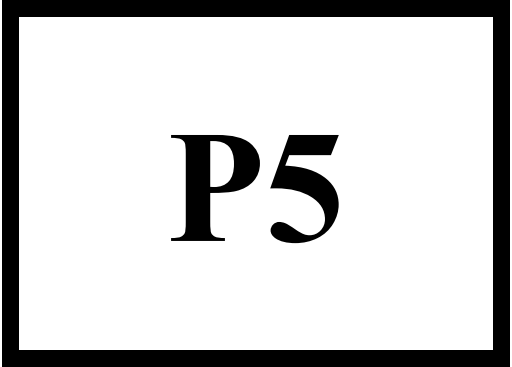




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On spectral and thermal behaviors of AlGaInP light-emitting diodes under pulse-width modulation

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Behavior of the emission spectrum, junction temperature, and charge carrier temperature of low-power AlGaInP light-emitting diodes (LEDs) with different colors under pulse-width-modulation (PWM) dimming is investigated. The blueshift of the peak wavelength and the bandwidth narrowing in the emission spectra of the studied LEDs with shortening pulse are found. A linear relation of the junction temperature and carrier temperature of the studied LEDs to their duty cycle is detected. Perceivable changes in color of AlGaInP LEDs under the PWM scheme are observed. © 2007 American Institute of Physics. [DOI: 10.1063/1.2805198]

(Al_xGa_{1-x})_{0.5}In_{0.5}P material system has played a significant role in the development of light-emitting diodes (LEDs) emitting in wavelength range of 560–650 nm because of its direct band gap transition at that wavelength region.^{1–4} Application field of these LEDs has widened to, e.g., automotive lighting, traffic lights, and color displays in recent years. To achieve high reliability and luminous efficiency for LED applications, dependences of optical properties of LEDs on operating conditions such as electrical current and operating temperature need to be known. LED junction temperature that affects the lifetime, efficiency, forward voltage, and emission wavelength of the LED is a critical parameter when designing a high-quality light source. Several studies have been derived to determine the junction temperature of LEDs.^{5–8} It has been found that heating of an AlGaInP LED induces a redshift of the emission spectrum.⁵ For dimming LEDs, pulse-width modulation (PWM) is popularly used instead of continuous current reduction, because more broad control range and linear control for LED brightness may be obtained. Other advantage that is often associated with the use of PWM is that LEDs would be immune to any color changes when dimmed. However, emission wavelength shifts for high-power LEDs under PWM dimming have recently been observed.^{9,10}

The junction and charge carrier temperatures of LEDs under PWM dimming have not been reported earlier. In this letter, behaviors of the electroluminescence (EL) spectrum, junction temperature, and carrier temperature of three low-power epoxy encapsulated AlGaInP LEDs of type Tl₃⁴ (yellow from Toshiba and red from Agilent) and 10 mm (orange from Toshiba) at different PWM dimming levels are investigated. Variations in their chromaticity coordinates are also shown.

In the PWM dimming scheme, the width t of the square-shaped pulse is modulated, i.e., the period T of the modulation signal and the drive current i of the LED at the top of the pulse remain unchanged and, being a pulse low, the current is zero. The brightness of the LED controlled by the PWM is defined as a product of the duty cycle $D=t/T$ and constant

brightness obtained at continuous current i . In this study, behavior of AlGaInP LEDs under the PWM dimming was investigated by varying D within a range of 0.03–1. LEDs were driven at a current of 20 mA and modulation frequency $1/T$ was 1 kHz. The EL spectra of LEDs to be studied were recorded with a calibrated, charge-coupled device, Minolta CS1000 spectroradiometer. The integration time of CS1000, which depends on light level, was more than 10T.

To show spectral changing feature of low-power AlGaInP LEDs under the PWM dimming, the EL spectra of the studied LEDs at three duty cycles are presented in Fig. 1. Their peak wavelengths shifted toward shorter wavelengths and spectral band narrowed with decreasing duty cycle. This is similar finding as in Refs. 9 and 10. Figure 2 shows the peak wavelength shift and narrowing of the EL spectra of the studied AlGaInP LEDs at different duty-cycle levels. The PWM control of the yellow LED, whose EL spectrum changed the most, shifted the peak wavelength by 2.3 nm and the bandwidth by 0.9 nm. The blueshift of the peak wavelength with decreasing duty cycle is explained by cooling of the semiconductor chip, therefore the band gap energy of the semiconductor broadens with dropping temperature.¹¹ The temperature effect can be understood with alternate heat-

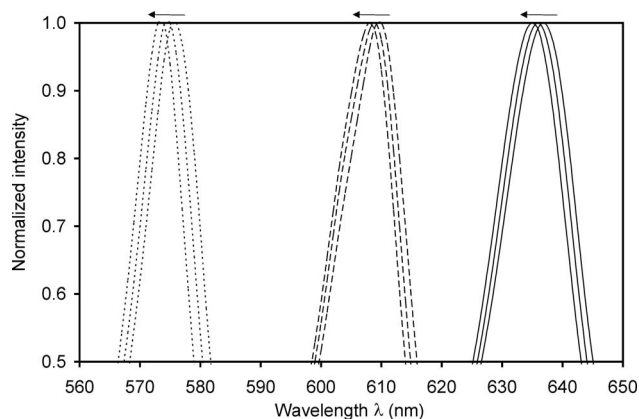


FIG. 1. Normalized EL spectra of the yellow (dotted lines), orange (dashed lines), and red (solid lines) AlGaInP LEDs at three duty cycles (0.03, 0.5, and 1). The arrows indicate the blueshift of the peak wavelength of the LED with decreasing duty cycle.

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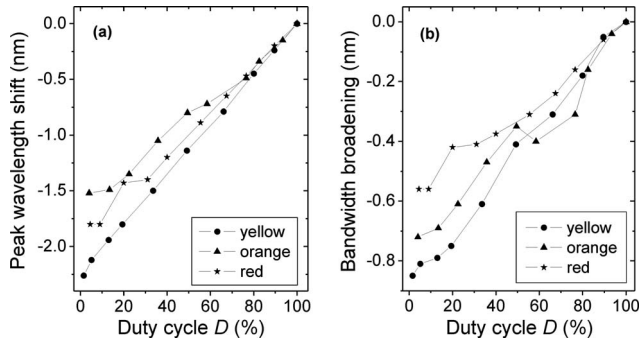


FIG. 2. (a) The peak wavelength shift and (b) bandwidth broadening of the studied AlGaInP LEDs as a function of the duty cycle. The bandwidths of the LEDs have been calculated on the basis of the full width at half maximum.

ing and cooling of the LED chip when the current pulse is high and low, respectively. When lessening the duty cycle, the relation of heating rate to cooling rate decreases, then, the LED spectrum moves toward shorter wavelengths.

The temperature effect of LEDs was studied by determining the charge carrier temperature and junction temperature during their PWM control. The junction temperatures of the studied AlGaInP LEDs at different duty cycles were evaluated with the peak-wavelength shift method.^{5–8} To do that, a LED to be calibrated for the peak-wavelength shift with temperature was mounted to a thermal contact with a specific aluminum body having a temperature control and was driven at a current of 20 mA with 1 kHz modulation frequency. Using a low duty-cycle level of 0.003, the LED junction temperature could be assumed to be sufficiently close to the temperature of the aluminum body. The EL spectra of the studied LEDs at various temperatures were then determined in a range of 18–50 °C. The junction temperature coefficient $k = d\lambda_p/dT_j$ of the peak wavelength and the peak wavelength λ_{p0} of the LED in 0 °C temperature were used as free parameters when fitting the peak wavelengths λ_p determined at corresponding temperatures T_j to the equation

$$\lambda_p(T_j) = kT_j + \lambda_{p0}. \quad (1)$$

The results from the determination of coefficient $d\lambda_p/dT_j$ for the studied AlGaInP LEDs are shown in Fig. 3(a). Our result $d\lambda_p/dT_j = 0.1384$ nm/°C for the red AlGaInP LED and values of 0.1562, 0.1157, and

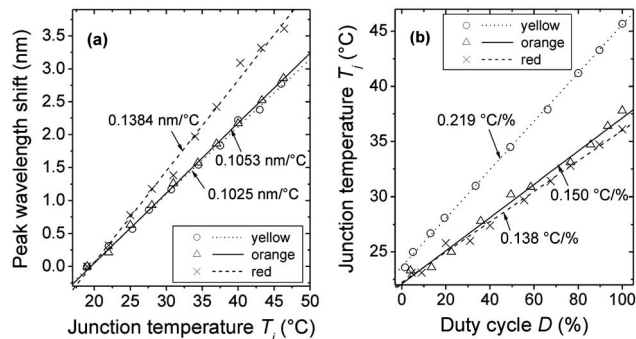


FIG. 3. (a) The peak wavelength shifts in calibration measurement of the junction temperature and (b) the junction temperatures under the PWM control for the studied AlGaInP LEDs. Junction temperature coefficient $d\lambda_p/dT_j$ of the peak wavelength and duty cycle coefficient dT_j/dD of the junction temperature for each LED are shown.

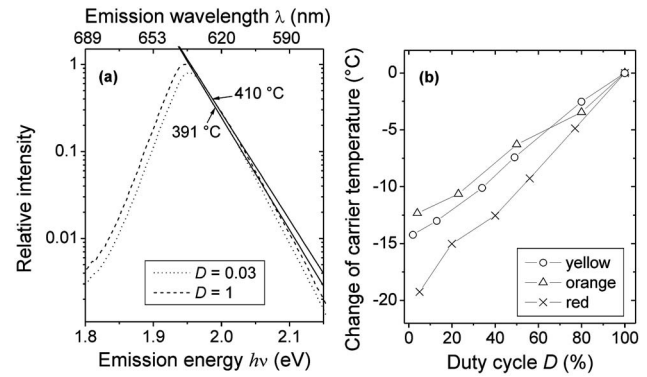


FIG. 4. (a) Illustration of the carrier temperature determination of the red AlGaInP LED at duty cycles of 0.03 and 1. The solid lines show fits to Eq. (2). Obtained values for the carrier temperature of the LED at given duty cycles are also displayed. (b) Change of the carrier temperature of the studied AlGaInP LEDs as a function of the duty cycle.

0.1376 nm/°C published in Refs. 5–7 for AlGaInP red LEDs are within good agreement. The junction temperature of the LED at known duty cycle may be inferred by determining the peak wavelength of the LED having the same duty cycle and utilizing values of k and λ_{p0} determined above. The junction temperatures of the studied AlGaInP LEDs as a function of the duty cycle are presented in Fig. 3(b). Varying the LED duty cycle from 0.03 to 1 causes a rise of 22, 15, and 13 °C in the junction temperature of the yellow, orange, and red LEDs, respectively. Thus, the influence of the PWM control on the change in the junction temperature of the AlGaInP LED is somehow inversely proportional to its emission wavelength. Therefore, electrical power of an LED having longer emission wavelength is lower and, thus, heats the LED chip less than in the case of a LED having shorter emission wavelength. Other reason might be the thermal conductivity of alloy $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}$, which is inversely dependent on Al content.¹² Thus, the thermal conductivity of the yellow AlGaInP LED, which has larger Al content than the red LED, is smaller and, in this case, it heats more sensitively than AlGaInP LED emitting in longer wavelength does. Variations in the LED junction temperature during the PWM dimming are obviously such large change that it should be catered to when designing lighting system having a brightness control based on AlGaInP LEDs.

When determining the carrier temperature of AlGaInP LEDs, the charge carrier distribution was approximated by the Boltzmann distribution in the high-energy side of LED spectrum close to its peak emission energy.^{5,8,11} The Boltzmann distribution can be expressed in the form

$$\ln I = -\frac{h\nu}{kT_c}, \quad (2)$$

where I is the relative intensity of radiation, h is the Planck constant, ν is the frequency of a photon, k is the Boltzmann constant, and T_c is the charge carrier temperature of the LED. T_c can be determined by fitting the high-energy slope to the EL spectrum determined experimentally using T_c as free parameter. Figure 4(a) demonstrates the determination of the carrier temperature of the red LED. Changes in the carrier temperature of the studied AlGaInP LEDs at a few duty cycles are shown in Fig. 4(b). The carrier temperatures of the studied LEDs pretty linearly correlate with duty cycle.

Changes in the carrier temperatures and junction tempera-

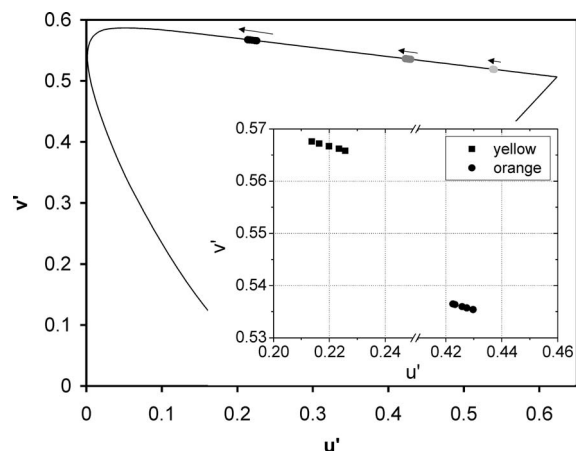


FIG. 5. $u'v'$ chromaticity coordinates of three AlGaInP LEDs at duty cycles of 0.03, 0.2, 0.5, 0.8, and 1.0 in CIE 1976 uniform chromaticity scale diagram. The arrows show the direction and magnitude of the chromaticity change of the studied LEDs as their duty cycle decreases. The inset illustrates the chromaticity change of the yellow and orange AlGaInP LEDs.

tures of LEDs under the PWM control are approximately of the same order, but the carrier temperature is higher than the actual junction temperature [see Fig. 4(a)], as well as the actual carrier temperature, due to the alloy-broadening effect occurring in ternary and quaternary semiconductor alloys.¹¹ With Eq. (2) and Fig. 4(b), narrowing of the bandwidth of the studied LEDs with lessening duty cycle can be explained; therefore, the high-energy side of the spectrum becomes sharper at lower carrier temperatures.

To investigate whether the spectral variations of the studied LEDs presented above cause perceivable changes in the human eye, chromaticity coordinates of them were determined in CIE 1976 uniform chromaticity scale (UCS) diagram and they are presented in Fig. 5. The order of the chromaticity shifts were studied with quantity

$$\Delta u'v' = \sqrt{(u'_2 - u'_1)^2 + (v'_2 - v'_1)^2}, \quad (3)$$

where coordinates (u'_1, v'_1) and (u'_2, v'_2) in the UCS diagram are the chromaticity points of the LED determined at the lowest and highest studied duty cycles, respectively. The values of $\Delta u'v'$ for the yellow, orange, and red LEDs are 0.012, 0.007, and 0.002, respectively. The smallest color difference that the human eye is able to sense is approximately 0.003 in the yellow and orange regions and 0.004 in the red region. Those values were calculated with the MacAdam ellipses transformed to the UCS diagram.¹¹ Thus, variations in the

EL spectra of the yellow and orange LEDs during the PWM dimming cause perceivable chromaticity shifts.

In conclusion, spectral and thermal behaviors of three low-power AlGaInP LEDs under PWM dimming were investigated. The blueshift and narrowing of the EL spectrum with lessening duty cycle for the studied LEDs were found. The results are explained by temperature effect. The junction temperature and the peak wavelength of the yellow LED, which of the studied LEDs most sensitively responded to varying duty cycle, were evaluated to change even by 22 °C and 2.3 nm, respectively, in the studied duty-cycle range. Spectral changes caused perceivable chromaticity shifts in the cases of yellow and orange LEDs. The influence of the PWM dimming on LED color is so large that it should be taken into account when designing satisfactory light source based on AlGaInP LEDs, e.g., for lighting system, signal lighting, and background lighting of LED displays. The results presented above suggest that information about spectral and color variations under the PWM control is recommended to be included in the datasheets by the LED manufacturers.

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