along with band diagrams showing properties of individual layers with and without external bias.

FIG. **5** shows a diagram of electroluminescence intensity vs. photon wavelength for a graded p-n junction LED under increasing forward bias.

DETAILED DESCRIPTION OF INVENTION

One or more embodiments of the present disclosure are directed to a light emitting device (LED) capable of emitting light over a wide spectrum, from ultra-violet to near-infrared, without the use of phosphor materials, based on three recent advancements: (1) progress in the growth of group III-nitrides on Si substrates; (2) successful formation of p/n junctions in partially phase-separated InGaN; and (3) improved ability to grow compositionally graded n-type and p-type layers of InGaN, with a composition range from 0% to 40% In. Various embodiments are described herein using the case of InGaN alloys, but the present teachings are also applicable to InAlN ternary or InGaAlN quaternary alloys. Further, while various embodiments are described herein using the case of group III-nitrides formed on Si substrates, the present teachings could in principle be formed on other substrates, such as sapphire or SiC, with properly modified growth conditions.

In a first embodiment, the basic structure of the new light emitting device consists of a heavily doped (e.g., doped at 5×1018-2×1019 cm−3) p-type Si (111) substrate followed by a buffer layer, as shown in FIG. **1**. In FIG. **1**, section a shows the layer structure of the light emitting from the device, section b shows a band diagram with no bias applied, and section c shows a band diagram with external bias, V_{ext}. While the buffer layer in the illustrated embodiment consists of a thin AlN nucleation layer, any other suitable nucleation layer may be utilized. The buffer layer is followed by an n-type GaN layer. In one embodiment, the n-type GaN layer is doped at 10^{18}-10^{19}cm^{-3}. The GaN layer is followed by an n-type InGaN layer graded from GaN to a target InGaN composition having a desired percentage of In. In one embodiment, the GaN layer is followed by an n-type InGaN layer graded from GaN to a target InGaN composition having 40% In on average. However, it should be noted that the target composition depends on the desired LED color range. The graded n-type InGaN layer is followed by an n-type InGaN layer and a p-type InGaN layer of the target composition (i.e., the target InGaN composition having a desired percentage of In). The p/n junction is formed in the InGaN of the target composition or in the graded n-type region. The alloy composition and/or the thickness of the InGaN p/n junction is adjusted to optimize the intensity and to select the wavelength of the emitted light. For example, the parameters of the target composition of the InGaN p/n junction can be adjusted to allow the device to be tuned to produce Green and longer wavelength LEDs or other multi-color and/or white light spectrums. The p/n InGaN layers of the constant target composition are followed by a p-type InGaN layer graded from the target InGaN composition to GaN (i.e., the final grading is absent In).

Finally the structure is capped with a layer of p-type GaN. An ohmic contact (not shown) for injecting current is formed on the back of the p-Si substrate using a metal deposition. A top ohmic contact is formed on the top surface of the p-type GaN layer. This top contact to the p-type GaN can be made using a semi-transparent NiAl layer, a metallic grid or a transparent conducting oxide (TCO). Details as to the formation of ohmic contacts can be found in PCT Patent Application No. PCT/US2008/004572 entitled "Low Resistance Tunnel Junctions for High Efficiency Tandem Solar Cells" filed Apr. 9, 2008, and in U.S. Provisional Patent Application

No. 60/910,734 filed Apr. 9, 2007, the entire disclosures of which are incorporated herein by reference. In these disclosures, the inventors teach how p-type Si forms a low resistance ohmic contact with n-type InGaN. In the context of the present invention, this will facilitate the electrical contact from the substrate to the active device.

In one or more embodiments, the group III-nitride layers (or other layers) are deposited using molecular beam epitaxy (MBE) techniques, but it is understood that the various layers can also be deposited using metal-organic chemical vapor deposition (MOCVD), hydride vapor phase epitaxy (HYPE), remote plasma chemical vapor deposition (RPCVD), or any other appropriate deposition method.

The energy band diagram of the device structure is schematically shown in FIG. **1** at section b. The graded region on the n-type side of the device structure confines the holes whereas the graded region on the p side confines the electrons.

InGaN undergoes phase separation into the regions of larger and smaller In content. The phase separation is especially severe at high In content, e.g., greater than 30% In content. The origin of this phenomenon is not well established. However, there are indications that it could be attributed to the higher chemical binding energy of GaN compared with InN molecule. Consequently, with higher Ga content, e.g., greater than 60% Ga, larger band gap regions will be formed at growth initiation regions such as grain boundaries and dislocations, whereas with large In content, e.g., greater than 30% In, small band gap regions will be removed away from such internal surfaces. This also leads to spatial variations of the carrier lifetime as the regions close to the grain boundaries and/or dislocations have larger densities of non-radiative recombination centers. Clusters with larger In content are exemplary indicated as a few wells in the band diagrams in FIG. **1** at sections b and c, and in FIG. **4** at sections b and c.

When, as shown in FIG. **1** at section c, the device structure is forward biased, the electrons (e) and holes (h) are injected into the InGaN region. They tend to agglomerate in the high In, low band gap regions. The observed electroluminescence (EL) energy is expected to be lower than that predicted by the average composition. Also, the EL should be more efficient because of the lower density of non-radiative centers in the In-rich region.

The present inventors have grown and tested several device structures as shown in FIG. **1** at section a. The testing included a composition variation measured by Rutherford Backscattering Spectroscopy (RBS), with the results of such testing shown in FIG. **2**. In particular, FIG. **2** shows a composition profile of an LED structure in accordance with an embodiment of the invention, as determined by RBS. In the insert, maximum average indium fraction determined in the InGaN region is ~8%. The p/n junction in the InGaN layer was fabricated using Mg doping. The average In composition of the InGaN junction region was 8% (i.e., the target InGaN composition possessed 8% In). However, EL measurements of this device structure have shown, as illustrated in FIG. **3**, a strong peak at 2.3 eV in the green range of the visible spectrum (540 nm).

This emission energy corresponds to much larger In content of 30%. The low energy EL indicates phase separation and formation of clusters with In composition of 30%, which is larger than the average In content of 8%. In accordance with one or more embodiments, a key advantage here is that the p/n junction is formed in the InGaN target layer before the top graded layer. The rectifying properties are determined by the low In composition (majority) phase, whereas emission prop-