Photon Recycling Semiconductor Light Emitting Diode

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Abstract: A new white light emitting diode, the photon recycling semiconductor light emitting diode (PRS-LED) is demonstrated. The device consists of a GaInN/GaN LED emitting in the blue spectral range and an AlGaInP photon recycling semiconductor emitting at the complementary color. The PRS-LED thus has two emission lines, one in the blue and one in the amber wavelength range. The theoretical luminous efficiency of the PRS-LED exceeds 300 lm/W, higher than the efficiency of phosphor-based white LEDs.

Keywords : photon recycling, white LED, efficiency

Introduction

Currently, white-light LEDs are based on photo-excitation of phosphors by a GaInN/GaN LED emitting in the blue or ultraviolet (UV) range of the spectrum. The quantum efficiencies of both, optically excited high-quality semiconductors and photoluminescent phosphors, can be close to 100 % [1,2,3]. YAG-based phosphors are known to have broad emission spectra, while the emission spectra of semiconductors are much narrower. A typical phosphor-based white LED has a broad emission spectrum[4] ranging from 425 to 700 nm.

Due to the fact that the human eye sensivity decreases rapidly when approaching IR and UV wavelengths, white light emission based on the emission of a *broad* spectrum does not have the maximum possible luminous efficacy. Since there are only three types of color-sensitive receptors or *cones* in the human eye, one can generate white light by the generation of light with two or three distinct colors. One can show that the most efficient white light source consists of two monochromatic sources emitting at complementary wavelengths. For two 100 % efficient monochromatic sources emitting at 448 nm and 569 nm[3,5], the maximum theoretical luminous efficacy to produce white light is 400 lumens per Watt of optical power [1,5].

In this publication, we report on a dichromatic semiconductor light source emitting two complementary colors. The higher-energy light is emitted by a current-injection blue LED. An electrically passive semiconductor, optically excited by the blue LED, re-emits light at lower energy. The wavelengths of the two sources are chosen is such a way that they are complementary wavelengths, as shown in Fig. 1. The combination of the two complementary colors according to Fig. 1 yields white light with a location on the chromaticity diagram identical to Illuminant C.

The schematic structure of the device is shown in Fig. 2. The figure indicates that a fraction of the light emitted by the blue LED is absorbed by the AlGaInP active region and re-emitted ("recycled") as lower energy photons. In order to obtain white light, the intensity of the two light sources must have a certain ratio that will be calculated below. The schematic power budget of the device is shown in Fig 3. It is assumed that the electrical input power is P_0, and the output powers in the blue and amber spectral range are P_1 and P_2, respectively. The efficiency of the blue LED and the photon-recycling semiconductor are assumed to be r_1 and r_2, respectively. A detailed calculation of efficiency and luminous performance of the device will be performed in a subsequent section of this publication.

The energy loss occurring in the photon recycling process must be taken into account when determining the optimum choice of wavelengths for highest efficiency. Note that energy is lost even if the recycling process occurs with unity quantum efficiency. To calculate the optimum wavelength of operation, we represent white light by the *Illuminant C* standard, whose chromaticity coordinates are $x_c = 0.3101$, $y_c = 0.3163$, $z_c = 0.3736$. Using these chromaticity coordinates, the pairs of complementary wavelengths, shown in Fig. 1, can be determined[5].

Calculation of Power Ratio

Next, we calculate the light power ratio between two sources and the luminous performance of the photon-recycling semiconductor LED. We refer to λ_1 and λ_2 as the primary (short) and secondary (long) wavelength, respectively, and assume that $\lambda_1 < \lambda_2$. For white light, λ_1 and λ_2 are pairs of complementary wavelengths. We define the color masses of the two light sources as

$$m_1 = x_1^* + y_1^* + z_1^* \quad \text{and} \quad m_2 = x_2^* + y_2^* + z_2^* \qquad (1)$$

Where x_1^*, y_1^*, z_1^*, x_2^*, y_2^*, z_2^* are color matching functions of two light sources[6,7,8,9]. We define the power ratio of the two light sources as

$$R = P_2 / P_1 \qquad (2)$$

where P_1 and P_2 are the optical powers of short wavelength source (λ_1) and long wavelength source (λ_2), respectively. The chromaticity coordinates of the newly generated color are then given by:

$$y_c = \frac{P_1 y_1^* + P_2 y_2^*}{P_1 m_1 + P_2 m_2} = \frac{(y_1^* + R y_2^*) P_1}{(m_1 + m_2 R) P_1} = \frac{y_1^* + R y_2^*}{m_1 + m_2 R} \quad (3)$$

$$x_c = \frac{x_1 * + R x_2 *}{m_1 + m_2 R} \quad (4)$$

For a white light emitter, x_c and y_c are chromaticity coordinates of the *Illuminant C* standard[10,11]. Solving Eq. (4) for the power ratio R yields:

$$R = \frac{y_1^* - y_c m_1}{y_c m_2 - y_2^*} \quad (5)$$

The power ratio as calculated from Eq. (5) is shown in Fig. 4.

Calculation of Luminous Performance

To produce the optical power P_2 at the wavelength of λ_2 through the recycling of photons from the primary source with wavelength λ_1, the optical power required from the primary source is given by:

$$\frac{P_2}{r_2} \frac{\lambda_2}{hc} \frac{hc}{\lambda_1} = \frac{P_2 \lambda_2}{r_2 \lambda_1} \quad (6)$$

where r_2 is the optical-to-optical conversion efficiency of the photon recycling light source. If P_0 is the electrical input power, then optical power emitted by the primary LED source is $r_1 P_0$, where r_1 is the electrical-to-optical power conversion efficiency of the primary LED. Thus the optical power emitted by the primary LED is given by

$$P_1 + \frac{P_2 \lambda_2}{r_2 \lambda_1} = r_1 P_0 \quad (7)$$

Solving the equation for the electrical input power yields:

$$P_0 = \frac{P_1}{r_1} + \frac{R P_1 \lambda_2}{r_1 r_2 \lambda_1} = P_1 \left(\frac{1}{r_1} + \frac{R \lambda_2}{r_1 r_2 \lambda_1} \right) \quad (8)$$

The total optical output power of the PRS-LED is given by

$$P_{out} = P_2 + P_1 = (1+R) P_1 \quad (9)$$

so that the total efficiency of the photon-recycling dichromatic light source is given by:

$$\eta = \frac{P_{out}}{P_0} = \frac{P_1(1+R)}{P_1\left(\frac{1}{r_1} + \frac{R \lambda_2}{r_1 r_2 \lambda_1} \right)} = \frac{(1+R)}{\left(\frac{1}{r_1} + \frac{R \lambda_2}{r_1 r_2 \lambda_1} \right)} \quad (10)$$

In the following calculation, X_c, Y_c, Z_c are the tristimulus values of the white light emitted by the PRS-LED [10,11].

The tristimulus value Y_c, *i. e.* the luminosity function [11] of the new color, is given by:

$$Y_c = y_1^* P_1 + y_2^* P_2 = y_1^* P_1 + y_2^* R P_1 = (y_1^* + y_2^* R) \quad (11)$$

Then the luminous efficacy (measured in lumens per optical Watt) of the photon-recycling semiconductor LED is given by:

$$\frac{Y_c}{P_{out}} = \frac{y_1^* + y_2^* R}{1 + R} \quad (12)$$

Thus, the luminous performance (measured in lumens per electrical Watt) of the PRS-LED is given by

$$\frac{Y_c}{P_0} = \frac{Y_c}{P_{out} / \eta} = \eta \frac{Y_c}{P_{out}} \quad (13)$$

Using this formula, we calculate the luminous performance as a function of the primary wavelength. The result of the calculation is shown in Fig. 5 for ideal monochromatic sources, *i. e.* for $r_1 = r_2 = 100\ \%$.

The maximum efficiency occurs if the primary wavelength source emits at 440 nm. A theoretical luminous performance of 335.8 lm/W is obtained for this wavelength. Note that we assume in the calculation that both light sources emit monochromatic light. However, the spontaneous emission from semiconductors has a $1.8kT$ spectral width. Taking into account a 5 nm linewidth, the expected luminous performance would be slightly lower, approximately 326 lm/W.

Experimental Results

A prototype PRS-LED has been demonstrated using a GaInN/GaN LED emitting in the blue and an electrically passive AlGaInP photon recycling semiconductor emitting in the red part of the spectrum. The emission spectrum of the device is shown in Fig. 6. It shows the emission spectrum of the primary LED at 470 nm and a second emission line at 630 nm due to absorption of 470nm light in the AlGaInP layer and re-emission of light at 630 nm.

To avoid absorption of light in the GaAs substrate, the GaAs substrate of the AlGaInP epitaxial layer was removed. First, the AlGaInP/GaAs recycling semiconductor was mounted on a glass slide. Subsequently the GaAs substrate was removed by polishing and selective wet chemical etching. Then, the primary LED and the photon-recycling semiconductor were brought into close contact. The experimental result indicates that LED light is sufficiently intense for optical pumping and also indicates good quantum efficiency of the recycling semiconductor. The recycling semiconductor used in this experiment is a standard AlGaInP/GaAs double heterostructure. At the present time, the photon-recycling semiconductor is planar and no surface texturing has been performed.

A program was developed to calculate the general color rendering index and luminous performance of the different emitters. The results are shown in Table 1. Note that a dichromatic light source has a lower color-rendering index as compared to a spectrally broad emitter. It can be shown that there is a fundamental trade off between color rendering and luminous performance of light-emitting devices[12]. Inspection of Table 1 indeed reveals that an increased luminous performance can be attained at the expense of the color rendering capability of the device. The color rendering capability is estimated by the general color-rendering index (CRI). In order to improve the general CRI of the dichromatic PRS LED, we consider two possibilities. First, the emission lines can be intentionally broadened, *e. g.* by compositional grading. Second, a second photon-recycling semiconductor can be added thus creating a tri-chromatic PRS-LED. Such a trichromatic semiconductor white LEDs has a color-rendering index of 60. Also note that the overall efficiency of our device is currently limited by the quantum efficiency of the primary blue LED.

Conclusion

In conclusion, we have demonstrated and analyzed a white-light emitting photon-recycling semiconductor LED. The device consists of a primary current-injection LED and a photon-recycling semiconductor that is optically excited by the primary LED. Based on our calculation, luminous performances exceeding 300 lm/W can be expected for an ideal device with unity quantum efficiency. Due to the narrow emission spectra of the two light sources, the PRS-LED has a higher luminous performance than phosphor-based white LEDs. A PRS-LED and the emission of near-white light is demonstrated by using a GaInN/GaN LED emitting in the blue and an AlGaInP/GaAs photon recycling semiconductor emitting in the red-to-amber part of the spectrum.

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Spectra distribution	FWHM (nm)	Luminescence Performance (lumens/Watt)	Chromaticity coordinates (x, y)	General CRI
Dichromatic	5	326	0.31, 0.32	10
Broadened Dichromatic	20	306	0.31, 0.32	26
Trichromatic LED	5	283	0.31, 0.32	60
Phosphorous based LED	100	280	0.31, 0.32	57

Table 1. Comparison of calculated white LED in efficiency and general color rendering index (CRI) for a given full width at half-maximum (FWHM) of each peak in the emission spectrum. For the phosphorous-based white LED, the CRI is based on the spectra provided by the commercial vendor.

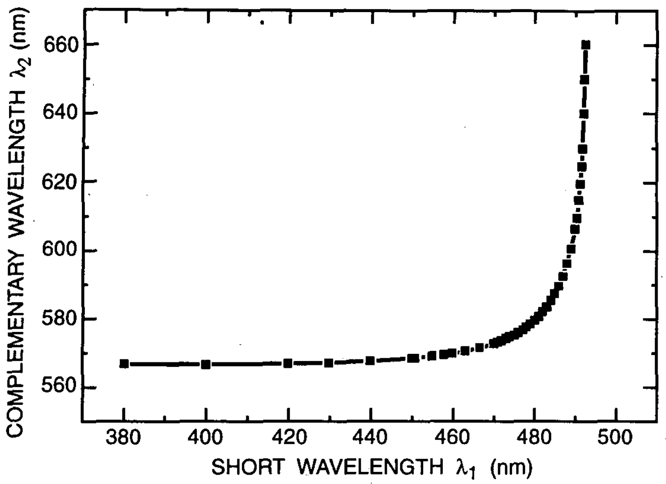

Fig. 1 Complementary wavelengths yielding the color of the standard white Illuminant C.

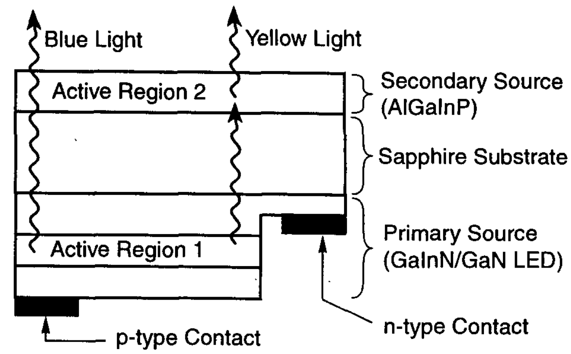

Fig. 2 Schematic structure of the photon-recycling semiconductor LED (PRS-LED).

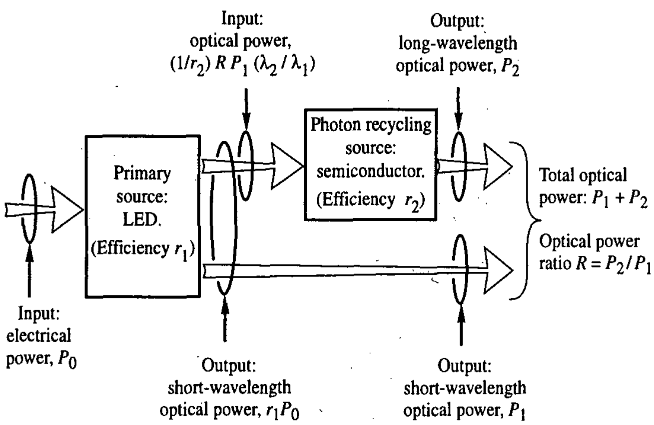

Fig. 3 Power budget of the PRS-LED.

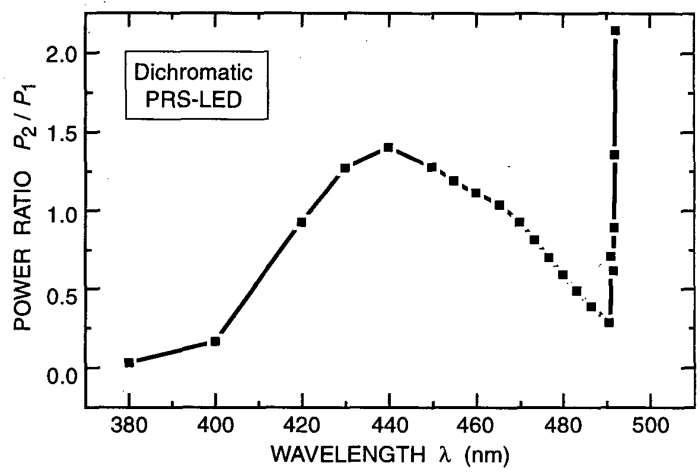

Fig. 4 Power ratio of two monochromatic light sources $P(\lambda_2) / P(\lambda_1)$, where $\lambda_2 > \lambda_1$, required to obtain white light.

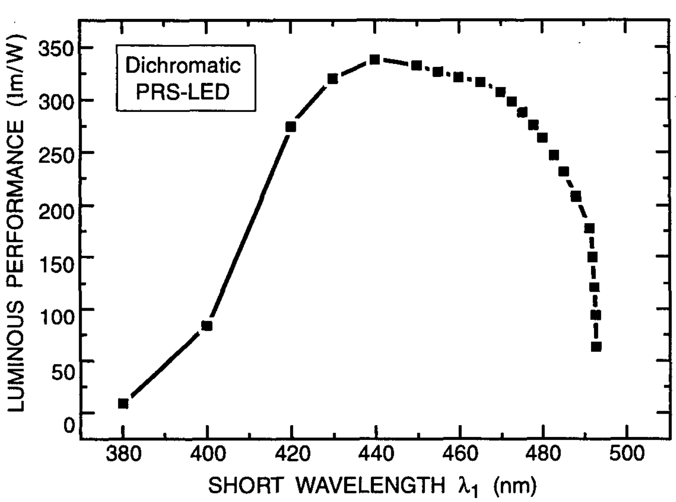

Fig. 5 Luminous performance versus primary light source wavelength of ideal photon-recycling semiconductor LED.

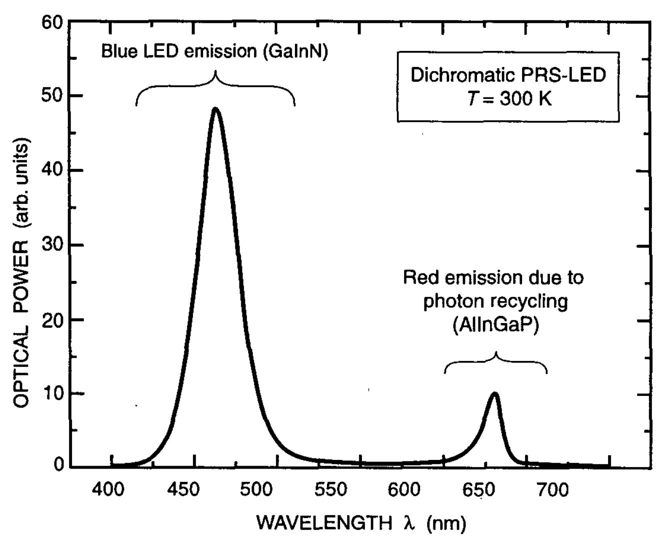

Fig. 6 Room temperature luminescence spectrum of a photon-recycling semiconductor LED showing the blue GaInN/GaN LED emission and the red AlGaInP emission due to photon recycling.