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Eu-Doped GaN-Based Red LEDs as A Key Technology for Micro-LED Displays with Ultrahigh Resolution

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ABSTRACT

A novel red LED using Eu-doped GaN is a promising component for next-generation display with ultrasmall-size, full-color, and high-resolution. The LED exhibits narrow-band red emission and the wavelength is almost independent of ambient temperature and injected current. The size dependence of emission efficiency is negligibly small compared with conventional AlInGaP-based red LEDs. We also demonstrated monolithic integration of vertically stacked full-color LEDs.

1 Introduction

Micro-light-emitting diodes (μ-LEDs) have been attractive because they are one of the next-generation display techniques for various applications, such as smartphones/watches, vehicle displays, and wearable glasses for augmented reality and virtual reality. High resolution is an important aspect for displays to present an excellent visual experience. In high-resolution displays, ultra-small (< 10 μm) μ-LEDs should be required.

For the fabrication of the μ-LED display, InGaN/GaN-based blue/green LEDs and a AlInGaP/GaAs-based red LED are used and arranged using a pick-and-place technique to make a pixel. In this case, the efficiency of the red LED is severely degraded with decreasing chip size.

There has been a strong demand to develop red LEDs using nitride semiconductors for monolithic integration of the three primary colors (RGB), resulting in the realization of a nitride-based display with ultrasmall-size, full-color, and high-resolution. In 2009, we invented a novel red LED using Eu-doped GaN (GaN:Eu) [1]. In this presentation, current status of the red LED is reviewed. Vertically-stacked integration with conventional blue/green LEDs is successfully demonstrated as a key technology for a next-generation μ-LED display.

2 Red LED using Eu-doped GaN

Figure 1 shows electroluminescence (EL) spectrum of a LED using GaN:Eu, which was fabricated by organometallic vapor phase epitaxy (OMVPE). A main emission line with a half width of less than 1 nm is observed at 621 nm, which can be assigned to the $^5D_0$–$^7F_2$ transition of Eu^{3+} ions. The wavelength is extremely stable against ambient temperature and injected current. Due to optimization of the device processing, the output power of the LED has been increasing steadily to 1 mW [2]. High external quantum efficiency over 9 % is also obtained at low current injection, which is very suitable to next-generation micro-LED displays.

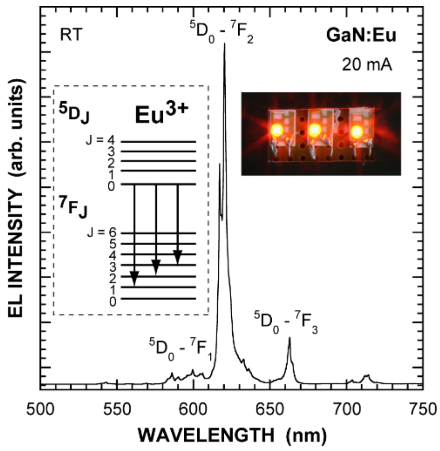

Fig. 1 EL spectrum from a red LED using GaN:Eu.

3 Size dependence of quantum efficiency

When the dimensions of μ-LEDs decrease below ~100 μm there arises an increasing influence of their sidewalls, leading to non-radiative recombination due to imperfections induced by the fabrication process, and lower the internal conversion efficiency (IQE). Solutions to this problem have dramatically improved the efficiency of conventional InGaN-based blue μ-LEDs and as a result they show nearly no decrease of IQE down to 5 μm sizes. However, for AlInGaP-based red μ-LEDs, these problems remain and their efficiency drops quickly when the pixel size shrinks. This is mainly due to the combination of long carrier diffusion lengths allowing carriers to reach the sidewalls from a larger distance, and the high surface recombination coefficient.

While the carrier diffusion length in nitrides is already considerably lower than that of phosphides, this parameter is even more reduced in GaN:Eu. The Eu^{3+} ions are extremely efficient in trapping injected carriers, giving typical carrier diffusion lengths of ~100 nm, and preventing the carriers from reaching the sidewalls altogether. This effect is clearly demonstrated in the emission properties of a set of square GaN:Eu structures ranging from 1 to 100 μm (see Figure 2) [3]. The IQE stays fairly constant down to sizes of 10 μm and only slowly decreases when going to even smaller sizes. For the smallest structure of 1 μm the IQE remains 70% of the maximum. This is without any post-treatment of the sidewalls, and could thus be further improved by employing the process optimizations developed for the blue GaN-based LEDs.

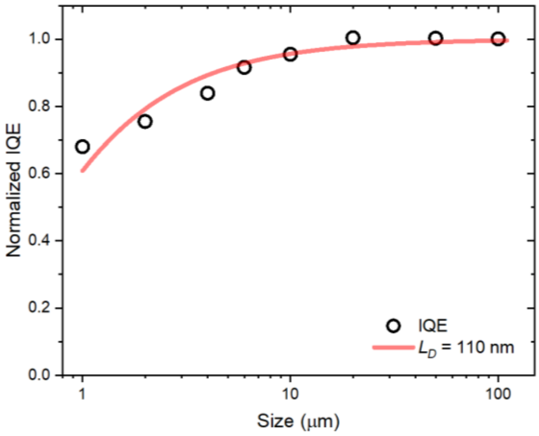

Fig. 2 Normalized IQE as function of mesa size. The red line indicates the modeled IQE for carrier diffusion length L_D = 110 nm.

4 Monolithic integration of three primary-color LEDs

We demonstrated monolithic integration of vertically stacked full-color LEDs consisting of GaN:Eu and InGaN quantum wells (QWs) (see Figure. 3) [4]. The integrated LEDs were grown on a single sapphire substrate using OMVPE without any additional preparation. All three primary colors can be selected anywhere in the wafer by controlling the etching-depth and position.

The individual EL spectra are clearly obtained at room temperature and show a high color purity, which determines the capability of generating reproducible colors of displays. The maximum color purity for the red, green, and blue emission were 100%, 97.1%, and 99.7%, respectively, at 600 μA current injection. GaN:Eu luminescence has an extremely high color purity under any current injection due to the stable intra-4*f* shell transitions in Eu ions.

Reproducible colors of displays are typically characterized by color space on the International Commission on Illumination (CIE) chromaticity diagram. The light emission gamut for the RGB LEDs obtained by the EL spectra shows an exceptionally large coverage corresponding to 105.5% (147.0%) of the area with 91.2% (96.5%) coverage of the standards of Rec.2020 (DCI-P3) at the maximum. Hence, this color gamut satisfies the requirement of the Ultra HD Premium TV standard. In addition, the RGB LEDs have a maximum luminance of ~3100 cd/m^2, which already satisfies the minimum requirement for outdoor applications.

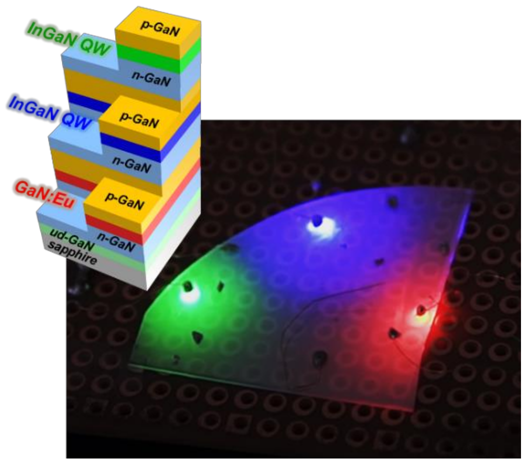

Fig. 3 Schematic of the vertically stacked RGB LEDs and photograph of EL from monolithically integrated LEDs on the same sapphire substrate under simultaneous operating conditions.

5 Conclusions

Current status of the GaN:Eu red LEDs is reviewed. The LED has superior properties compared with conventional AlInGaP-based red LEDs. The successful demonstration of monolithic integration of vertically stacked full-color LEDs indicated a high potential for the applications to a nitride-based display with ultrasmall-size, full-color, and high-resolution.

Acknowledgements

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