Enhanced Quantum Dot Conversion Layer Using Light Recycling Structure for Blue μ-LED Display

Juwon Jung[1], **Young-Joo Kim**[1]

juwon0840@yonsei.ac.kr

[1]Department of Mechanical Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 03722, South Korea

Keywords: Quantum Dot(QD) nanocrystals, Micro-LED display, patterned photoresist, Long Pass Filter(LPF), Aluminum coating

ABSTRACT

This study reports efficient and cost-effective color conversion structure with Al-coating layer and Long Pass Filter(LPF). Compared with conventional structure and micro-LED/QD-film with Al-coating LPF, it was confirmed that maximum optical powers of red and green lights in proposed structure were increased by 71.73% in 0.4wt% and 66.12% in 0.8wt%.

1 Introduction

The Micro-LED display, which has a long lifetime and high luminous efficiency, can be expected to become the mainstream of the next-generation display technology with the progress of semiconductor manufacturing technology[1-3]. On the other hand, it is still difficult to overcome some challenges, such as the transfer printing of micro-LED chips for mass production. Especially, in design, the drive circuit configuration for three different light sources is complex. In manufacturing process for the transfer printing of micro-LED chips for mass production, in addition, it is complex to transfer three kinds of chips made through three different epitaxial growth processes to each subpixel's circuit place[4-5]. One approach to avoid the mass-transferring of three different kind of chips is GaN-based micro-LED structure combining with Quantum Dot(QD) film [6-7]. Optical characteristics of QD, a narrow FWHM forming a wider color gamut and emission spectra corresponding to a particle size of QD nanoparticle, are especially good properties for display, but a large amount of energy is lost in a process of absorbing unconverted light which is undesirable energy. As thermal energy increases the temperature of the device itself, the redshift and photoluminescence quantum yield reduction due to the light conversion mechanism of QD[8-10]. Therefore, research on the structure of QD nanoparticle themselves or QD conversion layer has been conducted to increase light conversion efficiency[11-13]. In the micro LED structure applied to a large display, unlike the existing display structure, the area occupied by the LED chip is quite small compared to the subpixel's area, so the new structure suitable for a GaN based micro-LED in the large area display is required. In this work, the efficient and economical new color conversion layer, having two optical filters placed above and below QD-dispersed polymer film to increase the light-recycling effect for low QD concentration, was applied to GaN-based micro-LED display to increase the color conversion efficiency performed by ray-tracing simulation(LightTools software).

2 Simulation

2.1 QD-dispersed polymer film

The optical simulation model for the QD nanophosphors in the polymer matrix should be differently implemented from the typical micro-scale phosphor. The method of calculating the mean free path(MFP) for QD-dispersed polymer film was reported[14]. In order to obtain MFP of the film itself, MFP can be obtained through the relationship between thickness and transmittance. MFP can be expressed as follows:

$$MFP = -\frac{t}{\ln T} \tag{1}$$

where t is the thickness of QD-dispersed polymer film and T is the transmittance of QD-dispersed polymer film.

MFP can be also expressed as a linear relationship between inverse concentration and MFP.

$$MFP = a\left(\frac{1}{wt\%}\right) + b \tag{2}$$

where a and b are constant for QD-dispersed polymer film and wt% is QD concentration in polymer matrix.

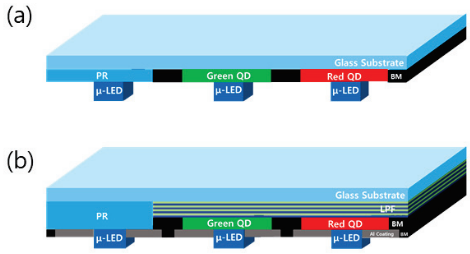

Fig.1 The schematic configuration of GaN based micro-LED structure with (a)conventional QD structure and (b)enhanced QD structure

Using those two MFP equations, trend line equations for red QD and Green QD-dispersed PR polymer film were experimentally acquired by finding out constant a and b respectively.

In addition, the absorption and emission spectra of red QD and green QD were used to reflect the optical characteristics of the QD-dispersed polymer film in the simulation. The conditions of the QD film in the simulation were that thickness was set to 50um and polymer matrix was the SU-8 negative photoresist(PR), and then the simulation was conducted by changing QD concentration from 0.1wt% to 4wt%.

2.2 Design for Long Pass Filter

In order to maximize the reflectance of light of the blue wavelength in the LPF, two materials with large difference in reflective index were selected as SiO2(about 1.4 refractive index)/TiO2(about 2.3 refractive index) pair, and a [(1/2H)L(1/2H)]-type periodic structure was adopted to minimize reflectance of the wavelength between 500nm to 700nm.

$$(a_1, a_2, ..., a_n) = Min\{R(a_1[(1/2H)L(1/2H)]/ \\ a_2[(1/2H)L(1/2H)]/.../a_n[(1/2H)L(1/2H)])\} \quad (3)$$

where a_n is nth period thickness coefficient, H is high refractive index material's quarter wavelength thickness and L is low refractive index material's quarter wavelength thickness.

In addition, the thickness constants for each cycle with the optical film's minimum reflectivity in the range of wavelength between 500nm to 700nm were obtained(Equation.3), and optical films with a small number of layers were designed with high reflectivity in blue light and low reflectivity in green and red light.

An appropriate SiO2/TiO2 thickness combinations for 4 pairs to 10 pairs were found, and the spectrums for the reflectivity of 7 kinds of LPF is analyzed at 0 to 89 incident angles as shown in Fig.3.

2.3 Aluminum coating Layer

To reflect back-propagating light converted from QD film and reflected from the top optical filter in the external horizontal region of LED chip, a metallic layer structure, deposited outside the micro-LED chip, was designed, and aluminum with relatively economical and excellent reflectivity characteristics was selected as a metallic mirror's material. Like aluminum on a general glass substrate, it was confirmed that aluminum on SU-8 which is a QD-dispersed polymer has about 88% reflectivity in the visible region.

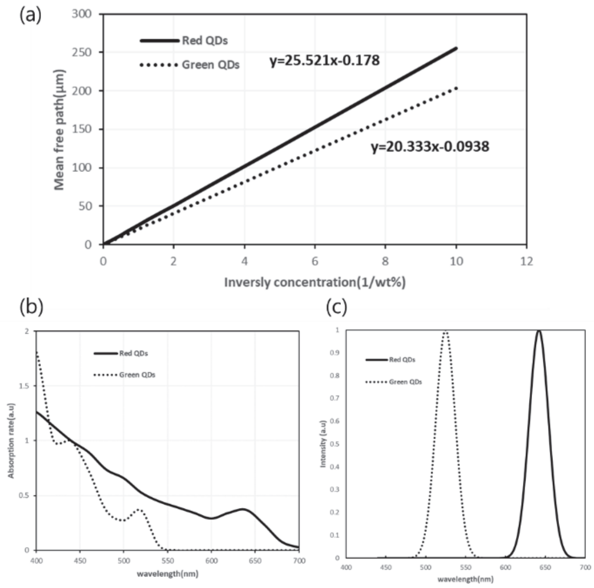

Fig.2 QD nanostructure's optical property: (a) the linear relationship between inverse concentration and MFP, (b) absorption spectra. (c) emission spectra

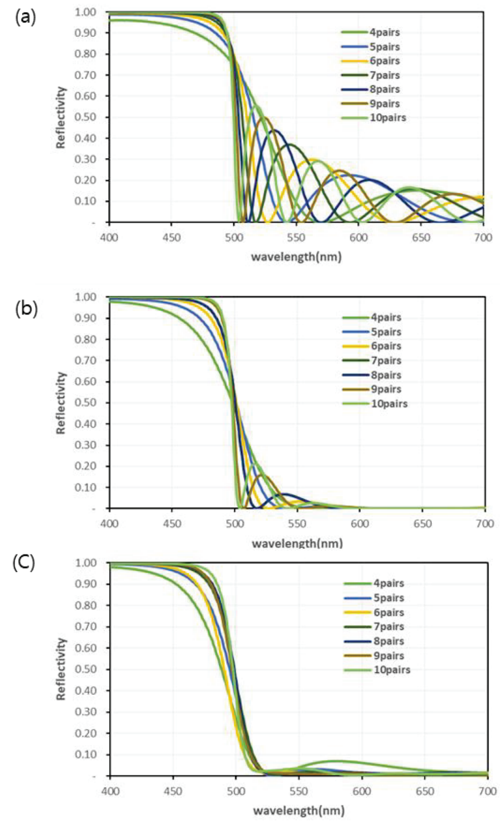

Fig.3 The Reflectance Spectra of (a) [LH]n stack, (b) [(1/2H)L(1/2H)]n stack, (c) [(1/2H)L(1/2H)]n modulated stack

2.4 Micro LED-QD film structure

As shown in Figure 1(b), modeling was constructed with a stacked structure of glass substrate/LPF/QD-film (50um)/Al-coating/GaN LED, and Black Matrix was added to prevent cross talk between subpixels. The size of the LED chip in the subpixel was 100umx 100um, and the size of QD film was 1mm x 1mm.

3 Results and Discussion

In Figure 4a, the efficiency improvement was confirmed for 7 kinds of LPF in red and green QD-dispersed polymer film. Converted light increased by between 111 to 113% in 5-6 pairs and by between 119 to 121% in 7-10 pairs in 0.4wt% red QD concentration. Converted light increased by 133% in 5-6 pairs and by between 147 to 150% in 7-10 pairs in 0.8wt% green QD concentration. The 7 pairs LPF, involved in the high efficiency improvement rate group in both red and green both cases, was considered as the most suitable LPF for the proposed structure due to having the least number of layers in the high efficiency group. And in Figure 4b, improvement for converting light was confirmed according to structure with or without al-coating and LPF which is the case of 7 pairs LPF. In the red QD, it shows that the improvement is 22.74% with only the al-coating layer, the improvement is 58.95% with only 7 pairs LPF, and the improvement is 120.73% with both the al-coating and LPF in 0.4wt% QD concentration. And in the green QD, it shows that the improvement is 34.05% with only the al-coating layer, the improvement is 40.27% with only 7 pairs LPF, and the improvement is 102.55% with both the al-coating and 7 pairs LPF in 0.8wt% QD concentration.

Figure 5 shows the distribution of the normalized converted light intensity in four cases with a basic QD film structure, with only Al-coating layer, with only 7 pairs of LPF, and with al-coating and LPF together according to the QD concentration. In all cases, the amount of converted light which propagated outside made a single peak for specific a QD concentration. And we compared the peak value among 4 cases by normalizing based on a peak value for QD-dispersed film-only structure. In the red QD, the QD-dispersed film structure showed maximum efficiency at 0.8 wt% and, in the case of both optical layers, the enhanced maximum efficiency of 71.73% was shown at 0.4 wt%. And in the green QD, the QD-dispersed film structure showed maximum efficiency at 1.5 wt% and, in the case of both optical layers, the enhanced maximum efficiency of 66.12% was shown at 0.8 wt%.

Figure 6 shows the normalized relative radiant intensity distribution of the converted light for four cases with a basic QD film structure, with only Al-coating layer, with only 7 pairs LPF, and with al-coating and 7 pairs LPF together.

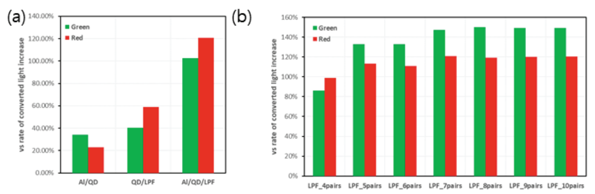

Fig.4 Color Conversion Enhanced rate for 0.4wt% red QD and 0.8wt% Green QD concentration (a) at each pairs LPF with al-coating, (b) at 7 paris LPF structure prepared with and without al-coating and LPF

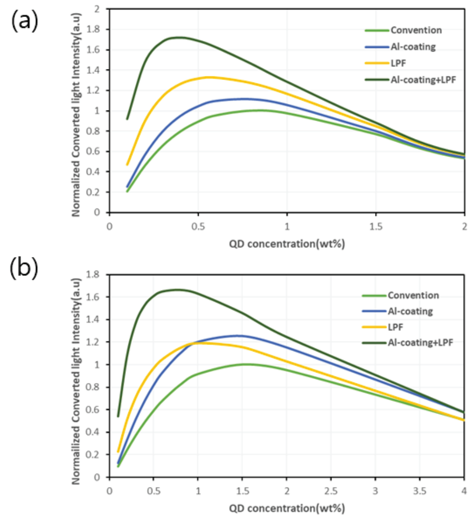

Fig.5 Intensity of converted light between 0.1wt% to 4wt% QD concentration at 7 paris LPF structure prepared with and without al-coating and LPF for (a) red QD and (b) Green QD

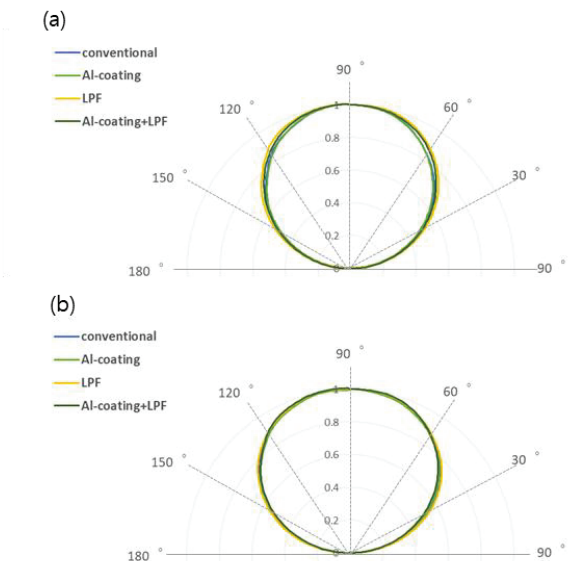

Fig.6 Normalized relative radiant intensity prepared with and without al-coating and 7 pairs LPF for (a) 0.4wt% red QD and (b) 0.8wt% Green QD concentration

4 Conclusions

Two optical films, LPF and al-coating, were added to the micro LED chip and the QD-dispersed polymer film at the top, and through this structure, the increase in optical conversion efficiency was obtained as an important result, increasing 71.73% for maximum efficiency in the case of 0.4wt% red QD film and 66.12% in the case of 0.8wt% green QD film, respectively. In addition, it can be expected that higher thermal stability, peak wavelength stability and higher converted light intensity can be obtained in that the amount of thermal energy absorbed by the QD film itself can be minimized by increasing the converted light.

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