# GALLIUM NITRIDE WAFER SUBSTRATE FOR SOLID STATE LIGHTING DEVICES, AND ASSOCIATED SYSTEMS AND METHODS

## TECHNICAL FIELD

**[0001]** The present disclosure is generally related to wafer fabrication, and more particularly is related to a substrate, system and method for growing gallium nitride suitable for use in solid state lighting devices.

## BACKGROUND

**[0002]** Mobile phones, personal digital assistants ("PDAs"), digital cameras, MP3 players, and other portable electronic devices utilize solid state lighting ("SSL") devices (e.g., LEDs) for background illumination. SSL devices are also used for signage, indoor lighting, outdoor lighting, and other types of general illumination. Figure 1A is a cross-sectional view of a conventional SSL device 10a with lateral contacts. As shown in Figure 1A, the SSL device 10a includes a substrate 20 carrying an LED structure 11 having an active region 14, e.g., containing gallium nitride/indium gallium nitride (GaN/InGaN) multiple quantum wells ("MQWs"), positioned between N-type GaN 15, and P-type GaN 16. The SSL device 10a also includes a first contact 17 on the P-type GaN 16 and a second contact 19 on the N-type GaN 15. The first contact 17 typically includes a transparent and conductive material (e.g., indium tin oxide ("ITO")) to allow light to escape from the LED structure 11. Figure 1B is a cross-sectional view of another conventional LED device 10b in which the first and second contacts 17 and 19 are opposite of each other, e.g., in a vertical rather than lateral configuration. During formation of the LED device 10b, a substrate 20, similar to the substrate 20 shown in Figure 1A, initially carries an N-type GaN 15, an active region 14 and a P-type GaN 16. The first contact 17 is disposed on the P-type GaN 16, and a carrier 21 is attached to the first contact 17. The substrate 20 is removed, allowing the second contact 19 to be disposed on the N-type GaN 15. The structure is then inverted to produce the orientation shown in Figure 1B. In the LED device 10b, the first contact 17 typically includes a reflective and conductive material (e.g., aluminum) to direct light toward the N-type GaN 15.

[0003] As discussed in more detail below, the various elements of the SSL devices typically have different coefficients of thermal expansion (CTE). During temperature excursions that occur in manufacturing processes and/or during use, the difference in CTEs of the device elements may cause the elements to crack or delaminate. Due to differences in the coefficient of thermal expansion (CTE) for the various elements that form the wafers used for SSL manufacturing, and in particular, the CTE of sapphire relative to the CTE of GaN, wafers over four inches in diameter may be difficult to produce in a manner that results in high yields. Accordingly, there remains a need for substrates that improve the performance and reliability of the resulting device, and that reduce the cost and time associated with manufacturing such devices.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0004] Many aspects of the present disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale. Instead, emphasis is placed upon illustrating clearly the principles of the present disclosure. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

[0005] Figure 1A is a schematic cross-sectional diagram of an SSL device in accordance with the prior art.

[0006] Figure 1B is a schematic cross-sectional diagram of another SSL device in accordance with the prior art.

[0007] Figure 2 is a partially schematic, cross-sectional illustration of a support member configured in accordance with an embodiment of the present disclosure.

[0008] Figure 3 is a partially schematic, cross-sectional illustration of the support member shown in Figure 2 with a seed material and an at least partially crystal-oriented material in accordance with an embodiment of the present disclosure.

[0009] Figure 4A is a partially schematic, cross-sectional illustration of the support member shown in Figure 3 with the at least partially crystal-oriented material annealed in accordance with an embodiment of the present disclosure.

[0010] Figure 4B is a partially schematic, cross-sectional illustration of the support member shown in Figure 4A after a preferential etch in accordance with an embodiment of the present disclosure.

[0011] Figure 4C is a partially schematic, cross-sectional illustration of the support member shown in Figure 4B with the crystals of the at least partially crystal-oriented material regrown in accordance with an embodiment of the present disclosure.

[0012] Figure 5 is a partially schematic, cross-sectional illustration of the support member shown in Figure 4C with a gallium nitride layer formed in accordance with an embodiment of the present disclosure.

[0013] Figure 6 is a flowchart illustrating a method of forming the support member shown in Figures 2-5, in accordance with an embodiment of the present disclosure.

[0014] Figures 7A and 7B are partially schematic, cross-sectional illustrations of the support member shown in Figure 5 during construction of a vertical LED structure in accordance with embodiments of the present disclosure.

[0015] Figure 8 is a partially schematic, cross-sectional illustration of the support member shown in Figure 5 during construction of a vertical LED structure in accordance with embodiments of the present disclosure.

## DETAILED DESCRIPTION

[0016] Embodiments of the present disclosure are directed generally to substrates for growing gallium nitride, and associated systems and methods. The gallium nitride can be used to form solid state lighting ("SSL") devices. As used hereinafter, the term "SSL device" generally refers to devices with light emitting diodes ("LEDs"), organic light emitting diodes ("OLEDs"), laser diodes ("LDs"), polymer light emitting diodes ("PLEDs"), and/or other suitable sources of illumination other than electrical filaments, a plasma, or a gas. Briefly described, one embodiment of the system includes a support substrate, an intermediate structure formed on the support substrate, and a seed material formed on the intermediate structure. An amorphous and/or at least partially crystal-oriented material (e.g., silicon with a (111) crystal orientation) is disposed on the seed material, e.g., by plasma-enhanced chemical vapor deposition (PECVD). The amorphous and/or at least partially crystal-oriented material can be annealed and selectively etched to increase the number of crystals with a (111) crystal

orientation. At this point, the material is at least partially crystal-oriented, even if it was amorphous prior to annealing. The system can further include an epitaxially-grown gallium nitride (GaN) material (e.g., a GaN layer) over the crystals. It is expected that embodiments of the present disclosure can provide advantages over existing methods by eliminating the need for bonding a silicon- and/or gallium-nitride-containing substrate to an aluminum-nitride-containing substrate or other substrate that is thermally tailored to support GaN. Instead, the silicon and/or gallium nitride can be formed *in situ* on a single substrate.

**[0017]** Other systems, methods, features, and advantages of the present disclosure will be or become apparent to one of ordinary skill in the art. Several details describing structures or processes that are well-known and often associated with the disclosed systems and methods, but that may unnecessarily obscure some significant aspects of the disclosure, are not set forth in the following description for purposes of clarity. Moreover, although the following disclosure sets forth several embodiments of different aspects of the technology disclosed herein, several other embodiments can have different configurations or different components than those described in this section. Accordingly, the disclosed technology may have other embodiments with additional elements, and/or without several of the elements described below with reference to Figures 2-8.

**[0018]** Figure 2 is a partially schematic, cross-sectional illustration of a support member 110 (e.g., a wafer), configured in accordance with an embodiment of the present disclosure. The support member 110 can include a support substrate 112. The support substrate 112 can include materials having suitable properties that facilitate forming the additional structures described herein. In particular embodiments, the material selected for the support substrate 112 can include polycrystalline aluminum nitride (pAlN), or another material selected for its thermal expansion characteristics. Such characteristics include a coefficient of thermal expansion (CTE) that is approximately the same as or otherwise approximates or approaches the CTE for the subsequently formed GaN material. By selecting the material for the support substrate 112 in this manner, the quality, uniformity and/or producability of the GaN material can be improved. Further details regarding aspects of suitable support substrates 112 and associated methods are included in copending U.S. Application No. 12/861,706, filed on August 23, 2010, and incorporated herein by reference.

**[0019]** The support substrate 112 can include a suitable encapsulation layer 111 to prevent or at least restrict materials from diffusing from the support substrate 112 during subsequent

processes. The encapsulation material 111 can also be selected to match or approach the CTE of the subsequently deposited GaN. In at least some embodiments, the encapsulation material 111 includes silicon nitride or another silicon-based compound. An outer surface of the encapsulation material 111 can include an oxide 113, e.g., a layer of silicon dioxide. In at least some embodiments, the silicon dioxide by itself can support subsequently disposed materials. In other embodiments, an intermediate structure 114 shown in Figure 2 can perform this function.

**[0020]** The intermediate structure 114 can include silicon dioxide, silicon nitride, silicon carbide, or another suitable material selected to compensate, at least in part, for CTE differences between the support substrate 112 and subsequently disposed materials. Accordingly, the intermediate structure 114 can minimize or at least reduce bowing at temperatures that are useful for metal-organic chemical vapor deposition (MOCVD), e.g. temperatures from about 570°C to about 1100°C. The foregoing materials of the intermediate structure 114 can be disposed on the support substrate 112 in the form of sequential layers, in particular embodiments. In another embodiment, the intermediate structure 114 can include silicon carbide which is then oxidized to produce the silicon carbide and silicon dioxide constituents of the intermediate structure 114. The characteristics of these layers can be selected in a manner that depends at least in part on the range of GaN thicknesses that are subsequently deposited on the support member 110, for example, as described in co-pending U.S. Application No. 12/878,815, filed on September 9, 2010 and incorporated herein by reference. The layer characteristics can also be selected to provide chemical compatibility with subsequent processes and/or subsequently disposed materials. One or more of the layers may be combined, eliminated, or removed depending on the process details.

**[0021]** Figure 3 is a partially schematic cross-sectional illustration of the support member 110 of Figure 1 with a seed material 116 (e.g., a seed layer) and an initial material 117 disposed thereon, in accordance with an embodiment of the present disclosure. In particular embodiments, the seed material 116 includes aluminum nitride or a combination of titanium disposed on the intermediate structure 114 and nickel disposed on the titanium. The foregoing materials can be disposed via evaporation processes or other suitable processes. The initial material 117 can include an amorphous material and/or an at least partially crystal-oriented material (hereinafter, "crystal-oriented material"). The initial material 117 can be disposed on the seed material 116 by thermal or e-beam evaporation, sputtering, CVD, PECVD, atomic layer deposition (ALD), or another suitable technique. When the initial material 117 includes an

amorphous component, the amorphous component generally does not include crystals. When the initial material 117 includes a crystal-oriented material, the microstructure of the crystal-oriented material includes at least some crystals oriented in a common direction. For example, the crystal-oriented material can be polycrystalline (e.g., polysilicon), or can include a mixture of grains having various crystalline orientations. Known deposition techniques may be used to produce films with relatively high fractions of grains oriented along specific directions. For example, when the crystal-oriented material includes polysilicon, such techniques can be used to deposit the crystal-oriented material with at least some crystals having a (111) orientation, which is typically desirable for support a subsequent GaN layer having an (0001) crystal orientation. In other embodiments, e.g., if the crystal-oriented material is primarily composed of an element other than silicon, the crystal-oriented material can have a high fraction of grains that are oriented in a direction other than (111), while still providing a suitable support for a subsequent GaN layer having a (0001) crystal orientation. In still further embodiments, the crystal-oriented material can have grains oriented in a direction that supports GaN with a crystal orientation other than (0001). In at least some embodiments, the initial material 117 can be patterned, e.g., in stripes or other shapes (e.g., using a photolithographic masking and etching process) to enhance the effects of subsequent chemical treatments. In some cases, enhancing these effects includes higher rates of recrystalization. In any of these embodiments, the degree of crystallinity in the initial material 117 may be developed, established and/or improved by a combination of physical and chemical reactions/processes, as will be described further with reference to Figures 4A-4C.

**[0022]** The initial material 117 includes silicon in some embodiments and in particular embodiments, only silicon. In other embodiments, the initial material 117 includes materials other than silicon, provided they form a suitable starting layer for GaN growth. Such materials include, but are not limited to, AlN, SiC, $Al_2O_3$ (sapphire), and spinel. In particular embodiments, the initial material 117 can include GaN. In other embodiments, however, GaN is not included in the support member 110 until it is disposed in the process described later with reference to Figure 5. The materials can be disposed on the support member 110 via any of a variety of suitable techniques, including thermal or e-beam evaporation, DC or RF sputtering, electroplating, molecular beam epitaxy (MBE), ALD, pulsed-laser deposition (PLD), spin coating, MOCVD, hydride vapor phase epitaxy (HVPE), and liquid phase epitaxy (LPE). In a particular embodiment, the initial material 117 includes polysilicon deposited in a low pressure

CVD process (LPCVD) using silane as a precursor gas. The initial material 117 can be annealed and/or can undergo chemical reactions following deposition, or after additional materials or reactants are deposited or placed in proximity to it. The resulting structure can have an enhanced or increased degree of crystallinity, ranging up to a single-crystal structure.

**[0023]** Figure 4A is a partially schematic, cross-sectional view of the support member 110 shown in Figure 3, with the initial material 117 shown in Figure 3 annealed to form a crystal-oriented material 118. Accordingly, even if the initial material 117 included an amorphous component prior to annealing, the post-anneal, crystal-oriented material 118 shown in Figure 4A has at least some crystals oriented in a common direction. If the initial material 117 already included a crystal-oriented material component, the annealing process causes the number or population of crystals having a particular crystal orientation to increase. For example, when the seed material 116 and/or the intermediate structure 114 are selected to favor the growth of crystals having a (111) orientation, annealing the initial material 117 can cause additional crystals to form and/or align with the (111) orientation (indicated schematically by the upwardly pointing arrows in Figure 4A). Typical annealing parameters include temperatures in the range of from about 450°C to about 900°C. In at least some embodiments, the annealing process can include a zone melt recrystalization process in which areas of the initial material 117 are sequentially exposed to high temperatures, forming a recrystalization "front" that progresses through the material 117. Other annealing processes are used in other embodiments, and in any of these embodiments, the process can increase the population of crystals having the (111) orientation, thus facilitating the subsequent growth of device-quality GaN films. The crystallization process can include other techniques to further enhance crystalinity, as described further below.

**[0024]** Figure 4B is a partially schematic, cross-sectional illustration of the support member 110 shown in Figure 4A. In Figure 4B, the crystal-oriented material 118 has undergone a preferential etch process in accordance with an embodiment of the present disclosure. The preferential etch process can be used to remove grains with a less desirable orientation, e.g., grains with an orientation other than (111). For example, Si (001) etches much faster than Si (111) in KOH. The (111) grains may shrink but not completely disappear while still providing the crystal-oriented material 118 with a greater fraction of crystals having the (111) orientation. After this preferential etching, a combination of annealing and chemical reaction steps may be performed to modify the physical and chemical properties of the crystal-oriented material 118

and/or the seed material 116 which can be exposed during the etching process. The preferential etch may include selective wet etch processes and/or other processes, such as oxidation processes, diffusion processes, or other processes with or without dependence on crystal orientation. Accordingly, the overall preferential etch process can be performed to selectively remove grains having crystal orientations other than (111), but the process can include steps or subprocesses that are not dependent on crystal orientation.

**[0025]** Figure 4C is a partially schematic, cross-sectional view of the support member 110 shown in Figure 4B after the crystal-oriented material 118 has undergone a regrowth process in accordance with an embodiment of the present disclosure. In a particular aspect of this embodiment, the crystal-oriented material 118 undergoes a regrowth process that can increase the size of the crystals having the desired orientation (e.g., the (111) orientation), thus increasing the surface area of such crystals. The regrowth process can include successively running the support member 110 through a silicon epitaxial reactor, or through a GaN epitaxial reactor running silicon precursors (e.g., silane). After the regrowth process, the crystal-oriented material 118 can be further annealed to increase the level of (111) crystallization. The foregoing annealing, removal and growing operations may be performed repeatedly to increase the level of (111) crystal orientation, thus facilitating the subsequent growth of device-quality GaN films.

**[0026]** Figure 5 is a partially schematic cross-sectional view of the support member 110 shown in Figures 4A-4C with a gallium nitride material 120 (e.g., a GaN layer) formed thereon, in accordance with an embodiment of the present disclosure. As shown in Figure 5, an optional buffer material 122 can be formed on the crystal-oriented material 118 to enhance the formation of the GaN material 120. For example, the buffer material 122 can include aluminum gallium nitride ($Al_xGa_{1-x}N$ ($0<x\leq1$), or AlGaN), with the crystal-oriented material 118 serving as an appropriate base surface on which the AlGaN is epitaxially grown. A thin silicon nitride layer can be disposed on or included in the buffer material 122. The GaN material 120 can be disposed via a suitable crystal-growth process, e.g., MOCVD or HVPE. The particular process can be selected based on the desired end results. For example, HVPE processes are generally faster than MOCVD processes, and can accordingly be used to grow relatively thick GaN layers, e.g., from about 10$\mu m$ to about 300$\mu m$ thick and in a representative embodiment, about 50$\mu m$ or more thick. Such thick layers may be particularly suitable for large wafers (e.g., wafers having a diameter of at least six inches) to reduce dislocation densities. Such a support member, e.g., a support member 110 having a thick layer of GaN (initially without a light-emitting material) and

a support substrate 112 with a CTE selected to match or approximate the GaN CTE is accordingly expected to perform better during typical LED formation processes than are existing substrates and support members. Even greater film thicknesses (e.g., greater than 300$\mu m$ thick) can in some instances be used to produce a stand-alone GaN substrate, if the remaining portions of support member 110 are removed. For example, it is expected that a 500$\mu m$ thick layer (or a thicker layer) on a six-inch support member wafer can be self-supporting, allowing the remainder of the support member to be removed after the GaN layer is formed. The thickness of the layer can be 500$\mu m$ or more (e.g., up to or greater than 1000$\mu m$) for wafers having larger diameters (e.g., greater than six inches). In general, thicker layers are expected to result in lower dislocation densities.

**[0027]** The crystal-oriented material 118 can be sufficiently thin that the thermal expansion characteristics of the overall structure are dominated by the underlying portion of the support member 110 (e.g., by the support substrate 112). In particular embodiments, the GaN material 120 and/or the buffer material 122 may have relatively high concentrations of microstructural defects and/or voids at the onset of growth. After a few microns of growth, it is expected that the GaN film will fully coalesce, resulting in a defect density low enough to produce GaN suitable for SSL devices such as LEDs. In any of the foregoing embodiments, the degree and microstructure of (111) crystallization is expected to at least partially control the formation (e.g., the crystal orientation) of the GaN material 120, with or without the buffer material 122. For example, it is expected that the increased level of (111) crystalinity in the crystal-oriented material 118 will decrease the density of threading dislocations in the overlying GaN material 120. In particular embodiments, the resulting GaN material 120 can have a dislocation density of $10^{10}/cm^2$ or less, and more particularly, $10^9/cm^2$ or less, e.g., in the light-emitting region of the GaN.

**[0028]** Certain aspects of the embodiments described herein can be modified or combined to produce the desired GaN features. For example, the various elements and/or process parameters used to form the structures described above can be selected based on the starting characteristics of the support substrate 112 or on the characteristics of successive materials disposed on the support substrate 112. The characteristics of the resulting structure may also be selected based on the requirements of the final SSL device or other device to be constructed with the GaN material.

**[0029]** Figure 6 is a flowchart 600 illustrating a method for growing gallium nitride 120 on a substrate 112 to form the support member 110, in accordance with an embodiment of the present disclosure. It should be noted that any process descriptions or blocks in the flow chart can represent modules, segments, portions of code, or steps that include one or more instructions (e.g., instructions encoded on a computer-readable medium) for implementing specific logical functions in the process. In other embodiments, certain functions may be executed in an order different from that shown or described below, including substantially concurrently or in reverse order, depending on the functionality involved, as will be understood by those of ordinary skill in the relevant art.

**[0030]** Block 602 includes providing a support substrate, e.g., any of the support substrates described above. Block 604 includes forming an intermediate structure on the support substrate, and block 606 includes disposing a seed material on the intermediate structure. As discussed above, the intermediate structure and the seed material can be selected and disposed to facilitate growing a GaN structure with a (0001) or other selected crystal orientation. As was also discussed above, in at least some embodiments, the functions of the intermediate structure and/or the seed material can be combined or performed by other structures. Block 608 includes forming an initial material on the seed material (or in another manner in which it is carried by the support substrate), e.g., by PECVD or another suitable process. In block 610, the initial material is annealed and/or otherwise processed to form a crystal-oriented material with an increased number, population, and/or extent of crystals having a selected orientation, e.g., a (111) orientation for silicon. An optional buffer layer can be formed over the crystal-oriented material to support the gallium nitride material, which is then formed (e.g., epitaxially grown) on, over, or otherwise, so as to be carried by the crystal-oriented material (block 612).

**[0031]** One feature of the foregoing process is that it can be completed without bonding preformed structures, as a unit, to the support substrate. For example, the foregoing process does not require that a separate substrate (e.g., a wafer) carrying a silicon or gallium nitride layer be bonded as a unit (e.g., via Van der Waal's forces) to a corresponding thermally matched or otherwise tailored substrate carrying an aluminum nitride or other layer. Instead, aspects of the present disclosure are directed to using a deposition and/or growth process to build a suitable structure from much smaller elements, typically on the order of microns in size. In particular, the processes described above can form a crystal-oriented material having a crystal structure that is predominantly in a predetermined direction (e.g., (111) in the case of silicon), with the

predetermined direction selected to facilitate, enhance and/or otherwise improve the composition of the subsequently-formed GaN material. The GaN material is then formed to have crystals also oriented predominantly in a preferred or selected direction (e.g., (0001)).

**[0032]** An advantage of the present arrangement is that the existing wafer bonding processes typically require high forces between the structures (wafers) that are bonded to each other. Most existing fabrication tools used to perform such bonding processes are limited to a peak force. As the wafers or other substrates supporting such structures increase in size, e.g., from a diameter or other widthwise dimension of 4 inches to 6 inches, 8 inches, 10 inches, then 12 inches or more, the pressure provided by the fixed-force tools decreases linearly as a function of the increasing area of the bonded devices, which can reduce the efficacy of the bonding process. Accordingly, the techniques described above with reference to Figures 2-6 can facilitate forming suitable gallium nitride materials on large diameter wafers, without requiring the bonder to operate at forces beyond those for which they were built. This in turn can allow a manufacturer to produce large quantities of LEDs or other SSL devices using existing equipment.

**[0033]** Another feature of at least some of the foregoing embodiments is that they eliminate the need for implanting elements (e.g., hydrogen) in a substrate to facilitate separating a substrate layer (after bonding to a thermally tailored or matched substrate) in a later high-temperature process. Eliminating this process can improve the throughput of the overall manufacturing process.

**[0034]** The GaN material 120 described above can be used to form a variety of LEDs or other SSL devices having a corresponding variety of structural arrangements. In particular, such devices can be formed using a vertical arrangement or a lateral arrangement. In a vertical arrangement, the support substrate 112 is removed via a wet etch process, and the intermediate structure 114 can serve the additional function of a wet etch stop, thus facilitating efficiently removing the support substrate 112 and/or other material between the support substrate 112 and the intermediate structure 114. A wet chemical etch, a reactive ion etch (RIE) or other etching technique known to those having ordinary skill in the art can be used to remove the intermediate structure 114 and/or a metal layer (e.g., the seed material 116), as is typical for a vertical arrangement.

**[0035]** Figures 7A and 7B are partially schematic, cross-sectional illustrations of the support member 110 of Figure 5 as it is used to construct a vertical LED structure 150a in

accordance with an embodiment of the present disclosure. Beginning with Figure 7A, epitaxially grown multiple quantum wells (MQWs), are formed on the GaN material 120 by alternating "well" material layers with "barrier" material layers in a manner known to those of ordinary skill in the relevant art, resulting in an active light-emitting region 132. A region of P-type GaN 134 is further formed on the light-emitting region. A P-contact 130 is formed on the P-type GaN region 134, and a bonding layer 133 (e.g., a gold-tin or nickel-tin alloy or other suitable bonding material) is formed on the P-contact 130. The bonding layer 133 is used to attach a suitable carrier 135 (e.g., a silicon wafer or submount, or a CuW carrier) to the support member 110. As shown in Figure 7B, the support substrate 112 and the crystal-oriented material 118 are then etched off using a combination of wet chemistry, plasma etching, and/or grinding. At least a portion of the GaN material 120 includes N-type GaN. Accordingly, an N-contact 131 can be directly disposed on the GaN material 120, with the light-emitting region 132 between the N-contact 131 and the P-contact 130. Vertical cavity surface-emitting lasers (VCSELs) may be formed via a generally similar process.

**[0036]** Figure 8 is a partially schematic cross-sectional illustration of the support member 110 shown in Figure 5 used to form a lateral LED structure 150b in accordance with another embodiment of the present disclosure. The device fabrication is carried out in a manner generally similar to that used for existing lateral arrangements. Figure 8 illustrates a lateral LED 150b with both the P-contact 130 and the N-contact 131 on an upwardly-facing surface of the GaN material 120 on opposite sides of the light-emitting region 132, after etching a suitable portion of the P-region forming the P-contact 130, and the active region 132 below. The fabrication of semiconductor lasers, high-electron mobility transistors (HEMTs) and/or other diodes, rectifiers, photodetectors, and/or other suitable semiconductor devices is expected to follow a similar layout. The LED 150b shown in Figure 8 can be used in a "flip chip" arrangement by inverting the LED 150b and connecting the contacts 130, 131 to a suitable PCB or other substrate.

**[0037]** In a particular embodiment, the portion of the support member 110 below the GaN material 120 (e.g., the crystal-oriented material 118, the seed material 116, the intermediate structure 114 and the support substrate 112) can be separated from the LED 150b. In another embodiment, the foregoing portion of the support member 110 can be left in place because (unlike the vertical LED 150a described above) it is not necessary to remove this material in order to form the N-contact 131. Accordingly, this arrangement can be used where the volume

of the LED is a less significant design constraint, and/or where the cost of the LED is a more significant design constraint.

**[0038]** From the foregoing, it will be appreciated that specific embodiments of the technology have been described herein for purposes of illustration, but that various modifications may be made without deviating from the disclosed technology. For example, the materials disposed on the support substrate can be disposed in accordance with processes and/or process parameters different than those expressly described above. In one particular embodiment, the order in which the seed material 116 and the crystal-oriented material 118 (or its precursor, the initial material 117) are formed can be reversed from the arrangement shown in Figures 3-4C. That is, the seed material 116 can be disposed on the crystal-oriented material 118 rather than vice versa. In a particular embodiment, the seed material 116 can include nickel, and in other embodiments, it can include other elements or compounds. In any of these embodiments, the seed material 116 can perform the same function (e.g., facilitating the (111) crystal orientation of the crystal-oriented material 118) whether it is disposed before or after the crystal-oriented material 118. When it is disposed after the crystal-oriented material 118, it can be removed by a different etchant than is used to remove the crystal-oriented material 118, or by the same etchant, depending on the composition of the seed material 116, the crystal-oriented material 118, and the etchant. In any of these embodiments, an advantage of disposing the seed material 116 after the crystal-orientation material 118 is that it will be removed as part of the etching process and therefore will be less likely to influence (e.g., diffuse into) other structures. Conversely, disposing the seed material 116 before the crystal-oriented material 118 can, in at least some embodiments, provide a greater crystal orientation influence on the crystal-oriented material 118.

**[0039]** Certain aspects of the technology described in the context of particular embodiments may be combined or eliminated in other embodiments. For example, in one embodiment, the seed material described above can be combined with the intermediate structure. In other embodiments, the seed material can be formed directly on the support substrate without the need for the intermediate structure. In still further embodiments, both the seed material and the intermediate structure can be eliminated and the corresponding functions provided by these materials/structures can be carried out by a silicon dioxide layer formed directly on the support substrate or on the encapsulant carried by the support substrate. In other embodiments, certain process steps can be eliminated. For example, treating the crystal-oriented layer 118 can include

etching or annealing, but not both, in at least some embodiments. Further, while advantages associated with certain embodiments have been described in the context of those embodiments, other embodiments may also exhibit such advantages, and not all embodiments need necessarily exhibit such advantages to fall within the scope of the present technology. Accordingly, the present disclosure and associated technology can encompass other embodiments not expressly shown or described herein.

## CLAIMS

I/We claim:

1. A method of making a solid state lighting ("SSL") device substrate, the method comprising:

forming a region of silicon over a support substrate, the region of silicon including first crystals having a (111) crystal orientation and second crystals not having the (111) crystal orientation;

etching the region of silicon to preferentially remove material from the second crystals relative to material from the first crystals;

forming additional silicon over the region of silicon after etching the region of silicon; and

forming gallium nitride over the region of silicon after forming the additional silicon, the gallium nitride forming with a (0001) crystal orientation.

2. The method of claim 1, wherein forming the region of silicon over the support substrate includes forming the region of silicon over a support substrate that includes polycrystalline aluminum nitride.

3. The method of claim 1, further comprising removing the gallium nitride from the region of silicon.

4. The method of claim 1, further comprising forming a buffer material over the region of silicon, wherein forming the gallium nitride includes forming the gallium nitride over the buffer material.

5. The method of claim 4 wherein forming the buffer material includes forming a buffer material that includes aluminum gallium nitride.

6. The method of claim 1 wherein forming the gallium nitride includes forming gallium nitride using a metal organic chemical vapor deposition ("MOCVD") process.

7. The method of claim 1 wherein forming gallium nitride includes forming gallium nitride having a dislocation density of $10^9/cm^2$ or less.

8. The method of claim 1 wherein:

the method further comprises—

growing an intermediate structure over the support substrate, and

disposing a seed material over the intermediate structure; and

forming the region of silicon over the support substrate includes forming the region of silicon over the intermediate structure.

9. The method of claim 8, further comprising annealing the region of silicon by zone melt recrystallization.

10. The method of claim 8 wherein growing the intermediate structure includes forming a layer having at least one of silicon dioxide, silicon carbide and silicon nitride.

11. The method of claim 8 wherein disposing a seed material includes disposing the seed material comprising aluminum nitride.

12. The method of claim 8 wherein disposing a seed material includes disposing the seed material comprising titanium and nickel.

13. The method of claim 3, further comprising forming an SSL device from the removed gallium nitride.

14. The method of claim 1 wherein the region of silicon includes a layer containing only silicon.