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# High-Efficiency White Polymer Light-Emitting Diodes Based on Blended RGB Polymers

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# High-Efficiency White Polymer Light-Emitting Diodes Based on Blended RGB Polymers

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*We have fabricated white polymer light-emitting devices (WPLEDs) from RGB polymer blending systems using ITO/PEDOT:PSS/blended polymers/LiF/Al structure. The highest current efficiency reached 5.34 cd/A and the maximum brightness value of 27,000 cd/m$^2$ at 11.4 V was obtained. As the green dopant concentration increased, the spectrum deviated from the white because of more energy transfer from host to guest. As a result, the 450 nm blue peak was reduced by increasing green dopant ratio. On the other hand, 600 nm red shoulder peaks were slightly increased at the same conditions. Therefore, red-orange and green electroluminescence emissions are promoted by excitation energy and charge transfer from the blue host polymer to the dopants.*

**Keywords:** blend; conjugated polymer; energy transfer; high efficiency; light-emitting diode; PLED; white; WOLED

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## INTRODUCTION

Recently, white organic light-emitting devices (WOLEDs) have been studied for various applications such as lighting sources, full color displays through color filters and backlights for liquid crystal displays. Especially, large area white light-emitting diode (LED) is of paramount importance for the full-color flat-panel displays. It can be combined with color filters to give red, green, and blue light-emitting pixels. There have been many methods to obtain white OLEDs from small-molecule or polymer materials. The small-molecular based WOLEDs using vacuum deposition process have shown quite high efficiency with complicated structure of multiple emissive layers [1]. This approach is somewhat difficult to achieve low cost mass-production for large area displays [2–6].

In the polymer-based devices, white polymer LEDs (WPLEDs) fabricated by spin-coating or ink jet printing have advantages for simple and less expensive manufacturing process [7,8] and can be easy to approach large area applications. Therefore, the blending with blue and red polymers was previously reported for such WPLED applications [9]. This blend system provides easy tuning of white color by changing weight/weight ratios between host and guest materials.

In general, the blending polymer system showed much higher efficiency and brightness value compared to individual devices because of some additional pathways related to light production. The dopant can be directly excited by capturing charge carriers or through energy transfer from host to guest. As a result, light emission comes from both host and guest, and thus the combined effect results in high efficiency and high brightness value. So far, the WPLED's with two component emissions were reported from several groups. There was no report to generate three emission peaks of white lights with blended RGB polymers. In this paper, we fabricated high efficiency and high brightness WPLEDs having white lights with three colors.

## EXPERIMENTAL

The sheet resistance of ITO (Indium Tin Oxide) for WPLEDs was $\sim 10\,\Omega/\square$. Line patterns of ITO were formed on glass by the photolithography process. The substrates of $2\,\text{cm} \times 2\,\text{cm}$ were cleaned by sonification in an isopropylalcohol (IPA), rinsing in deionized water, acetone and methanol and finally irradiated with UV/Ozone before use.

Figure 1 shows a cross sectional view of WPLED, ITO(150 nm)/PEDOT:PSS (40 nm)/blended polymers (80 nm)/LiF(2 nm)/Al(100 nm). The PEDOT:PSS was spin-coated on the ITO substrate pretreated with

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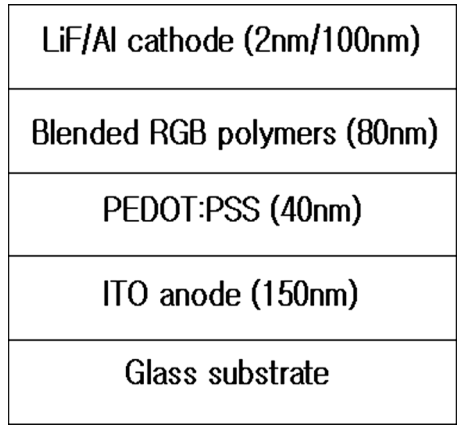


**FIGURE 1** A cross sectional view of a WPLED: [ITO(150 nm)/PEDOT:PSS (40 nm)/Polymer blend/LiF(2 nm)/Al(100 nm)].

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UV/Ozone. Samples were dried at 100°C for 10 min on a hot plate to remove water from the polymer layer. The polyfluorene-type blue polymer (SKB) and green polymer (SKG) was supplied by SK Corporation. MEH-PPV is a well-known material for a red-orange emitter of PLED. SKB, SKG and MEH-PPV are dissolved in toluene with 0.9, 0.85, 0.05 wt%, respectively and then three solutions were mixed by stirring with a magnetic bar. The RGB blended solution was spin-coated on the PEDOT:PSS layer. The film was baked for 1 hour at 100°C. These processes were carried out in a glove box system. Then, LiF and Al layers were deposited in a vacuum system without breaking vacuum. The deposition rates of LiF and Al were 0.1 Å/s and 5 ~10 Å/s, respectively. The emission area of white devices was 2 mm × 2 mm.

The current density-voltage (I-V) and luminance-voltage (L-V) characteristics of these PLEDs were measured with a Keithley SMU 238 and a Minolta CS-100A, respectively. Electroluminescence (EL) spectra and CIE color coordinates were obtained using a PR-650 (Photoresearch Co.).

## RESULTS AND DISCUSSION

Figure 2 shows the I-V-L data of individual pure blue (a), pure green (b), and pure MEH-PPV (c) polymer devices. The pure blue (SKB) PLED as a host polymer exhibited the maximum luminance of 9,258 cd/m$^2$ and maximum efficiency of 3 cd/A as shown in Figure 2 (a). A green (SKG) PLED, one of dopants, showed the maximum

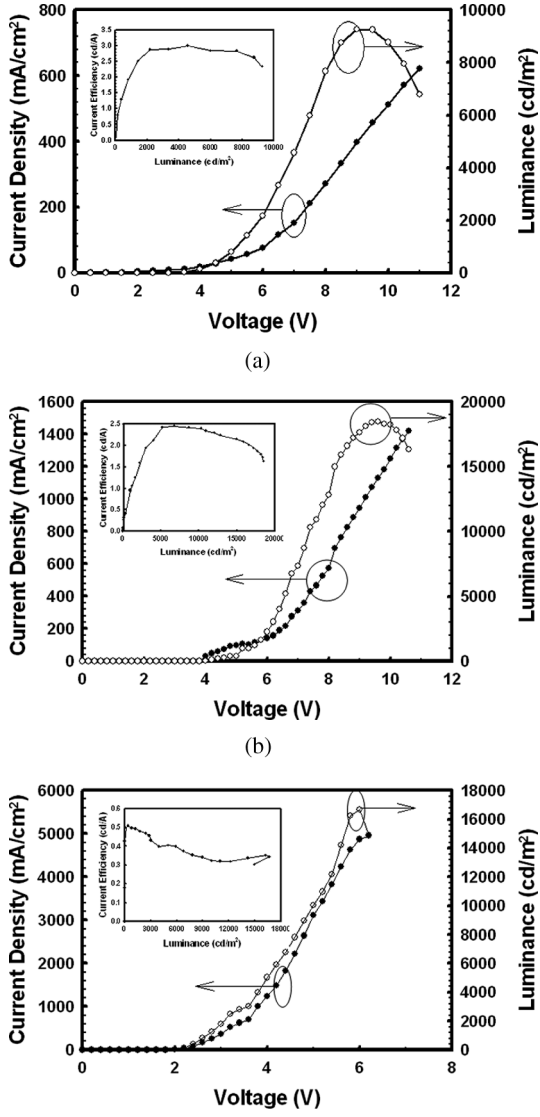


**FIGURE 2** The I-V-L data of pure RGB devices, the inset is the current efficiency versus luminance graph for (a) pure blue, (b) pure green and (c) pure red.

luminance of 18,500 cd/m$^2$ and maximum efficiency of 2.4 cd/A as shown in Figure 2 (b). The red-orange (MEH-PPV) PLED, one of dopants, exhibited the maximum luminance of 16,500 cd/m$^2$ and

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maximum efficiency of 0.5 cd/A as shown in Figure 2 (c). Insets of Figures 2 (a), (b), and (c) are the current efficiency vs. luminance of three pure PLEDs with CIE coordinates, ($x = 0.15$, $y = 0.10$) for blue, ($x = 0.32$, $y = 0.53$) for green, and ($x = 0.59$, $y = 0.40$) for red, respectively.

Table 1 shows the composition ratios of three RGB polymers to make three component WPLEDs. The composition ratio of red and blue polymers was fixed based on the balance of light intensity in blue and red colors. In our previous results, WPLEDs using blended red and blue polymers exhibited the current efficiency of 4.3 cd/A with two electroluminescent peaks [10]. The emission peaks were obtained at 450 nm and 565 nm. The blue peak does not show any changes after both polymer blended. However, the red peak shifted to shorter wavelength by ~30 nm. This shift is probably caused by a direction to shorten conjugation length through reducing internal interactions among MEH-PPV polymer chains. Even though WPLEDs using blended red and blue polymers were made successfully, the green color peak was required to get real natural white colors. To get three peaks of white lights, we added a green polymer which has about a 530 nm peak as electroluminescence (EL). The green polymer was added to the solution of blue and red polymers from 6 to 10% in 2% step.

Figure 3 shows the I-V (a) and L-V (b) data for the three WPLEDs. The maximum luminance value was 15,120 cd/m$^2$ (at 9.6 V), 27,000 cd/m$^2$ (at 11.4 V), and 21,670 cd/m$^2$ (at 9.6 V) for device 1(green ratio 6%), 2 (8%) and 3 (10%), respectively. Compared to pure blue and green devices, the maximum luminance of about 9,000 cd/m$^2$ and 18,000 cd/m$^2$, three WPLED devices show better brightness values. This is originated by energy transfer from host (blue) to dopants (green and red-orange polymers) and/or the direct dopant emission via capturing charge carriers in the device.

Figure 4 shows the current efficiency (a) and power efficiency (b) vs. luminance for the devices 1, 2 and 3, respectively. The maximum current efficiency for the device 1 was 2.57 cd/A at 7.8 V. In case of the device 2, the maximum current efficiency was 5.34 cd/A at 7.6 V. Device 3 showed the current efficiency of 4.06 cd/A at 7.0 V. The maximum power efficiency was 1.13 lm/W at 6.8 V for

**TABLE 1** The Bleeding Ratio of R, G, B Polymers (weight/weight)

| | Device 1 | Device 2 | Device 3 |
|---|---|---|---|
| Blue:Green:Red | 100:6:0.83 | 100:8:0.83 | 100:10:0.83 |

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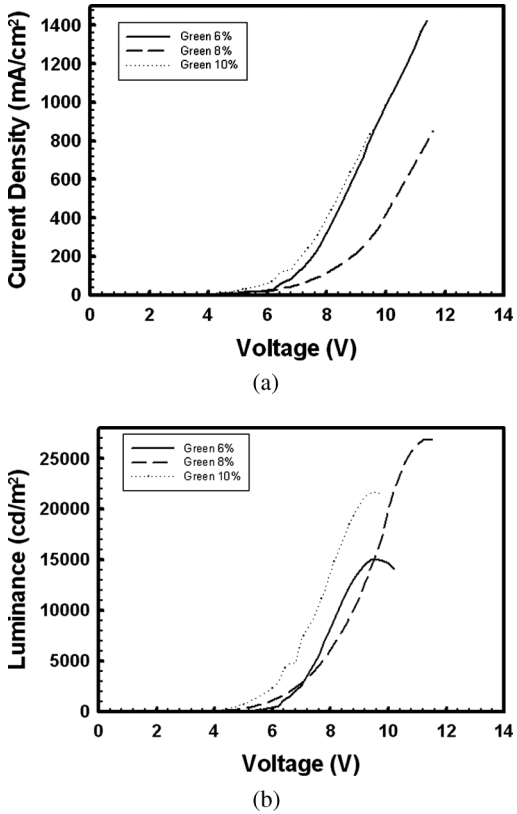


**FIGURE 3** The I-V-L graph of WPLEDs; (a) current density vs. voltage and (b) luminance vs. voltage.

device 1, 2.7 lm/W at 5.8 V for device 2, and 2.1 lm/W at 5.6 V for device 3. The best performance was obtained when the R:G:B ratio was 0.83:8:100.

As this emission of blending system is divided emission of R, G, B components itself and energy transfer from host to guest [11]. Luminance and efficiency of polymer blending device are dramatically changed by increasing concentration of green dopant [12,13]. This reason is that luminance of blue host is decrease by concentration of green dopant. The main emission of device 1 is blue host and device 3 is green host. In the device 2 it is match up blue emission and Förster energy transfer from blue host to green dopant.

The maximum quantum efficiency of each device was 1.11% at 7 V for device 1, 2.46% at 8.5 V for device 2, and 1.6% at 7.5 V for device 3.

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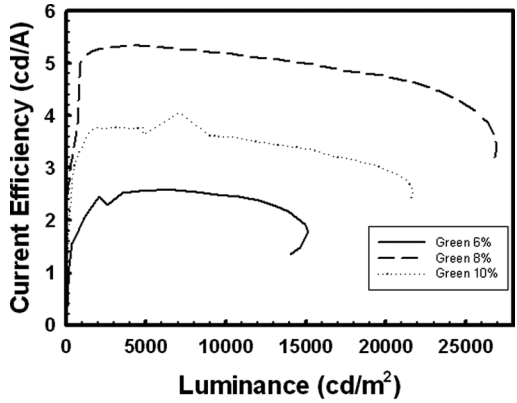
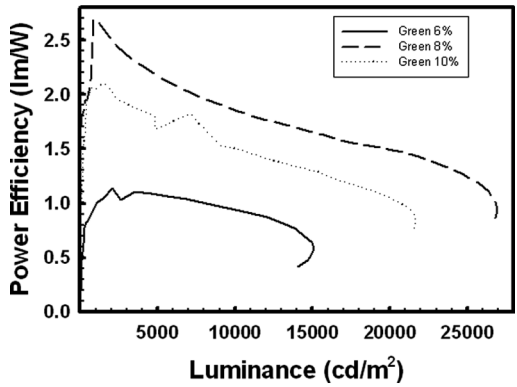



(a)




(b)

**FIGURE 4** The efficiency vs luminance graph of WPLEDs; (a) current efficiency vs luminance and (b) power efficiency vs luminance.

Table 2 is the summary of device performances with various green dopant ratios. The end line of Table 2 included the data of WPLED that make using blue and red blending in our previous work [10].

Figure 5(a) shows the normalized individual EL spectra for red, green, and blue devices. The EL peaks for red, green, and blue devices were 590 nm, 530 nm, and 450 nm, respectively. Figure 5(b) shows the three peaks of three WPLEDs in EL spectra at applied voltage of 9 V. The 600 nm as a shoulder peak, 550 nm as a maximum peak, and 450 nm as a weak peak could be obtained. The white color coordinates in these devices are located slightly to green region as shown in

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**TABLE 2** The Device Performance of WPLEDs with Various Green Dopant Ratios

| | Max. luminance ($cd/m^2$) | Current efficiency (cd/A) | Power efficiency (lm/W) | Max. Q.E. (%) |
|---|---|---|---|---|
| Device 1 | 15,120 (9.6 V) | 2.57 (7.8 V) | 1.13 (6.8 V) | 1.11 (7 V) |
| Device 2 | 27,000 (11.4 V) | 5.34 (7.6 V) | 2.7 (5.8 V) | 2.46 (8.5 V) |
| Device 3 | 21,670 (9.6 V) | 4.06 (7 V) | 2.1 (5.6 V) | 1.6 (7.5 V) |
| Blue + Red | 21,430 (9.2 V) | 4.32 (6.4 V) | 2.12 (5.8 V) | 1.9 (7 V) |

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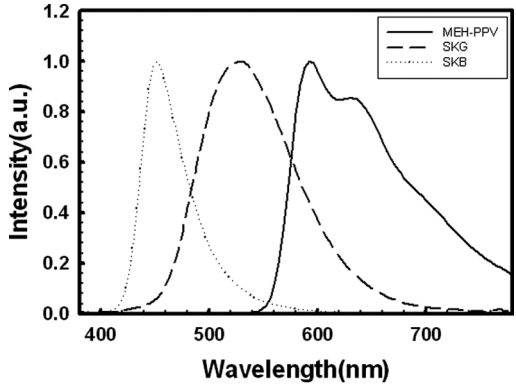
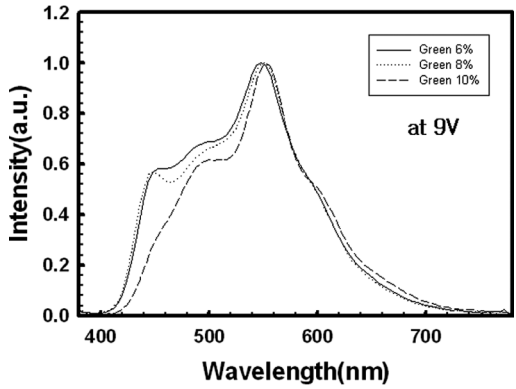



(a)




(b)

**FIGURE 5** The EL spectra of red, green, blue, and white devices; (a) The EL spectra of pure red, green, and blue devices. (b) The EL spectra of WPLEDs with various green dopant ratios.

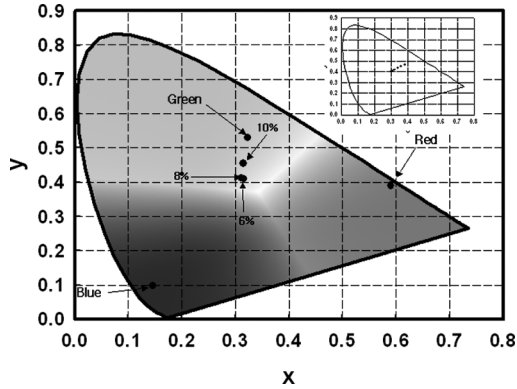



**FIGURE 6** The 1931 CIE coordinates of pure red, green, blue and WPLEDs with various green dopant ratios. Inset if the 1931 CIE coordinate at various applied voltages from 4 V to 9 V for the device 2.

Figure 6. As the dopant concentration further increased, the spectrum deviated from the white because of more energy transferred from host to guest. It is expected that the EL spectra and CIE coordinates of the WPLEDs could be further optimized by adjusting the dopant concentration. Thus the 450 nm blue peak was reduced by increasing green dopant ratio. On the other hand, 600 nm red shoulder peaks were slightly increased at the same conditions.

Inset of Figure 6 shows the 1931 CIE coordinate at various applied voltages from 4 V to 9 V for the device 2. The white point of color coordinates at 4 V was (0.38, 0.46) and the point at 9 V was (0.30, 0.40). The CIE coordinate of this device shifted slightly toward blue-emitting region when the applied voltage was increased. The reason is that the most of blending systems are separate each R, G, B components after spin-coating, thus it have different turn-on voltages [14,15].

## CONCLUSION

The RGB polymer blending system is good approach to develop white LEDs due to its simple manufacturing method. A series of white polymer light emitting devices has been fabricated by using polyfluorene-based blue (SKB), green (SKG) and MEH-PPV polymer blending systems. The white polymer device exhibited the current efficiency of 5.34 cd/A at 7.6 V and a maximum luminance of 27,000 cd/m$^2$ at 11.4 V.

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