Monolithic Polychromatic InGaN Light-Emitting Diodes Based on Micro-facet Structures

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Abstract

Nitride semiconductor based light-emitting diodes attain a new functionality of polychromatic emission by the use of three-dimensionally faceted microstructures, which may lead to an advanced lighting technology in which the light source spectra are synthesized so as to meet requirements of the application.

1. Introduction

The color spectra required for illumination strongly depend on the application. For example, the color temperature of general lighting should be chosen to fit the situation, while specific lighting in medicine such as surgery or endoscopy should highlight the subtle difference in the color (red) of living organs, which is determined by the degree of oxygen super-saturation of hemoglobin. For the former purpose, illuminations that can well approximate the chromaticity of blackbody radiators are favorable, but for the latter, illuminations composed of red (600-780 nm) and its complementary color of blue-green (480-500 nm) are suitable. That is, in order to emphasize desired colors of objects, spectral syntheses of the light source are indispensable.

In a related lighting issue, there is a strong demand for improving lighting efficiency because ~20% of the generated electricity is currently consumed in lighting. Solid-state lighting (SSL) based on semiconductor light-emitting diodes (LEDs) features high emission quantum efficiencies, long lifetime, and harmless constituent atoms, which causes displacement of the traditional fluorescent lamps and incandescent bulb.[1] Thus, realizing advanced LED-based SSL with higher emission color controllability, which we call "tailor-made SSL", would be the ultimate goal of lighting technology.

Toward this goal, several LEDs have been proposed, as shown in Fig. 1. It should be noted that to achieve spectral syntheses, multi-wavelength emissions must be mixed with an arbitrary relative intensity. The most successful proposal is white LEDs,[2-5] which consist of an InGaN blue LED pumping a yellow phosphor. Considerable efforts have been devoted to improvements of both the light extraction efficiency[5,6] and the internal quantum efficiency.[3,4] As a result, the luminous efficiency has recently reached 169 lm/W, which is far beyond that of the fluorescent lamps.[4] Once the production cost is reduced, the displacement of the traditional lighting with this revolutionary lighting will be tremendously accelerated. However, their performances in terms of color controllability are insufficient to meet specific requirements mainly because of the broad phosphor emission. Furthermore, Stokes energy loss inevitably occurs in the phosphor due to the color conversion from blue to yellow.

Another design, which uses stacked quantum well (QW) structures, includes multiple InGaN QWs emitting different sandwiched in a GaN-based pn junction diode.[7,8] This design enables us to control the

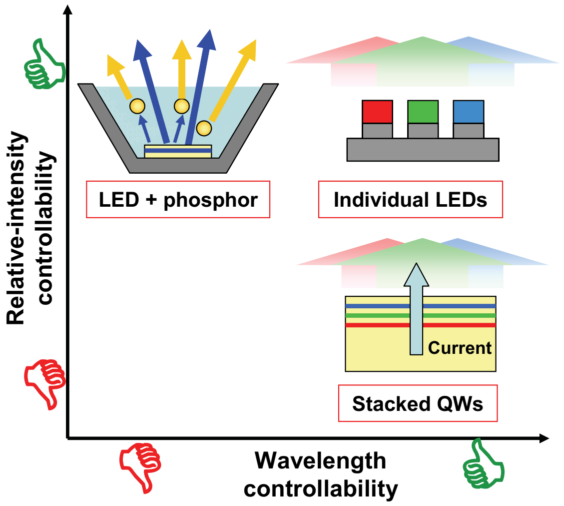

Fig.1. Current SSL schemes offering emission color controllability.

emission wavelengths. However, each QW in this device is in series in terms of the current flow, and hence, the relative emission intensities of the QWs are primarily determined by their intrinsic optical properties. This difficulty in controlling relative-intensity leads to poor apparent color tunability. To date, the device configuration that has the highest emission color controllability is to use three individual blue, green, and red LEDs. The drawbacks of this device configuration are the necessity of outer optics to thoroughly mix the outputs from three LEDs and the difficulty of device assembly.

Herein, we demonstrate a new class of monolithic, polychromatic InGaN/GaN LEDs in which InGaN QWs emitting different colors are electrically connected in parallel in order to achieve high color controllability.

2. Device concept

Figure 2 schematically explains the device concept. InGaN QWs were selected as the light emitting layer, because changing the In composition can tune the bandgap energy of InGaN from 0.6 eV (InN)[9] to 3.4 eV (GaN), which covers the full-visible region. As shown in Fig. 2(a), the conventional LEDs are grown on sapphire (0001) substrates and have planar structures. On the other hand, it has been reported that regrowth of GaN on patterned SiO_2 masks by metalorganic vapor phase epitaxy (MOVPE) creates three-dimensional microstructures, which consist of several facets such as (0001), {11-22}, and {11-20} planes.[10] These results have inspired us to fabricate InGaN/GaN LEDs on microfacets, as shown in Fig. 2 (b). To date, we have investigated MOVPE growth conditions and their optical properties,[11-14] and found that they exhibit facet-dependent emission colors due to the facet-dependent InGaN well thickness and the In composition. Furthermore, varying the SiO_2 mask geometry alters microfacet structures such as ***A*** and ***B*** in Fig. 2(b), which provides another opportunity to control the emission color. In our microfacet LEDs, two different structures, ***A*** and ***B***, were involved within one LED chip to strengthen the emission color controllability. (The new period, which was composed of *m* periods of ***A*** and *n* periods of ***B***, is denoted as ***A***:***B*** = *m*:*n*.) Consequently, the wavelengths and relative intensities of the emission bands can be tuned separately,[14] which may lead to a much greater emission color controllability compared to vertically stacked QWs or conventional white LEDs. Figure 2(b) displays a cross sectional scanning electron microscopy (SEM) image of a microfacet LED before the device process. In this particular case, ***A***:***B*** = 1:1. In this study, the mask openings for ***A*** and ***B*** were 5 and 15 m wide, respectively, and the mask was 5 μm wide for both.

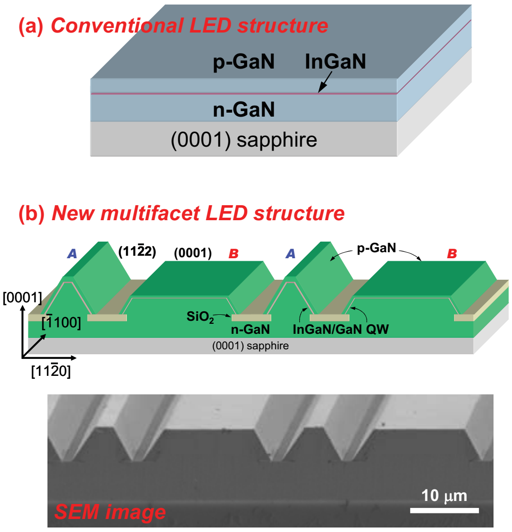

Fig.2. (a) Schematic of conventional InGaN LED structure and (b) schematic and a cross-sectional SEM image of newly developed microfacet InGaN LEDs.

3. Device fabrication

The microfacet LEDs used in this study were fabricated by low-pressure (300 Torr) MOVPE on sapphire (0001) substrates. We can form microfacet structures by using processes allied to those employed for epitaxial lateral overgrowth (ELOG), the widely used technique for cutting threading dislocation densities in GaN heteroepitaxial layers. Initially ~5 μm GaN layers were grown. Then SiO_2 mask stripes were formed along the [1-100] direction by photolithography. Subsequent regrowth of GaN created microstructures composed of (0001), {11-22}, and {11-20} facets along the [1-100] direction. Finally, InGaN/GaN three-period QWs and p-GaN cap layers were fabricated on these microfacets. The details of the growth can be found in Refs. 13 and 14.

The device processes were rather conventional, although we optimized the photolithography to meet our three-dimensional structures. Initially, LED mesas were formed by inductive coupled plasma reactive ion etching to isolate each LED and to simultaneously remove a portion of p-GaN and QWs in order to

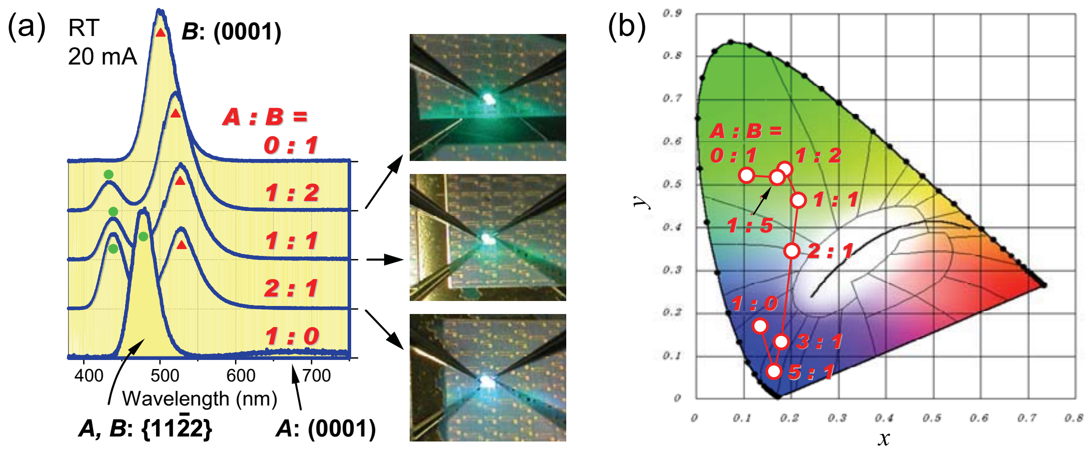

Fig.3. (a) EL spectra and photographs of microfacet LEDs grown on different mask patterns composed of microstructures of A and B with ratios indicated in the figure. (b) CIE diagram.

expose the underlying n-GaN. Then, Ni/Au and Ti/Al ohmic electrodes were formed on p- and n-GaN, respectively, from the sample surface, similar to current commercial InGaN-based LEDs. The LEDs were on-wafer without packages. The EL spectra were acquired at room temperature under the dc operation.

4. Results and discussion

Figure 3 shows typical results. Although those LEDs were fabricated under the same growth run, the pattern mixture widely varied the emission color from green to blue. More interestingly, the emission colors obtained with the mixed patterns were rather whitish, as indicated by the photograph in Fig. 3(a), due to the polychromatic emissions. This was confirmed by plotting the spectra on the Commission Internationale de I'\'Eclairage (CIE) 1931 chromaticity diagram [Fig. 3(b)]. The emissions from LED with ***A***:***B*** = 1:2, 1:1, and 2:1 were located at (0.185, 0.535), (0.214, 0.463), and (0.200, 0.345), respectively in the diagram, all of which are far away from pure colors. Such pastel colors cannot be realized by conventional LEDs, because the bandgap of the light emitting layer dictates the emission color, and consequently, the color must be monochromatic. In contrast, arbitrary colors may be extracted from nitride-based LEDs using the proposed microstructures, even though phosphors are not used as color convertors. The most extreme example is white LEDs. Figure 4 displays a microfacet white LED with ***A***:***B*** = 1:1 that is emitting at a color temperature of 5000 K.

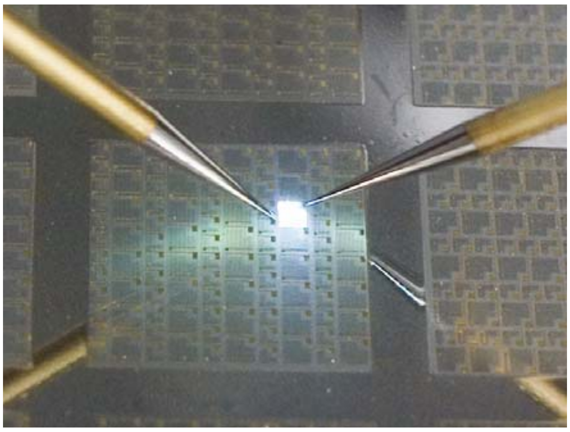

Fig.4. A microfacet white LEDs (*A*:*B*=1:1) emits at a color temperature of 5000 K.

5. Summary

We demonstrated the proof-of-concept LEDs composed of GaN-based microstructures. The microfacet LEDs feature polychromatic emissions and high emission color controllability, both of which cannot be realized by the conventional LEDs. In addition, the proposed LEDs are free of phosphors that cause Stokes energy loss. Therefore, our monolithic, polychromatic LEDs will be a key device for the next-generation lighting.

6. References

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