Color tunable monolithic InGaN/GaN LED having a multi-junction structure

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Abstract: In this study, we have fabricated a blue-green color-tunable monolithic InGaN/GaN LED having a multi-junction structure with three terminals. The device has an n-p-n structure consisting of a green and a blue active region, i.e., an n-GaN / blue-MQW / p-GaN / green-MQW / n-GaN / Al2O3 structure with three terminals for independently controlling the two active regions. To realize this LED structure, a typical LED consisting of layers of n-GaN, blue MQW, and p-GaN is regrown on a conventional green LED by using a metal organic chemical vapor deposition (MOCVD) method. We explain detailed mechanisms of three operation modes which are the green, blue, and cyan mode. Moreover, we discuss optical properties of the device.

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References and links
1. Introduction

The InGaN/GaN-based light-emitting diode (LED) has already found a wide utilization for general illumination and is now also finding uses in other applications such as displays and wearable devices due to its high brightness and high efficiency characteristics [1–3]. In particular, a wearable device such as a head-mounted display or a smart glass demands an efficient color-tunable display for which LEDs are well suited because of improved color emission and efficiencies of the LEDs.

Previous studies have introduced various structures and methods to realize GaN-based microdisplays [4–7]. These structures have involved for the most part conventional LED concepts including, in particular, three LED chips each emitting red, green, and blue light arranged laterally, thus requiring a very dense circuitry for driving the individual color emission [8] and a large foot print when applied as a display pixel. A few research groups have notably tried to realize a color-tunable LED device with three LED chips vertically arranged [9–12], but the designs did not lend themselves to fully independent controls of the colors.

Thus, to address this need, many studies on an LED device for emitting full color are ongoing, and to that end, the role of a monolithic LED structure of InGaN/GaN having multiple emission colors is expected to be central. Some research groups have reported visible-color LEDs fabricated using, for example, InGaN/GaN nanostructures [13, 14]. However, while these studies have demonstrated multiple color emissions, no independent color control has been achieved. This is due to the fact that the control of the current for each of the active regions producing a color is not independent.

In this study, we demonstrate a blue-green color tunable monolithic LED having a multi-junction structure. This is achieved by growing a blue LED on a conventional green LED by metal-organic chemical vapor deposition (MOCVD). We will explain the detailed mechanisms of three operation modes which are the green mode, blue mode, and cyan mode using an equivalent circuit model approach. Moreover, we discuss the optical properties of the device and also present a video demonstration of each of the operating modes as a supplementary material (Visualization 1).

2. Experiment

The LED in this research has a typical LED structure consisting of layers of n-GaN, blue MQW, and p-GaN are regrown on a conventional green LED using an MOCVD method. The conventional green MQW with In0.21Ga0.79N is grown on a 2-inch c-plane sapphire substrate. The LED structure is comprised of a 2-μm thick Si-doped n-type GaN, five periods of the InGaN/GaN MQWs, and a 150-nm thick Mg-doped p-type GaN layer.

For the blue LED, we performed a selective area regrowth on the conventional green LED. Figure 1(a) shows schematic diagrams of steps for realizing the color tunable monolithic InGaN/GaN LED having a multi-junction structure using the selective area regrowth technique. A 300 nm SiO2 layer was deposited and patterned on the green LED template using a plasma-enhanced chemical vapor deposition (PECVD) process to form a regrowth mask. Then, a 150-nm thick p-GaN, five periods of InGaN/GaN blue QW forming a MQW active region, and a 200-nm thick Si-doped n-GaN were sequentially regrown by MOCVD. Finally, a 150 nm-thick layer of ITO for current spreading on the p-GaN was deposited on the top n-GaN layer after which the SiO2 mask was removed using an HF (HF:DI = 1:6) solution. Here, after depositing the ITO layer, the samples were annealed under an air ambient at 600 °C for 1 min in a rapid thermal annealing (RTA) chamber for activating the contact layer. Finally, Cr/Au (30/100nm) contact pads were formed on the bottom n-GaN,
and transparent ITO contacts were deposited for the middle p-GaN layer and the top n-GaN by e-beam evaporating. We show the SEM images of the final device in Figs. 1(b)-1(d).

>Fig. 1. (a) Schematic illustration of a multi-junction InGaN/GaN LED fabrication. (b) SEM image of the final device. (c) Cross-sectional SEM image of the final device. (d) SEM bird’s eye view of the device.

We can realize different emission colors by controlling the current injection mode of the device. Figure 2(a) shows the color change in a CIE 1931 x-y chromaticity diagram, from blue (460nm) to green (520nm). The four emission colors are, from the left to right, blue only, bluish cyan, greenish cyan, and green only. The two cyan emissions are simply two particular mixes of blue and green in different proportions and represent two points of a continuum of simultaneous blue-green emission ratio. In Fig. 2(b), representative EL spectra of color modes in blue, cyan, and green at 20mA current injection are shown. We also present a video visualization of the color changing in the supplementary materials section as Visualization.
Fig. 2. Images of the color controlled device. (a) Color changing shown on a CIE 1931 x-y chromaticity diagram from blue (460nm) to green (520nm) with first and last points from independently operated blue and green emissions. (b) Representative EL spectra in a blue, cyan, and green mode at 20mA current injections. (see Visualization 1)

3. Results and discussion

The operation of the different color modes in the multi-junction LED using an equivalent circuit model [16, 17] is shown in Fig. 3 to explain the operation of the independent color emission modes. Here, the p-contact layer is a common anode, and the two n-contacts are cathodes at different voltages (both lower than the common p-contact voltage by the respective forward voltages of the junctions) required for the two junctions for the two basis colors. In the figure, V1 corresponding to a conventional forward voltage of a blue LED and V2 corresponding to a conventional forward voltage of a green LED control the two junctions shown. To achieve this completely independent control of the two junctions and thus two colors, two power supplies are connected with the higher potential terminals of the two supplies tied at the common p-contact. As expected, to control two junctions independently requires two independent power supplies; however, in this structure, there are only 3 terminals due to a common p-contact layer, and this demonstrates a new type of carrier injection mechanism into active regions of an LED device. For the blue emission, in the p-contact layer, hole carriers must clearly be able to diffuse sideways from the center to the edge for a uniform emission as shown in Fig. 4(a). Here, the intensity of the blue emission is weaker than that of the green emission despite a conventional single junction blue LED being more efficient than a conventional single junction green LED. In particular, when normalized by the light emitting areas of the blue and green LEDs of the multi-junction LED, the blue emission remains approximately 50% of the green LED (data not shown). This, taking into account the conventional ratio between blue and green efficiencies, amounts to the blue LED being approximately 25% efficient relative to a typical single junction LED. We attribute this efficiency to as yet a suboptimum regrowth conditions in the LED shown as well as currently suboptimal injection efficiency in the blue LED due to the relatively large device size. Current research effort includes addressing these issues.
Fig. 3. The operating circuit for fully independent color emissions in the multi-junction LED.

The LED device may also be operated with just one or the other active region powered. Figure 4 shows EL spectra of individual blue and green emissions with increasing current flow from 2mA to 20mA, and the corresponding equivalent circuit models are shown. In the blue mode, p-GaN and the bottom n-GaN are biased together at a positive voltage (V1) and the top n-GaN is grounded to achieve the blue emission shown in the Fig. 4(a). The reason for pinning the bottom n-GaN and the p-GaN together is that green MQW also otherwise lights up at high bias, indicating a diffusion of hole and electron carriers into the green active region where they recombine. In the green mode, p-GaN is biased at a positive voltage (V2), and the bottom n-GaN is grounded to achieve the green emission. For green, the top n-GaN is left floating because no blue emission is observed in this mode for the applied current range, i.e. the carriers are not seen to sufficiently diffuse to the blue active region.

Fig. 4. EL spectra and an equivalent circuit models for the multi-junction LED for (a) blue and (b) green.
Figure 5 shows EL spectra in cyan color. The cyan mode in the multi-junction LED consists of blue and green emissions and has already been shown to be independently controllable with three terminals and two power supplies. Here, we show an example of the cyan mode operation with increasing current injection into both green and blue active regions. The peak ratio in Fig. 5(a) are due to mixing blue (460nm) and green (520nm) at current values from 4mA to 20mA. Clearly, the mixing ratio of the blue and green peaks changes depending on the injection current from bluish cyan to greenish cyan. In cyan mode, the current level is the total amount of current in the device shown as Table 1. In this mode, the color of the device can be tuned by changing the injection current. Table 1 shows the peak ratio vs. current data.

Grown using the selective area regrowth technique, the series resistance in the blue LED is higher than in the green region due to current spreading in the common p-GaN. Therefore, the peak ratio is not constant despite linearly increasing current injection.

Table 1. The current injection and peak ratio in cyan mode from Fig. 5(a) with mixing blue (460nm) and green (520nm) at 4mA to 20mA.

<table>
<thead>
<tr>
<th>Total Current (mA)</th>
<th>Current Injection (mA)</th>
<th>Blue (mA)</th>
<th>Green (mA)</th>
<th>Peak ratio</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>3.5</td>
<td>0.5</td>
<td>0.9</td>
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<td>8</td>
<td>5.5</td>
<td>2.5</td>
<td>0.66</td>
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<td>20</td>
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</table>

4. Conclusion

In this study, we demonstrate a novel approach for producing a multi-junction LED. The device can emit blue (460nm) and green (520nm) light and a continuous mix of the two by controlling the current injection. The device has been shown to be controllable with various biasing configurations to result in fully independently controlled blue and green emissions, single emissions of blue and green emission, and a blue-green mix (i.e. cyan) emissions.
dependent on injected current. These modes are explainable using analyses involving uncomplicated equivalent circuits. As such, we believe that the device concept and structure are capable of realizing a high performance display pixel, and thus, promising for many future applications.

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