Electronic Supplementary Material (ESI) for Journal of Materials Chemistry C


**Electronic Supplementary Information**

# Enhanced phosphor conversion efficiency of GaN-based white light-emitting diodes having dichroic-filtering contacts

***Seung Jae Oh,[a] Gyeongmin Go,[a] Jong-Lam Lee,[a] E. Fred Schubert,[b] Jaehee Cho,[c] and Jong Kyu Kim*[a]***

[a]Department of Materials and Engineering, Pohang University of Science and Technology (POSTECH), Pohang, 790-784, Korea

[b]Future Chips Constellation, Electrical, Computer, and System Engineering Department, Rensselaer Polytechnic Institute (RPI), Troy, NY 12180, USA

[c]School of Semiconductor and Chemical Engineering, Semiconductor Physics Research Center, Chonbuk National University, Jeonju 561-756, Korea

## Ohmic contact formation between ITO and p-type GaN

Forming an ohmic contact between ITO and p-type GaN is important for LED performance. The I-V characteristics between the TLM pads were measured to obtain the total resistance (=2$R_c$ + $R_{sh}$, $R_c$: contact resistance, $R_{sh}$: sheet resistance). As shown in the Fig. S1, the I-V curves show a linear relation, i.e., an ohmic behavior.

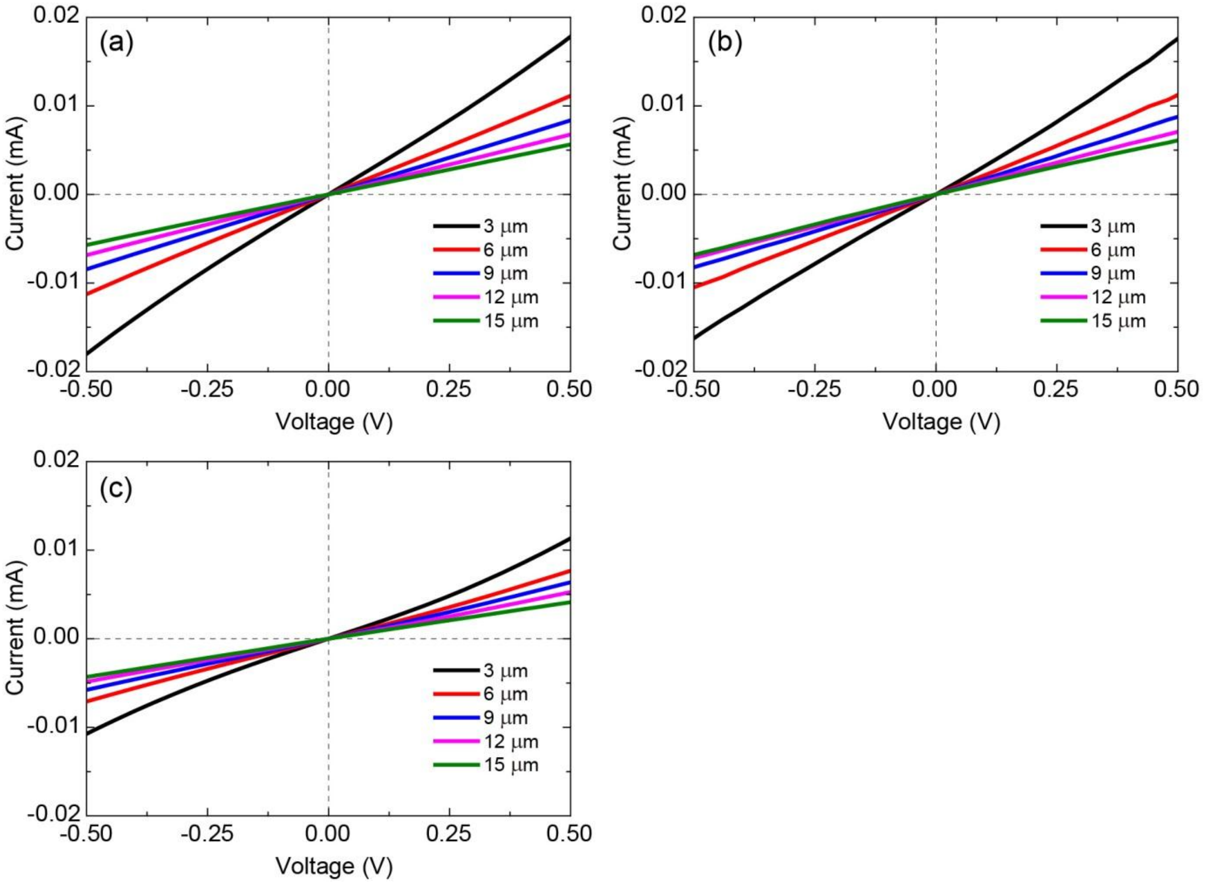


**Figure S1. The current-voltage (I-V) characteristics for (a) 200 nm ITO, (b) 3-layer DFC, and (c) 5-layer DFC to p-GaN, measured by changing the distance between the TLM pads.**

## Optical modeling for calculating phosphor conversion efficiency

The effectiveness of DFCs on improving the PCE of white LEDs is estimated by using an optical model described in Fig. S2 (a). The phosphor layer with thickness of $L$ and refractive index of $n$ ~ 1.7 is conformally coated on top of the contact (either an ITO layer orDFCs). The emission of yellow fluorescence emitted by the phosphor layeris isotropic in nature, the critical angle of total internal reflection (TIR) which defines the light escape cone should be considered for the estimation of the fraction of extracted fluorescence;

$$\frac{I_{escape}}{I_{source}} = \frac{1}{2}(1-\cos\theta_c)$$

where $\theta_c$ is the critical angle of TIR, which is approximately 36°.

It is assumed that $N$ is the number of phosphor particles with each particle having a negligible particle size. We assume that the phosphor particles are uniformly distributed with the same distance of $L/N$ in the phosphor layer along vertical direction. The distance within the phosphor layer traveled by a photon emitted by the phosphor is $nL/N$ for top-emission (toward air) and $2L$ - $nL/N$ for bottom-emission (toward the LED chip assuming that the photon is reflected by the LED chip). Then the average travel length of yellow fluorescenceis calculatedto be,

$$\frac{1}{N}\sum_{n=0}^{N}\left(\frac{L}{N}n\right)=\frac{1}{N}\frac{L}{N}\frac{N(N+1)}{2}\approx\frac{1}{2}L$$

for top-emission, and

$$\frac{1}{N}\sum_{n=0}^{N}\left(2L-\frac{L}{N}n\right)=\frac{1}{N}\left\{2(N+1)-\frac{L}{N}\frac{N(N+1)}{2}\right\}\approx\frac{3}{2}L$$

for bottom-emission.

Self-absorption of the fluorescence by the phosphor, $\alpha$, is considered to calculate the probability of fluorescence extraction; $\alpha$ is proportional to the optical travel length. The fluorescence which is not absorbed by the phosphor layer can be extracted and the extraction probability can be calculated by,

$$T_{blue}\times p_{excite}\times\frac{1}{2}(1-\cos\theta_c)\times\left\{\frac{1}{2}\left(1-\frac{1}{2}\alpha\right)+\frac{1}{2}R\left(1-\frac{3}{2}\alpha\right)+\frac{1}{2}\beta(1-R)\left(1-\frac{3}{2}\alpha\right)\right\}$$

where $T_{blue}$ is the fraction of blue light transmitted through the p-type contact, $p_{excite}$ is the excitation probability of the phosphor by blue light, $R$ is the reflectance of the contacts, and $\beta$ is reflectance of the LED chip for yellow fluorescence, which is about 0.1,as estimated by ray-tracing simulations.

The parameters $A$ (electroluminescence (EL) intensity from the LED chip transmitted through the p-type contact), $B$ (EL intensity passing through the phosphor layer without exciting the phosphor), and $C$ (yellow fluorescence intensity),shown in figure 8(a) are expressed by,

$$A=T_{blue}$$
$$B=T_{blue}\times(1-p_{excite})$$
$$C=T_{blue}\times p_{excite}\times\frac{1}{2}(1-\cos\theta_c)\times\left\{\frac{1}{2}\left(1-\frac{1}{2}\alpha\right)+\frac{1}{2}R\left(1-\frac{3}{2}\alpha\right)+\frac{1}{2}\beta(1-R)\left(1-\frac{3}{2}\alpha\right)\right\}$$

Then the overall PCE can be calculated by,

$$PCE=\frac{C}{A-B}=\frac{1}{2}(1-\cos\theta_c)\times\left\{\frac{1}{2}\left(1-\frac{1}{2}\alpha\right)+\frac{1}{2}R\left(1-\frac{3}{2}\alpha\right)+\frac{1}{2}\beta(1-R)\left(1-\frac{3}{2}\alpha\right)\right\}$$

Based on this modeling, the PCE enhancements of 3- and 5-layer DFCs over 200 nm-thick ITO contact are calculated to be 9.8% and 17.7%, respectively, when $\alpha$ is assumed to be 0.1.

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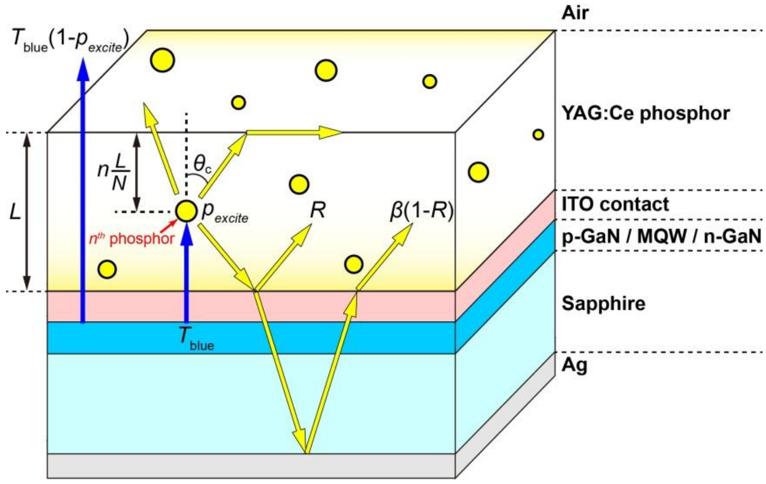


**Figure S2. Schematic model of a phosphor-converted dichroic white LED for calculating the PCE.**

## DFCs for highly-efficient trichromatic warm white LEDs

The effect of DFCs on trichromatic warm white LEDs based on the combination of a blue LED with mixture of yellow and red phosphors would be much more dramatic in terms of CCT and luminous efficacy of radiation than the dichromatic case. GA optimization calculations were performed considering additional weighting factor of red fluorescence spectrum with peak wavelength around 650 nm and full width at half maximum about 110 nm. The optimized structures of red-reflection-enhanced DFCs are summarized in Table S1. Figure S3(a) shows the wavelength dependent reflectance of 200 nm ITO and the GA-optimized 3-, 5-, 7-layer DFCs. As the number of layer increase, the high-reflection band near the red wavelength range becomes narrow and high while maintaining low reflection near blue EL range.

The emission spectra from the trichromatic white LEDs with 200 nm ITO and the GA-optimized 3-, 5-, 7-layer DFCs are simulated based on the optical modeling discussed in previous section (Fig. S2). For the simulation, measured spectrum of a typical warm-white LED (CCT: 4309 K) and the reflectance values of each DFC as a function of wavelength were used. The reference spectrum of the trichromatic white LED with 200 nm ITO contact (black line) shown in Fig. S3(b) is deconvoluted into a blue EL, a yellow and a red fluorescence spectra. Then, the relative enhancements of blue transmission, yellow and red reflections by DFCs are taken into account for calculating the EL and the fluorescent intensities, respectively. The simulated spectra of the trichromatic warm white LEDs with 3-, 5- and 7-layer DFCs are plotted in Fig. S3(b). When the 200 nm ITO contact is replaced with DFCs, the blue EL slightly increased, and yellow, red fluorescence much increased as the number of layer increases, due to the low reflectance in blue wavelength region (~ 460 nm) and the high reflectance in both wavelength regions, respectively. The CIE coordinates and the values of CCT and luminous efficacy of radiation are then calculated using the relative intensity of the simulated emission spectra (Fig. 10 (a) and (b)).

| | 3-layer DFC | 5-layer DFC | 7-layer DFC |
|---|---|---|---|
| | | | Dense ITO, 91 nm |
| | | | Porous ITO, 114 nm |
| | | Dense ITO, 85 nm | Dense ITO, 77 nm |
| **Structure** | | Porous ITO, 120 nm | Porous ITO, 104 nm |
| | Dense ITO, 96 nm | Dense ITO, 75 nm | Dense ITO, 81 nm |
| | Porous ITO, 113 nm | Porous ITO, 115 nm | Porous ITO, 129 nm |
| | Dense ITO, 30 nm | Dense ITO, 30 nm | Dense ITO, 30 nm |

**Table S1. The GA-optimized structures of red-reflection-enhanced 3-, 5-, and 7-layer DFCs on a GaN substrate.**

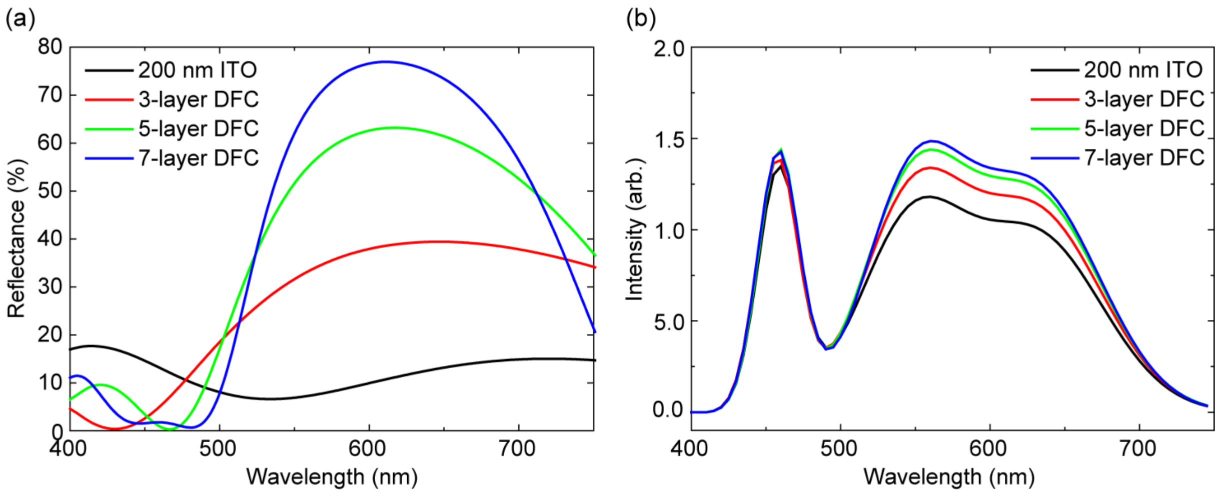


**Figure S3. (a) The calculated optical reflectance curves of red-reflection-enhanced 3-, 5-, and 7-layer DFCs, optimized by GA and (b) the resultant emission spectra of trichromatic warm white LEDs as a function of wavelength.**