaps) with the further III-N material **108**, and leading to formation of 2 DEG at or near (e.g., immediately below) that interface during operation of the III-N transistor **401**. In various embodiments, the polarization material **434** may include materials such as AlN, InAlN, AlGa_N, or Al.sub.xIn.sub.yGa.sub.1-x-yN, and may have a thickness between about 1 and 50 nanometers, including all values and ranges therein, e.g., between about 5 and 15 nanometers or between about 10 and 30 nanometers.

(54) As also shown in FIG. **1**, the III-N transistor **401** may include two S/D regions **436**, where one of the S/D regions **436** is a source region and another one is a drain region, where the “source” and the “drain” designations may be interchangeable. As is well-known, in a transistor, S/D regions (also sometimes interchangeably referred to as “diffusion regions”) are regions that can supply charge carriers for the transistor channel (e.g., for a transistor channel **452**) of the transistor (e.g., the III-N transistor **401**). In some embodiments, the S/D regions **436** may include highly doped semiconductor materials, such as highly doped InGa_N. Often, the S/D regions may be highly doped, e.g., with dopant concentrations of at least above 10^{21} dopants per cubic centimeter, in order to advantageously form ohmic contacts with the respective S/D contacts/electrodes of the III-N transistor **401** (e.g., the S/D contacts/electrodes **438** shown in FIG. **4**), although these regions may also have lower dopant concentrations in some implementations. Regardless of the exact doping levels, the S/D regions **436** are the regions having dopant concentration higher than in other regions between the source region (e.g., the S/D region **436** shown on the left side in FIG. **4**) and the drain region (e.g., the S/D region **436** shown on the right side in FIG. **4**), i.e., higher than in the further III-N material **108**. For that reason, sometimes the S/D regions are referred to as highly doped (HD) S/D regions. In further embodiments, one or more layers of metal and/or metal alloys may be used to form the S/D regions **436**.

(55) The electrically conductive material of the S/D contacts/electrodes **438** may include any suitable electrically conductive material, alloy, or a stack of multiple electrically conductive materials, such as any materials described with reference to the electrodes **110**, **112**. Furthermore, in some embodiments, the electrically conductive material of the S/D contacts/electrodes **438** may include a doped semiconductor, such as silicon or another semiconductor doped with an n-type dopant or a p-type dopant. Metals may provide higher conductivity, while doped semiconductors may be easier to pattern during fabrication. In some embodiments, the S/D contacts/electrodes **438** may have a thickness between about 2 nanometers and 1000 nanometers, preferably between about 2 nanometers and 100 nanometers. An electrically conductive material similar to that of the S/D contacts/electrodes **438** may also be used to form a gate contact/electrode **448**, i.e., to form electrical contact to the gate electrode material **442** of the III-N transistor **401**. In various embodiments, the exact material compositions of the electrically conductive materials may be the same or different when used to implement different contacts/electrodes of different devices within the IC device **400**.

(56) Turning to the gate stack **440** provided over the channel portion of the III-N transistor **401**, the gate stack **440** may include a layer of a gate dielectric material **444**, and a gate electrode material **442**.

(57) The gate dielectric material **444** is typically a high-k dielectric material, e.g., a material including elements such as hafnium, silicon, oxygen, titanium, tantalum, lanthanum, aluminum, zirconium, barium, strontium, yttrium, lead, scandium, niobium, and zinc. Examples of high-k

materials that may be used in the gate dielectric material **444** may include, but are not limited to, hafnium oxide, hafnium silicon oxide, lanthanum oxide, lanthanum aluminum oxide, zirconium oxide, zirconium silicon oxide, tantalum oxide, titanium oxide, barium strontium titanium oxide, barium titanium oxide, strontium titanium oxide, yttrium oxide, aluminum oxide, tantalum oxide, tantalum silicon oxide, lead scandium tantalum oxide, and lead zinc niobate. In some embodiments, an annealing process may be carried out on the gate dielectric material **444** during manufacture of the III-N transistor **401** to improve the quality of the gate dielectric material **444**. A thickness of the gate dielectric material **444** may be between 0.5 nanometers and 3 nanometers, including all values and ranges therein, e.g., between 1 and 3 nanometers, or between 1 and 2 nanometers.

(58) The gate electrode material **442** may include at least one p-type work function metal or n-type work function metal, depending on whether the III-N transistor **401** is a p-type MOS (PMOS) transistor or an n-type MOS (NMOS) transistor (e.g., p-type work function metal may be used as the gate electrode material **442** when the III-N transistor **401** is a PMOS transistor and n-type work function metal may be used as the gate electrode material **442** when the III-N transistor **401** is an NMOS transistor, depending on the desired threshold voltage). For a PMOS transistor, metals that may be used for the gate electrode material **442** may include, but are not limited to, ruthenium, palladium, platinum, cobalt, nickel, titanium nitride, and conductive metal oxides (e.g., ruthenium oxide). For an NMOS transistor, metals that may be used for the gate electrode material **442** include, but are not limited to, hafnium, zirconium, titanium, tantalum, aluminum, alloys of these metals, carbides of these metals (e.g., hafnium carbide, zirconium carbide, titanium carbide, tantalum carbide, and aluminum carbide), and nitrides of these metals (e.g., tantalum nitride, and tantalum aluminum nitride). In some embodiments, the gate electrode material **442** may include a stack of two or more metal layers, where one or more metal layers are work function metal layers and at least one metal layer is a fill metal layer.

(59) Further layers may be included next to the gate electrode material **442** for other purposes, such as to act as a diffusion barrier layer or/and an adhesion layer, not specifically shown in FIG. 4. Furthermore, in some embodiments, the gate dielectric material **444** and the gate electrode material **442** may be surrounded by a gate spacer, not shown in FIG. 4, configured to provide separation between the gates of different transistors. Such a gate spacer may be made of a low-k dielectric material (i.e., a dielectric material that has a lower dielectric constant (k) than silicon dioxide which has a dielectric constant of 3.9). Examples of low-k materials that may be used as the dielectric gate spacer may include, but are not limited to, fluorine-doped silicon dioxide, carbon-doped silicon dioxide, spin-on organic polymeric dielectrics such as polyimide, polynorbornenes, benzocyclobutene, and polytetrafluoroethylene (PTFE), or spin-on silicon-based polymeric dielectric such as hydrogen silsesquioxane (HSQ) and methylsilsesquioxane (MSQ)). Other examples of low-k materials that may be used as the dielectric gate spacer include various porous dielectric materials, such as for example porous silicon dioxide or porous carbon-doped silicon dioxide, where large voids or pores are created in a dielectric in order to reduce the overall dielectric constant of the layer, since voids can have a dielectric constant of nearly 1.

(60) The IC devices **100**, **400** illustrated in FIGS. 1 and 4 do not represent an exhaustive set of IC devices and assemblies in which one or more III-N diodes with n-doped wells and capping layers as described herein may be provided, but merely provide examples of such structures/assemblies. Although particular arrangements of materials are discussed with reference to FIGS. 1, 3, and 4, intermediate materials may be included in various portions of these figures. Note that FIGS. 1, 3, and 4 are intended to show relative arrangements of some of the components therein, and that various device components of these figures may include other components that are not specifically illustrated, e.g., various interfacial layers or various additional layers or elements. For example, although not specifically shown, the IC devices **100** and/or **400** may include a solder resist material (e.g., polyimide or similar material) and one or more bond pads formed on upper-most interconnect layers of these IC devices. The bond pads may be electrically coupled with further interconnect

structure(s) and configured to route the electrical signals between the III-N diode **101**, the III-N transistor **401**, and other external devices. For example, solder bonds may be formed on the one or more bond pads to mechanically and/or electrically couple a chip including the IC devices **100** and/or **400** with another component (e.g., a circuit board). The IC devices **100** and/or **400** may have other alternative configurations to route the electrical signals from the interconnect layers, e.g., the bond pads described above may be replaced by or may further include other analogous features (e.g., posts) that route the electrical signals to external components.

(61) Additionally, although some elements of the IC devices are illustrated in FIGS. **1**, **3**, and **4** as being planar rectangles or formed of rectangular solids, this is simply for ease of illustration, and embodiments of various ones of these elements may be curved, rounded, or otherwise irregularly shaped as dictated by, and sometimes inevitable due to, the manufacturing processes used to fabricate semiconductor device assemblies. For example, while FIG. **4** may illustrate some elements, e.g., the S/D regions **436**, the S/D electrodes **438**, etc., as having perfectly straight sidewall profiles, i.e., profiles where the sidewalls extend perpendicularly to the support structure **102**, these idealistic profiles may not always be achievable in real-world manufacturing processes. Therefore, descriptions of various embodiments of III-N diodes with n-doped wells and capping layers, provided herein, are equally applicable to embodiments where various elements of the resulting IC devices look different from those shown in the figures due to manufacturing processes used to form them.

(62) IC devices that include one or more III-N diodes with n-doped wells and capping layers as disclosed herein may be included in any suitable electronic device or component. FIGS. **5-8** illustrate various examples of devices and components that may include one or more III-N diodes with n-doped wells and capping layers as disclosed herein.

(63) FIGS. **5A-5B** are top views of a wafer **2000** and dies **2002** that may include one or more III-N diodes with n-doped wells and capping layers in accordance with any of the embodiments disclosed herein. In some embodiments, the dies **2002** may be included in an IC package, in accordance with any of the embodiments disclosed herein. For example, any of the dies **2002** may serve as any of the dies **2256** in an IC package **2200** shown in FIG. **6**. The wafer **2000** may be composed of semiconductor material and may include one or more dies **2002** having IC structures formed on a surface of the wafer **2000**. Each of the dies **2002** may be a repeating unit of a semiconductor product that includes any suitable IC (e.g., ICs including one or more III-N diodes with n-doped wells and capping layers as described herein). After the fabrication of the semiconductor product is complete (e.g., after manufacture of one or more III-N diodes with n-doped wells and capping layers as described herein, e.g., after manufacture of any embodiment of the IC device **100** described herein), the wafer **2000** may undergo a singulation process in which each of the dies **2002** is separated from one another to provide discrete “chips” of the semiconductor product. In particular, devices that include one or more III-N diodes with n-doped wells and capping layers as disclosed herein may take the form of the wafer **2000** (e.g., not singulated) or the form of the die **2002** (e.g., singulated). The die **2002** may include one or more diodes (e.g., one or more III-N diodes with n-doped wells and capping layers as described herein), one or more transistors (e.g., one or more III-N transistors as described herein) as well as, optionally, supporting circuitry to route electrical signals to the III-N diodes with n-doped wells and capping layers and III-N transistors, as well as any other IC components. In some embodiments, the wafer **2000** or the die **2002** may implement an ESD protection device, an RF FE device, a memory device (e.g., a static random-access memory (SRAM) device), a logic device (e.g., an AND, OR, NAND, or NOR gate), or any other suitable circuit element. Multiple ones of these devices may be combined on a single die **2002**.

(64) FIG. **6** is a side, cross-sectional view of an example IC package **2200** that may include one or more IC devices having one or more III-N diodes with n-doped wells and capping layers in accordance with any of the embodiments disclosed herein. In some embodiments, the IC package

2200 may be a system-in-package (SiP).

(65) As shown in FIG. 6, the IC package **2200** may include a package substrate **2252**. The package substrate **2252** may be formed of a dielectric material (e.g., a ceramic, a glass, a combination of organic and inorganic materials, a buildup film, an epoxy film having filler particles therein, etc., and may have embedded portions having different materials), and may have conductive pathways extending through the dielectric material between the face **2272** and the face **2274**, or between different locations on the face **2272**, and/or between different locations on the face **2274**.

(66) The package substrate **2252** may include conductive contacts **2263** that are coupled to conductive pathways **2262** through the package substrate **2252**, allowing circuitry within the dies **2256** and/or the interposer **2257** to electrically couple to various ones of the conductive contacts **2264** (or to other devices included in the package substrate **2252**, not shown).

(67) The IC package **2200** may include an interposer **2257** coupled to the package substrate **2252** via conductive contacts **2261** of the interposer **2257**, first-level interconnects **2265**, and the conductive contacts **2263** of the package substrate **2252**. The first-level interconnects **2265** illustrated in FIG. 6 are solder bumps, but any suitable first-level interconnects **2265** may be used. In some embodiments, no interposer **2257** may be included in the IC package **2200**; instead, the dies **2256** may be coupled directly to the conductive contacts **2263** at the face **2272** by first-level interconnects **2265**.

(68) The IC package **2200** may include one or more dies **2256** coupled to the interposer **2257** via conductive contacts **2254** of the dies **2256**, first-level interconnects **2258**, and conductive contacts **2260** of the interposer **2257**. The conductive contacts **2260** may be coupled to conductive pathways (not shown) through the interposer **2257**, allowing circuitry within the dies **2256** to electrically couple to various ones of the conductive contacts **2261** (or to other devices included in the interposer **2257**, not shown). The first-level interconnects **2258** illustrated in FIG. 6 are solder bumps, but any suitable first-level interconnects **2258** may be used. As used herein, a “conductive contact” may refer to a portion of electrically conductive material (e.g., metal) serving as an interface between different components; conductive contacts may be recessed in, flush with, or extending away from a surface of a component, and may take any suitable form (e.g., a conductive pad or socket).

(69) In some embodiments, an underfill material **2266** may be disposed between the package substrate **2252** and the interposer **2257** around the first-level interconnects **2265**, and a mold compound **2268** may be disposed around the dies **2256** and the interposer **2257** and in contact with the package substrate **2252**. In some embodiments, the underfill material **2266** may be the same as the mold compound **2268**. Example materials that may be used for the underfill material **2266** and the mold compound **2268** are epoxy mold materials, as suitable. Second-level interconnects **2270** may be coupled to the conductive contacts **2264**. The second-level interconnects **2270** illustrated in FIG. 6 are solder balls (e.g., for a ball grid array arrangement), but any suitable second-level interconnects **2270** may be used (e.g., pins in a pin grid array arrangement or lands in a land grid array arrangement). The second-level interconnects **2270** may be used to couple the IC package **2200** to another component, such as a circuit board (e.g., a motherboard), an interposer, or another IC package, as known in the art and as discussed below with reference to FIG. 7.

(70) The dies **2256** may take the form of any of the embodiments of the die **2002** discussed herein and may include any of the embodiments of an IC device having one or more III-N diodes with n-doped wells and capping layers, e.g., any of the IC devices **100**, described herein. In embodiments in which the IC package **2200** includes multiple dies **2256**, the IC package **2200** may be referred to as a multi-chip package. Importantly, even in such embodiments of an MCP implementation of the IC package **2200**, one or more III-N diodes with n-doped wells and capping layers may be provided in a single chip, in accordance with any of the embodiments described herein. The dies **2256** may include circuitry to perform any desired functionality. For example, one or more of the dies **2256** may be ESD protection dies, including one or more III-N diodes with n-doped wells and capping

layers as described herein, one or more of the dies **2256** may be logic dies (e.g., silicon-based dies), one or more of the dies **2256** may be memory dies (e.g., high bandwidth memory), etc. In some embodiments, any of the dies **2256** may include one or more III-N diodes with n-doped wells and capping layers, e.g., as discussed above; in some embodiments, at least some of the dies **2256** may not include any III-N diodes with n-doped wells and capping layers.

(71) The IC package **2200** illustrated in FIG. **6** may be a flip chip package, although other package architectures may be used. For example, the IC package **2200** may be a ball grid array (BGA) package, such as an embedded wafer-level ball grid array (eWLB) package. In another example, the IC package **2200** may be a wafer-level chip scale package (WLCSP) or a panel fan-out (FO) package. Although two dies **2256** are illustrated in the IC package **2200** of FIG. **6**, an IC package **2200** may include any desired number of the dies **2256**. An IC package **2200** may include additional passive components, such as surface-mount resistors, capacitors, and inductors disposed on the first face **2272** or the second face **2274** of the package substrate **2252**, or on either face of the interposer **2257**. More generally, an IC package **2200** may include any other active or passive components known in the art.

(72) FIG. **7** is a cross-sectional side view of an IC device assembly **2300** that may include components having one or more IC devices implementing one or more III-N diodes with n-doped wells and capping layers in accordance with any of the embodiments disclosed herein. The IC device assembly **2300** includes a number of components disposed on a circuit board **2302** (which may be, e.g., a motherboard). The IC device assembly **2300** includes components disposed on a first face **2340** of the circuit board **2302** and an opposing second face **2342** of the circuit board **2302**; generally, components may be disposed on one or both faces **2340** and **2342**. In particular, any suitable ones of the components of the IC device assembly **2300** may include any of the IC devices implementing one or more III-N diodes with n-doped wells and capping layers in accordance with any of the embodiments disclosed herein; e.g., any of the IC packages discussed below with reference to the IC device assembly **2300** may take the form of any of the embodiments of the IC package **2200** discussed above with reference to FIG. **6** (e.g., may include one or more III-N diodes with n-doped wells and capping layers in/on a die **2256**).

(73) In some embodiments, the circuit board **2302** may be a printed circuit board (PCB) including multiple metal layers separated from one another by layers of dielectric material and interconnected by electrically conductive vias. Any one or more of the metal layers may be formed in a desired circuit pattern to route electrical signals (optionally in conjunction with other metal layers) between the components coupled to the circuit board **2302**. In other embodiments, the circuit board **2302** may be a non-PCB substrate.

(74) The IC device assembly **2300** illustrated in FIG. **7** includes a package-on-interposer structure **2336** coupled to the first face **2340** of the circuit board **2302** by coupling components **2316**. The coupling components **2316** may electrically and mechanically couple the package-on-interposer structure **2336** to the circuit board **2302**, and may include solder balls (e.g., as shown in FIG. **7**), male and female portions of a socket, an adhesive, an underfill material, and/or any other suitable electrical and/or mechanical coupling structure.

(75) The package-on-interposer structure **2336** may include an IC package **2320** coupled to an interposer **2304** by coupling components **2318**. The coupling components **2318** may take any suitable form for the application, such as the forms discussed above with reference to the coupling components **2316**. The IC package **2320** may be or include, for example, a die (the die **2002** of FIG. **5B**), an IC device (e.g., the IC structure of FIGS. **1-2**), or any other suitable component. In particular, the IC package **2320** may include one or more III-N diodes with n-doped wells and capping layers as described herein. Although a single IC package **2320** is shown in FIG. **7**, multiple IC packages may be coupled to the interposer **2304**; indeed, additional interposers may be coupled to the interposer **2304**. The interposer **2304** may provide an intervening substrate used to bridge the circuit board **2302** and the IC package **2320**. Generally, the interposer **2304** may spread a

connection to a wider pitch or reroute a connection to a different connection. For example, the interposer **2304** may couple the IC package **2320** (e.g., a die) to a BGA of the coupling components **2316** for coupling to the circuit board **2302**. In the embodiment illustrated in FIG. 7, the IC package **2320** and the circuit board **2302** are attached to opposing sides of the interposer **2304**; in other embodiments, the IC package **2320** and the circuit board **2302** may be attached to a same side of the interposer **2304**. In some embodiments, three or more components may be interconnected by way of the interposer **2304**.

(76) The interposer **2304** may be formed of an epoxy resin, a fiberglass-reinforced epoxy resin, a ceramic material, or a polymer material such as polyimide. In some implementations, the interposer **2304** may be formed of alternate rigid or flexible materials that may include the same materials described above for use in a semiconductor substrate, such as silicon, germanium, and other group III-V and group IV materials. The interposer **2304** may include metal interconnects **2308** and vias **2310**, including but not limited to through-silicon vias (TSVs) **2306**. The interposer **2304** may further include embedded devices **2314**, including both passive and active devices. Such devices may include, but are not limited to, capacitors, decoupling capacitors, resistors, inductors, fuses, diodes, transformers, sensors, ESD protection devices, and memory devices. More complex devices such as further RF devices, power amplifiers, power management devices, antennas, arrays, sensors, and microelectromechanical systems (MEMS) devices may also be formed on the interposer **2304**. In some embodiments, the IC devices implementing one or more III-N diodes with n-doped wells and capping layers as described herein may also be implemented in/on the interposer **2304**. The package-on-interposer structure **2336** may take the form of any of the package-on-interposer structures known in the art.

(77) The IC device assembly **2300** may include an IC package **2324** coupled to the first face **2340** of the circuit board **2302** by coupling components **2322**. The coupling components **2322** may take the form of any of the embodiments discussed above with reference to the coupling components **2316**, and the IC package **2324** may take the form of any of the embodiments discussed above with reference to the IC package **2320**.

(78) The IC device assembly **2300** illustrated in FIG. 7 includes a package-on-package structure **2334** coupled to the second face **2342** of the circuit board **2302** by coupling components **2328**. The package-on-package structure **2334** may include an IC package **2326** and an IC package **2332** coupled together by coupling components **2330** such that the IC package **2326** is disposed between the circuit board **2302** and the IC package **2332**. The coupling components **2328** and **2330** may take the form of any of the embodiments of the coupling components **2316** discussed above, and the IC packages **2326** and **2332** may take the form of any of the embodiments of the IC package **2320** discussed above. The package-on-package structure **2334** may be configured in accordance with any of the package-on-package structures known in the art.

(79) FIG. 8 is a block diagram of an example computing device **2400** that may include one or more components with one or more IC devices having one or more III-N diodes with n-doped wells and capping layers in accordance with any of the embodiments disclosed herein. For example, any suitable ones of the components of the computing device **2400** may include a die (e.g., the die **2002** of FIG. 5B) including one or more III-N diodes with n-doped wells and capping layers in accordance with any of the embodiments disclosed herein. Any of the components of the computing device **2400** may include an IC device (e.g., any embodiment of the IC devices of FIGS. 1-4) and/or an IC package (e.g., the IC package **2200** of FIG. 6). Any of the components of the computing device **2400** may include an IC device assembly (e.g., the IC device assembly **2300** of FIG. 7).

(80) A number of components are illustrated in FIG. 8 as included in the computing device **2400**, but any one or more of these components may be omitted or duplicated, as suitable for the application. In some embodiments, some or all of the components included in the computing device **2400** may be attached to one or more motherboards. In some embodiments, some or all of

these components are fabricated onto a single SoC die.

(81) Additionally, in various embodiments, the computing device **2400** may not include one or more of the components illustrated in FIG. **8**, but the computing device **2400** may include interface circuitry for coupling to the one or more components. For example, the computing device **2400** may not include a display device **2406**, but may include display device interface circuitry (e.g., a connector and driver circuitry) to which a display device **2406** may be coupled. In another set of examples, the computing device **2400** may not include an audio input device **2418** or an audio output device **2408**, but may include audio input or output device interface circuitry (e.g., connectors and supporting circuitry) to which an audio input device **2418** or audio output device **2408** may be coupled.

(82) The computing device **2400** may include a processing device **2402** (e.g., one or more processing devices). As used herein, the term “processing device” or “processor” may refer to any device or portion of a device that processes electronic data from registers and/or memory to transform that electronic data into other electronic data that may be stored in registers and/or memory. The processing device **2402** may include one or more digital signal processors (DSPs), application-specific ICs (ASICs), central processing units (CPUs), graphics processing units (GPUs), cryptoprocessors (specialized processors that execute cryptographic algorithms within hardware), server processors, or any other suitable processing devices. The computing device **2400** may include a memory **2404**, which may itself include one or more memory devices such as volatile memory (e.g., DRAM), nonvolatile memory (e.g., read-only memory (ROM)), flash memory, solid-state memory, and/or a hard drive. In some embodiments, the memory **2404** may include memory that shares a die with the processing device **2402**. This memory may be used as cache memory and may include, e.g., eDRAM, and/or spin transfer torque magnetic random-access memory (STT-MRAM).

(83) In some embodiments, the computing device **2400** may include a communication chip **2412** (e.g., one or more communication chips). For example, the communication chip **2412** may be configured for managing wireless communications for the transfer of data to and from the computing device **2400**. The term “wireless” and its derivatives may be used to describe circuits, devices, systems, methods, techniques, communications channels, etc., that may communicate data through the use of modulated electromagnetic radiation through a nonsolid medium. The term does not imply that the associated devices do not contain any wires, although in some embodiments they might not.

(84) The communication chip **2412** may implement any of a number of wireless standards or protocols, including but not limited to Institute for Electrical and Electronic Engineers (IEEE) standards including Wi-Fi (IEEE 802.11 family), IEEE 802.16 standards (e.g., IEEE 802.16-2005 Amendment), Long-Term Evolution (LTE) project along with any amendments, updates, and/or revisions (e.g., advanced LTE project, ultramobile broadband (UMB) project (also referred to as “3GPP2”), etc.). IEEE 802.16 compatible Broadband Wireless Access (BWA) networks are generally referred to as WiMAX networks, an acronym that stands for Worldwide Interoperability for Microwave Access, which is a certification mark for products that pass conformity and interoperability tests for the IEEE 802.16 standards. The communication chip **2412** may operate in accordance with a Global System for Mobile Communication (GSM), General Packet Radio Service (GPRS), Universal Mobile Telecommunications System (UMTS), High Speed Packet Access (HSPA), Evolved HSPA (E-HSPA), or LTE network. The communication chip **2412** may operate in accordance with Enhanced Data for GSM Evolution (EDGE), GSM EDGE Radio Access Network (GERAN), Universal Terrestrial Radio Access Network (UTRAN), or Evolved UTRAN (E-UTRAN). The communication chip **2412** may operate in accordance with Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA), Digital Enhanced Cordless Telecommunications (DECT), Evolution-Data Optimized (EV-DO), and derivatives thereof, as well as any other wireless protocols that are designated as 3G, 4G, 5G, and beyond. The communication

chip **2412** may operate in accordance with other wireless protocols in other embodiments. The computing device **2400** may include an antenna **2422** to facilitate wireless communications and/or to receive other wireless communications (such as AM or FM radio transmissions).

(85) In some embodiments, the communication chip **2412** may manage wired communications, such as electrical, optical, or any other suitable communication protocols (e.g., the Ethernet). As noted above, the communication chip **2412** may include multiple communication chips. For instance, a first communication chip **2412** may be dedicated to shorter-range wireless communications such as Wi-Fi or Bluetooth, and a second communication chip **2412** may be dedicated to longer-range wireless communications such as global positioning system (GPS), EDGE, GPRS, CDMA, WiMAX, LTE, EV-DO, or others. In some embodiments, a first communication chip **2412** may be dedicated to wireless communications, and a second communication chip **2412** may be dedicated to wired communications.

(86) In various embodiments, IC devices having one or more III-N diodes with n-doped wells and capping layers as described herein may be particularly advantageous for use as part of ESD circuits protecting power amplifiers, low-noise amplifiers, filters (including arrays of filters and filter banks), switches, or other active components. In some embodiments, IC devices having one or more III-N diodes with n-doped wells and capping layers as described herein may be used in PMICs, e.g., as a rectifying diode for large currents. In some embodiments, IC devices having one or more III-N diodes with n-doped wells and capping layers as described herein may be used in audio devices and/or in various input/output devices.

(87) The computing device **2400** may include battery/power circuitry **2414**. The battery/power circuitry **2414** may include one or more energy storage devices (e.g., batteries or capacitors) and/or circuitry for coupling components of the computing device **2400** to an energy source separate from the computing device **2400** (e.g., AC line power).

(88) The computing device **2400** may include a display device **2406** (or corresponding interface circuitry, as discussed above). The display device **2406** may include any visual indicators, such as a heads-up display, a computer monitor, a projector, a touchscreen display, a liquid crystal display (LCD), a light-emitting diode display, or a flat panel display, for example.

(89) The computing device **2400** may include an audio output device **2408** (or corresponding interface circuitry, as discussed above). The audio output device **2408** may include any device that generates an audible indicator, such as speakers, headsets, or earbuds, for example.

(90) The computing device **2400** may include an audio input device **2418** (or corresponding interface circuitry, as discussed above). The audio input device **2418** may include any device that generates a signal representative of a sound, such as microphones, microphone arrays, or digital instruments (e.g., instruments having a musical instrument digital interface (MIDI) output).

(91) The computing device **2400** may include a GPS device **2416** (or corresponding interface circuitry, as discussed above). The GPS device **2416** may be in communication with a satellite-based system and may receive a location of the computing device **2400**, as known in the art.

(92) The computing device **2400** may include an other output device **2410** (or corresponding interface circuitry, as discussed above). Examples of the other output device **2410** may include an audio codec, a video codec, a printer, a wired or wireless transmitter for providing information to other devices, or an additional storage device.

(93) The computing device **2400** may include an other input device **2420** (or corresponding interface circuitry, as discussed above). Examples of the other input device **2420** may include an accelerometer, a gyroscope, a compass, an image capture device, a keyboard, a cursor control device such as a mouse, a stylus, a touchpad, a bar code reader, a Quick Response (QR) code reader, any sensor, or a radio frequency identification (RFID) reader.

(94) The computing device **2400** may have any desired form factor, such as a handheld or mobile computing device (e.g., a cell phone, a smart phone, a mobile internet device, a music player, a tablet computer, a laptop computer, a netbook computer, an ultrabook computer, a personal digital

assistant (PDA), an ultramobile personal computer, etc.), a desktop computing device, a server or other networked computing component, a printer, a scanner, a monitor, a set-top box, an entertainment control unit, a vehicle control unit, a digital camera, a digital video recorder, or a wearable computing device. In some embodiments, the computing device **2400** may be any other electronic device that processes data.

SELECT EXAMPLES

(95) The following paragraphs provide various examples of the embodiments disclosed herein.

(96) Example 1 provides an IC device that includes a support structure (e.g., a substrate, a wafer, a die, or a chip); a III-N layer, provided over a portion of the support structure, the III-N layer including an n-doped well of a III-N semiconductor material with n-type dopants at a dopant concentration of at least 5×10^{17} dopants per cubic centimeter; a first electrode, interfacing (e.g., in contact with) a first portion of the n-doped well; a capping layer, interfacing (e.g., in contact with) a second portion of the n-doped well, the capping layer including a semiconductor material with a dopant concentration below 10^{17} dopants per cubic centimeter; and a second electrode, where the capping layer is between the second portion of the n-doped well and the second electrode.

(97) Example 2 provides the IC device according to example 1, where the semiconductor material of the capping layer is a polarization material (e.g., a semiconductor material having stronger piezo-polarization behavior/properties than the III-N semiconductor material).

(98) Example 3 provides the IC device according to examples 1 or 2, where the semiconductor material of the capping layer includes aluminum, gallium, and nitrogen (e.g., $\text{Al}_{\text{sub.x}}\text{Ga}_{\text{sub.1-x}}\text{N}$).

(99) Example 4 provides the IC device according to example 3, where the semiconductor material of the capping layer further includes indium (e.g., $\text{Al}_{\text{sub.x}}\text{In}_{\text{sub.x}}\text{Ga}_{\text{sub.z}}\text{N}$).

(100) Example 5 provides the IC device according to any one of the preceding examples, where a thickness of the capping layer is between about 2 and 50 nanometers, e.g., between about 2 and 20 nanometers, or between about 5 and 10 nanometers.

(101) Example 6 provides the IC device according to any one of the preceding examples, where the dopant concentration of the semiconductor material of the capping layer is below 10^{16} dopants per cubic centimeter.

(102) Example 7 provides the IC device according to any one of the preceding examples, where the capping layer is a first capping layer, the IC device further includes a second capping layer, the second capping layer includes a semiconductor material with a dopant concentration below 10^{17} dopants per cubic centimeter, the first capping layer is between the second capping layer and the second electrode, and the second capping layer is between the first capping layer and the second portion of the n-doped well.

(103) Example 8 provides the IC device according to example 7, where a material composition of the semiconductor material of the second capping layer is different from a material composition of the semiconductor material of the first capping layer.

(104) Example 9 provides the IC device according to examples 7 or 8, where the semiconductor material of the second capping layer includes aluminum, gallium, and nitrogen (e.g., $\text{Al}_{\text{sub.x}}\text{Ga}_{\text{sub.1-x}}\text{N}$).

(105) Example 10 provides the IC device according to example 9, where the semiconductor material of the second capping layer further includes indium (e.g., $\text{Al}_{\text{sub.x}}\text{In}_{\text{sub.y}}\text{Ga}_{\text{sub.z}}\text{N}$).

(106) Example 11 provides the IC device according to any one of examples 7-10, where a thickness of the second capping layer is between about 2 and 50 nanometers, e.g., between about 2 and 20 nanometers, or between about 5 and 10 nanometers.

(107) Example 12 provides the IC device according to any one of the preceding examples, where the dopant concentration of the semiconductor material of the second capping layer is below 10^{16} dopants per cubic centimeter.

(108) Example 13 provides the IC device according to any one of the preceding examples, where a thickness of the n-doped well is between about 50 and 5000 nanometers, e.g., between about 50 and 2000 nanometers, or between about 100 and 1000 nanometers.

(109) Example 14 provides the IC device according to any one of the preceding examples, where the III-N semiconductor material includes nitrogen and gallium, and optionally, one or more of indium or aluminum (e.g., GaN, InGaN, or AlGaN).

(110) Example 15 provides the IC device according to any one of the preceding examples, where the dopant concentration of the n-type dopants of the n-doped well is at least 10^{18} dopants per cubic centimeter.

(111) Example 16 provides the IC device according to any one of the preceding examples, further including a further III-N semiconductor material between the III-N semiconductor material of the n-doped well and the support structure, where the dopant concentration of the further III-N semiconductor material is below 10^{17} dopants per cubic centimeter.

(112) Example 17 provides the IC device according to example 16, where a thickness of the further III-N semiconductor material is between about 50 and 5000 nanometers, e.g., between about 50 and 2000 nanometers, or between about 100 and 1000 nanometers.

(113) Example 18 provides the IC device according to any one of the preceding examples, further including a buffer material between the III-N layer and the support structure, where a band gap of the buffer material is greater than a band gap of the III-N semiconductor material.

(114) Example 19 provides the IC device according to example 18, where the buffer material includes a material including aluminum, gallium, and nitrogen (e.g., AlGaN), and/or a material including aluminum and nitrogen (e.g., AlN).

(115) Example 20 provides the IC device according to examples 18 or 19, where a thickness of the buffer material is between about 100 and 5000 nanometers, e.g., between about 250 and 500 nanometers.

(116) Example 21 provides the IC device according to any one of the preceding examples, where the support structure is a substrate, a die, a wafer, or a chip.

(117) Example 22 provides the IC device according to any one of the preceding examples, where a distance between the first portion of the n-doped well and the second portion of the n-doped well is between about 2 and 500 nanometers, e.g., between about 50 and 300 nanometers, or between about 80 and 200 nanometers.

(118) Example 23 provides an IC package that includes an IC die, the IC die including an IC device according to any one of the preceding examples, e.g., an IC device any one of examples 1-22, and a further IC component, coupled to the IC die. For example, the IC package may include an IC device that includes a III-N layer, the III-N layer including an n-doped well of a III-N semiconductor material with n-type dopants at a dopant concentration of at least 5×10^{17} dopants per cubic centimeter; a cathode, over (e.g., in contact with) a first portion of the n-doped well; a capping layer, over (e.g., in contact with) a second portion of the n-doped well, the capping layer including a semiconductor material with a dopant concentration below 10^{17} dopants per cubic centimeter; and an anode, where the capping layer is between the second portion of the n-doped well and the anode.

(119) Example 24 provides the IC package according to example 23, where the IC device further includes a III-N transistor provided over a portion of the III-N layer that includes a III-N semiconductor material with dopants at a dopant concentration below 10^{16} dopants per cubic centimeter.

(120) Example 25 provides the IC package according to example 24, where the n-doped well, the cathode, the anode, and the capping layer form a III-N diode, and the III-N diode is coupled to the M-N transistor.

(121) Example 26 provides the IC package according to example 25, where the III-N diode is to provide ESD protection for the III-N transistor.

(122) Example 27 provides the IC package according to any one of examples 23-26, where the further IC component includes one of a package substrate, an interposer, or a further IC die.

(123) Example 28 provides a method for fabricating an IC device, the method including providing a III-N layer over a support structure, the III-N layer including an n-doped well of a III-N semiconductor material with n-type dopants at a dopant concentration of at least 5×10^{17} dopants per cubic centimeter; providing a diode stack structure over a first portion of the n-doped well, the diode stack structure including one or more capping layers that include one or more semiconductor materials with a dopant concentration below 10^{17} dopants per cubic centimeter; providing a first electrode, interfacing (e.g., in contact with) the diode stack structure so that the one or more capping layers are between the first portion of the n-doped well and the first electrode; and providing a second electrode, interfacing (e.g., in contact with) a second portion of the n-doped well.

(124) Example 29 provides the method according to example 28, where providing the III-N layer includes depositing the III-N semiconductor material over the support structure, and providing the n-doped well in a portion of the III-N semiconductor material.

(125) Example 30 provides the method according to example 29, where providing the n-doped well in the portion of the III-N semiconductor material includes performing ion implantation of the n-type dopants in the portion of the III-N semiconductor material.

(126) Example 31 provides the method according to any one of examples 28-30, further including providing a III-N transistor over a portion of the III-N layer that includes the III-N semiconductor material with dopants at a dopant concentration below about 10^{16} dopants per cubic centimeter.

(127) Example 32 provides the method according to any one of examples 28-31, further including processes for forming the IC device according to any one of the preceding examples.

(128) Example 33 provides the method according to any one of examples 28-32, further including processes for forming the IC package according to any one of the preceding examples.

(129) Example 34 provides an electronic device (e.g., a computing device) that includes a carrier substrate; and an IC die coupled to the carrier substrate, where the IC die includes the IC device according to any one of examples 1-22, and/or is included in the IC package according to any one of examples 23-27.

(130) Example 35 provides the electronic device according to example 34, where the electronic device is a wearable or handheld electronic device.

(131) Example 36 provides the electronic device according to examples 34 or 35, where the electronic device further includes one or more communication chips and an antenna.

(132) Example 37 provides the electronic device according to any one of examples 34-36, where the carrier substrate is a motherboard.

(133) The above description of illustrated implementations of the disclosure, including what is described in the Abstract, is not intended to be exhaustive or to limit the disclosure to the precise forms disclosed. While specific implementations of, and examples for, the disclosure are described herein for illustrative purposes, various equivalent modifications are possible within the scope of the disclosure, as those skilled in the relevant art will recognize. These modifications may be made to the disclosure in light of the above detailed description.

Claims

1. An integrated circuit (IC) device, comprising: a base; a semiconductor layer over a portion of the base, wherein the semiconductor layer includes a region of a III-N semiconductor material with n-type dopants at a dopant concentration of at least 5×10^{17} dopants per cubic centimeter; a first electrode interfacing a first portion of the region; a first capping layer interfacing a second portion of the region, wherein the first capping layer includes a semiconductor material with a dopant

concentration below 10^{17} dopants per cubic centimeter; a second capping layer between the first capping layer and the second portion of the region, wherein the second capping layer includes a semiconductor material with a dopant concentration below 10^{17} dopants per cubic centimeter, and a thickness of the second capping layer is between about 2 and 50 nanometers; and a second electrode, wherein the first capping layer is between the second capping layer and the second electrode.

2. The IC device according to claim 1, wherein the semiconductor material of the first capping layer is a polarization material.

3. The IC device according to claim 1, wherein a thickness of the first capping layer is between about 2 and 50 nanometers.

4. The IC device according to claim 1, wherein the dopant concentration of the semiconductor material of the first capping layer is below 10^{16} dopants per cubic centimeter.

5. The IC device according to claim 1, wherein the dopant concentration of the semiconductor material of the second capping layer is below 10^{16} dopants per cubic centimeter.

6. The IC device according to claim 1, wherein a thickness of the region is between about 50 and 5000 nanometers.

7. The IC device according to claim 1, wherein the dopant concentration of the n-type dopants of the region is at least 10^{18} dopants per cubic centimeter.

8. The IC device according to claim 1, further including a further III-N semiconductor material between the III-N semiconductor material of the region and the base, wherein the dopant concentration of the further III-N semiconductor material is below 10^{17} dopants per cubic centimeter.

9. The IC device according to claim 8, wherein a thickness of the further III-N semiconductor material is between about 50 and 5000 nanometers.

10. The IC device according to claim 8, further including a transistor, wherein the transistor includes the further III-N semiconductor material.

11. The IC device according to claim 1, further including a further material between the semiconductor layer and the base, wherein a band gap of the further material is greater than a band gap of the III-N semiconductor material.

12. The IC device according to claim 1, wherein a distance between the first portion of the region and the second portion of the region is between about 2 and 500 nanometers.

13. The IC device according to claim 1, wherein the first capping layer is between the second portion of the region and the second electrode.

14. An integrated circuit (IC) package, comprising: an IC die comprising an IC device, wherein the IC device includes: a III-N layer comprising an n-doped well of a III-N semiconductor material with n-type dopants at a dopant concentration of at least 5×10^{17} dopants per cubic centimeter, a cathode over a first portion of the n-doped well, a capping layer over a second portion of the n-doped well, wherein the capping layer includes a semiconductor material with a dopant concentration below 10^{17} dopants per cubic centimeter, an anode, wherein the capping layer is between the second portion of the n-doped well and the anode, and a III-N transistor over a portion of the III-N layer that includes a III-N semiconductor material with dopants at a dopant concentration below 10^{16} dopants per cubic centimeter; and a further IC component, coupled to the IC die.

15. The IC package according to claim 14, wherein: the IC device includes a diode, the diode includes the n-doped well, the cathode, the anode, and the capping layer, and the diode is coupled to the III-N transistor.

16. The IC package according to claim 15, wherein the diode is an electrostatic discharge protection diode.

17. A process of making an integrated circuit (IC) device, the process comprising: providing a semiconductor layer over a base, the semiconductor layer including a region of a III-N

semiconductor material with n-type dopants at a dopant concentration of at least 5×10^{17} dopants per cubic centimeter; providing a diode stack structure over a first portion of the region, the diode stack structure including one or more capping layers that include one or more semiconductor materials with a dopant concentration below 10^{17} dopants per cubic centimeter; providing a first electrode, interfacing the diode stack structure so that the one or more capping layers are between the first portion of the region and the first electrode; providing a second electrode, interfacing a second portion of the region; and providing a transistor over a portion of the III-N layer that includes the III-N semiconductor material with dopants at a dopant concentration below about 10^{16} dopants per cubic centimeter.

18. The process according to claim 17, wherein providing the semiconductor layer includes: depositing the III-N semiconductor material over the base, and providing the region in a portion of the III-N semiconductor material.

19. The process according to claim 17, wherein the transistor is a III-N transistor.

20. An integrated circuit (IC) device, comprising: a support structure; a III-N layer over a portion of the support structure, the III-N layer including an n-doped well of a III-N semiconductor material with n-type dopants at a dopant concentration of at least 5×10^{17} dopants per cubic centimeter; a first electrode interfacing a first portion of the n-doped well; a capping layer interfacing a second portion of the n-doped well, wherein the capping layer includes a semiconductor material with a dopant concentration below 10^{17} dopants per cubic centimeter, and wherein a distance between the first portion of the n-doped well and the second portion of the n-doped well is between about 2 and 500 nanometers; and a second electrode, where the capping layer is between the second portion of the n-doped well and the second electrode.

21. The IC device according to claim 20, wherein: the capping layer is a first capping layer, the IC device further includes a second capping layer, the second capping layer includes a semiconductor material with a dopant concentration below 10^{17} dopants per cubic centimeter, the first capping layer is between the second capping layer and the second electrode, and the second capping layer is between the first capping layer and the second portion of the n-doped well.

22. The IC device according to claim 21, wherein a thickness of the second capping layer is between about 2 and 50 nanometers.

23. The IC device according to claim 20, wherein a thickness of the n-doped well is between about 50 and 5000 nanometers.
