MULTI-COLOR LIGHT EMITTING DEVICES WITH COMPOSITIONALLY GRADED CLADDING GROUP III-NITRIDE LAYERS GROWN ON SUBSTRATES

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a continuation application of U.S. Non-Provisional Application Ser. No. 13/541,836, filed Jul. 5, 2012, and entitled "Multi-Color Light Emitting Devices with Compositionally Graded Cladding Group III-Nitride Layers Grown on Silicon Substrates," by Walukiewicz et al., which claims priority to U.S. Provisional Patent Application No. 61/505,954 filed Jul. 8, 2011. The entire contents of these applications are incorporated by reference as is fully set forth herein.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The disclosure relates to a light emitting device (LED) based on group III-nitride semiconductors grown on Si substrates capable of emitting light over a wide spectrum, e.g., from ultra-violet to near-infrared.

2. Background Discussion

Light emitting diodes (LEDs) are semiconductor devices having P-N junctions which, when appropriately connected to a power supply, generate light. The high efficiency of the light generation in the short wavelength part of the light spectrum (e.g., ultra-violet and blue) has prompted the use of LEDs in many applications, including simple character or signal displays and more complex colored image displays. The use of LEDs for flashlights, brake lamps, signboards, etc, is well known. The current technique for the creation of colored light relies on the UV or blue emission of the nitride-based LEDs to excite phosphor granules embedded in an epoxy dome that, in turn, could generate green or red light. To generate white light, the blue light of the LED is mixed with the green and red emissions of phosphor granules. This technique, however, has low efficiency at the phosphor level and the epoxy encapsulant tends to degrade, thereby degrading the transparency due the interaction with high energy blue light. The emergence of white LEDs as potential sources for illumination, expected to replace conventional incandescent and fluorescent lighting, is based on the demonstrated high efficiency in the short wavelength spectrum, on the relative long lifetime and reliability of the devices, and on their simple and versatile control, potentially allowing color adjustments, just to mention a few of LEDs' advantages. However, it has been found that the high conversion efficiency of nitride LEDs cannot be easily extended toward wavelengths longer than blue, and this situation has become known in the literature as "the green gap."

Current LED operation is based on the fabrication of a multi-quantum well structure (MQW) in the active volume of the device that is sandwiched between n-type gallium nitride (n-GaN) and p-type gallium nitride (p-GaN) regions. The MQWs are also a succession of high band gap/low band gap layers of nanometer size, typically GaN/InGaN, that create within the quantum well intermediate energy levels between that of the high and low band gap of the material system. The distribution of the intermediate energy levels defines the device color and depends on the geometric parameters of the MQW structure as well as on the band gap levels of the component materials. Green color, for example, extends in the range of wavelengths from 495 nm to 570 nm. For the middle of the green domain range (~532 nm), a nitride GaN/InGaN semiconductor alloy system would have the lowest material gap of about or lower than 2.33 eV. This band gap requires a fraction of at least 29% indium in the composition of InGaN.

To exhibit high quantum efficiency, the formation of carrier recombination centers, such as misfit or threading dislocations, has to be avoided. Misfit strain arises from the difference between the in-plane lattice parameters of the epilayers. A basic concept in the epitaxial growth is that for very thin layers it is energetically favorable to accommodate the misfit strain elastically, while for thicker epilayers the strain is accommodated by introducing defects such as misfit dislocations. For this reason, the alternating layers are grown pseudomorphically, which requires the thickness of each of the alternating layers to remain below the limit at which the atomic bonds break and dislocations are formed. This limit is known as the critical thickness. The difficulty in the epitaxial fabrication of such a MQW system relates to the elastic properties of the InGaN/GaN layer system. According to various models, such as the van der Merwe model (e.g., Matthews, J. W. and Blakeslee, A. E., "Defects in epitaxial multilayers: 1. misfit dislocations," J. Crystal Growth, Vol. 27, December 1974, pp. 118-125, incorporated herein in its entirety), the force balance model (e.g., Srinivasan, S., Geng, L., Liu, R., Ponce, F. A., Narukawa, Y., and Tanaka, S., "Slip systems and misfit dislocations in InGaN epilayers," Appl. Phys. Lett., Vol. 83, No. 25, December, 2003, pp. 5187-5189, incorporated herein in its entirety), or the energy balance model (e.g., Park, S.-E., O, B., and Lee, C.-R., "Strain relaxation in InxGa1-xN epitaxial films grown coherently on GaN," J. Crystal Growth, Vol. 249, No. 3-4, March 2003, pp. 455-460, and Lu, W., Li, D. B., Li, C. R., and Zhang, Z., "Generation and behavior of pure-edge threading misfit dislocations in InxGa1-xN/GaN multiple quantum wells," J. Appl. Phys., Vol. 96, No. 9, November 2004, pp. 5267-5270, incorporated herein in their entirety), the critical thickness decreases with the increase of the indium fraction. The force balance and energy balance models both predict a critical thickness smaller than 2 nm for an Indium fraction of 30%, that decreases further with the increase of the Indium fraction. Experimental data suggests a critical thickness of approximately 3 nm at a 20% Indium fraction, a value that is lower than the approximate 6 nm value predicted by the aforementioned force balance or energy balance models. These results suggest that the fabrication of MQW LEDs having quantum wells with Indium fractions in the range of 30% or larger is associated with the increase of the misfit and threading dislocation Density—non-radiative defects—and a sudden decrease of the overall radiative carrier recombination efficiency, phenomenon known as the green gap.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a schematic cutaway side view illustrating a layer structure according to an embodiment of the invention, along with band diagrams showing properties of individual layers with and without external bias.

FIG. **2** shows a measured composition profile of a synthesized LED structure in accordance with an embodiment of the invention.

FIG. **3** shows a diagram of the emission intensity vs. wavelength for the LED structure shown in FIG. **2**. The electroluminescence spectrum shows a peak with a wavelength of 540 nm (2.3 eV) in the green part of the visible spectrum.

FIG. **4** shows a schematic cutaway side view illustrating a layer structure according to an embodiment of the invention,