Received: 1 April 2022 | Revised: 19 October 2022 | Accepted: 26 October 2022

IET Optoelectronics

DOI: 10.1049/ote2.12083

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH

Understanding and evaluating the mean photon energy and the external quantum efficiency of light-emitting diodes

Ilgyu Choi[1] | **Sangjin Min**[1,2] | **Jong-In Shim**[1,2] | **Dong-Soo Shin**[1,2]

[1]Department of Photonics and Nanoelectronics, Hanyang University ERICA, Ansan, Gyeonggi-do, Korea

[2]BK21 FOUR ERICA-ACE Center, Hanyang University ERICA, Ansan, Gyeonggi-do, Korea

Correspondence

Dong-Soo Shin, Department of Photonics and Nanoelectronics, Hanyang University ERICA, Ansan, Gyeonggi-do 15588, Korea.
Email: dshin@hanyang.ac.kr

Funding information

Korea Institute for Advancement of Technology, Grant/Award Number: P0016250

Abstract

The mean photon energy of a light-emitting diode (LED) as recently defined in the IEC standard is theoretically examined. It is pointed out that defining the mean photon energy as an arithmetic mean of photon energies in the emission spectrum is crucial in decomposing the power efficiency of an LED into the voltage efficiency and the external quantum efficiency (EQE). The mean photon energy thus defined and the photon energy calculated from the more convenient peak wavelength in the spectrum are then evaluated and compared for blue and red LED samples. The EQEs of the blue and red LEDs are subsequently obtained, demonstrating that the EQE values from the peak photon energy have small errors within 0.5%p of the true EQE values. The current work presents useful criteria in substituting the EQE value calculated from the peak wavelength for the true EQE value using the mean photon energy for both the blue and red LEDs.

1 | INTRODUCTION

A light-emitting diode (LED) emits a broad spectrum of light spanning tens of nanometres by spontaneous emission via recombination of electrons in the conduction band and holes in the valence band [1–3]. Owing to the broad spectrum, defining the mean photon energy of light emitted from an LED is a non-trivial matter. By defining the mean photon energy of light emitted from an LED, various LED efficiencies can be systematically defined [4].

The power efficiency (PE), sometimes referred to as the wall-plug efficiency, is the efficiency of the utmost importance that characterises an optoelectronic device, such as the LED. The PE indicates how much the input electrical power is converted to the output radiant (or optical) power. Since the spectrum of light emitted from an LED is broad, one needs to integrate the whole spectrum of radiant power, typically employing an integrating sphere. Once the light-current-voltage (L-I-V) characteristics of the device are measured, evaluating the PE of an LED is a straightforward matter.

On the other hand, other efficiencies, such as quantum efficiencies, involve the comparisons of particle numbers [4, 5]. In the case of LEDs, one compares the emitted photon number with the injected carrier (electron) number. In counting the photons emitted from an LED, it is essential to consider the broad spectrum. So far, the counting of photons and the definition of the mean (average) photon energy emitted from an LED have been mostly neglected. For example, in ref. [1], definitions of the internal quantum efficiency (IQE) and the external quantum efficiency (EQE) only mention the photon energy, not the *mean* photon energy, ignoring the spectral distribution of the radiant power from an LED. Recently, a new IEC standard has been published to define the various LED efficiencies, including the quantum efficiencies, and the mean photon energy essential in evaluating the quantum efficiencies [6]. At the moment, careful considerations of the theoretical background of the issue are rarely found in the literature.

Therefore, in this work, we intend to fill the gap in the literature, examining the definition of the mean photon energy in relation to the spectrum with the consideration of the probability of finding a photon at a particular wavelength interval in the given LED spectrum. We also relate how the mean photon energy is utilised in the definition of the EQE. It is pointed out for the first time that only by defining the mean photon energy as an arithmetic mean of the photon energies in the spectrum, the PE can be decomposed into the voltage efficiency (VE) and the EQE. As the EQE can be further decomposed into the IQE and the light-extraction efficiency [4], leading to the decomposition of various factors determining the LED performance [7, 8], the theoretical foundation set up in this work is of critical importance in the systematic understanding of an LED as an optoelectronic device.

Next, utilising the blue and red LED samples, it is experimentally demonstrated how the mean photon energies and EQEs are evaluated. Since the evaluation of the mean photon energy involves the integration of the emission spectrum, the photon energy from the peak wavelength of the spectrum is sometimes used for convenience. Thus, the errors involved in using the peak wavelengths to evaluate the EQEs are also investigated. Subtle differences between the blue and red LEDs, caused by the different shapes of the spectrum, are also discussed.

2 | DEFINITION OF THE MEAN PHOTON ENERGY

In defining the mean photon energy, one needs to consider the probability of finding the photon in an infinitesimal frequency interval between ν and $\nu + d\nu$ of the emission spectrum, which is denoted by $P_\nu(\nu)d\nu$. Then, the mean photon energy $h\overline{\nu}$ is defined as an arithmetic mean by multiplying the photon energy $h\nu$ with the probability of finding that photon and integrating over the entire frequency range:

$$h\overline{\nu} = \int h\nu P_\nu(\nu)d\nu, \tag{1}$$

where h is the Planck constant. Since the spectrum is often expressed as a function of the wavelength λ, Equation (1) is rewritten in terms of wavelength:

$$h\overline{\nu} = \int \frac{hc}{\lambda} P_\lambda(\lambda)d\lambda, \tag{2}$$

where $P_\lambda(\lambda)d\lambda$ denotes the probability of finding a photon at an infinitesimal wavelength interval between λ and $\lambda + d\lambda$. Here, c is the speed of light in vacuum and the relation $c = \nu\lambda$ is used.

The radiant power from an LED, Φ_e, has a spectral distribution as a function of the wavelength, which is denoted as $\Phi_{e,\lambda}(\lambda)$, that is, $\Phi_{e,\lambda}(\lambda) = \frac{d\Phi_e(\lambda)}{d\lambda}$. The radiant power from the LED is obtained by integrating the spectral distribution over the entire wavelength range, that is,

$$\Phi_e = \int \Phi_{e,\lambda}(\lambda)d\lambda. \tag{3}$$

With the spectral distribution $\Phi_{e,\lambda}(\lambda)$, the probability of finding a photon between λ and $\lambda + d\lambda$ is given as follows:

$$P_\lambda(\lambda)d\lambda = \frac{\frac{\Phi_{e,\lambda}(\lambda)}{hc/\lambda}d\lambda}{\int \frac{\Phi_{e,\lambda}(\lambda)}{hc/\lambda}d\lambda}, \tag{4}$$

since $\frac{\Phi_{e,\lambda}(\lambda)}{hc/\lambda}d\lambda$ represents the number of photons emitted per unit time in an infinitesimal interval between λ and $\lambda + d\lambda$. The integrated quantity in the denominator, $\int \frac{\Phi_{e,\lambda}(\lambda)}{hc/\lambda}d\lambda$, is the *total* number of photons emitted from an LED per unit time.

Now, by putting Equation (4) into Equation (2), one obtains the definition of the mean photon energy as an arithmetic mean:

$$h\overline{\nu} = \frac{\Phi_e}{\int \frac{\Phi_{e,\lambda}(\lambda)}{hc/\lambda}d\lambda}. \tag{5}$$

This definition is equivalent to *the radiant power divided by the total number of photons emitted by the LED per unit time.* Equation (5) can also be written as

$$h\overline{\nu} = \frac{hc\Phi_e}{\int \lambda\Phi_{e,\lambda}(\lambda)d\lambda}. \tag{6}$$

The denominator in Equation (6) contains a quantity called the centroid wavelength, λ_c [9], also known as the spectral centroid, which is defined by

$$\lambda_c = \frac{\int \lambda\Phi_{e,\lambda}(\lambda)d\lambda}{\Phi_e}. \tag{7}$$

Using the definition of the centroid wavelength λ_c, the mean photon energy can also be written as

$$h\overline{\nu} = \frac{hc}{\lambda_c}. \tag{8}$$

While the centroid wavelength can be calculated in an integrating-sphere system, the importance of the centroid wavelength has often been neglected in the LED community, unlike the dominant wavelength that is measured more frequently. The centroid wavelength calculated in the integrating-sphere system is typically prone to errors when the spectrum contains high background noise as encountered during the measurement at a low injection current.

The EQE, η_{EQE}, which evaluates the total number of photons emitted from an LED per unit time with respect to the number of electrons injected into the LED per unit time [4, 6], can be written as

$$\eta_{\text{EQE}} = \frac{\int \frac{\Phi_{e,\lambda}(\lambda)}{hc/\lambda} d\lambda}{\frac{I}{q}}, \tag{9}$$

where I is the injection current and q is the elementary charge. The denominator I/q then represents the number of electrons injected into the LED per unit time. Using the mean photon energy as defined in Equation (5), the EQE is written as follows:

$$\eta_{\text{EQE}} = \frac{\Phi_e / h\overline{\nu}}{I/q}. \tag{10}$$

Now, the VE, η_{VE}, is defined as the mean photon energy $h\overline{\nu}$ emitted from the LED with respect to the electrical energy qV supplied from the power source, where V is the applied voltage [4, 6], that is,

$$\eta_{\text{VE}} = \frac{h\overline{\nu}}{qV}. \tag{11}$$

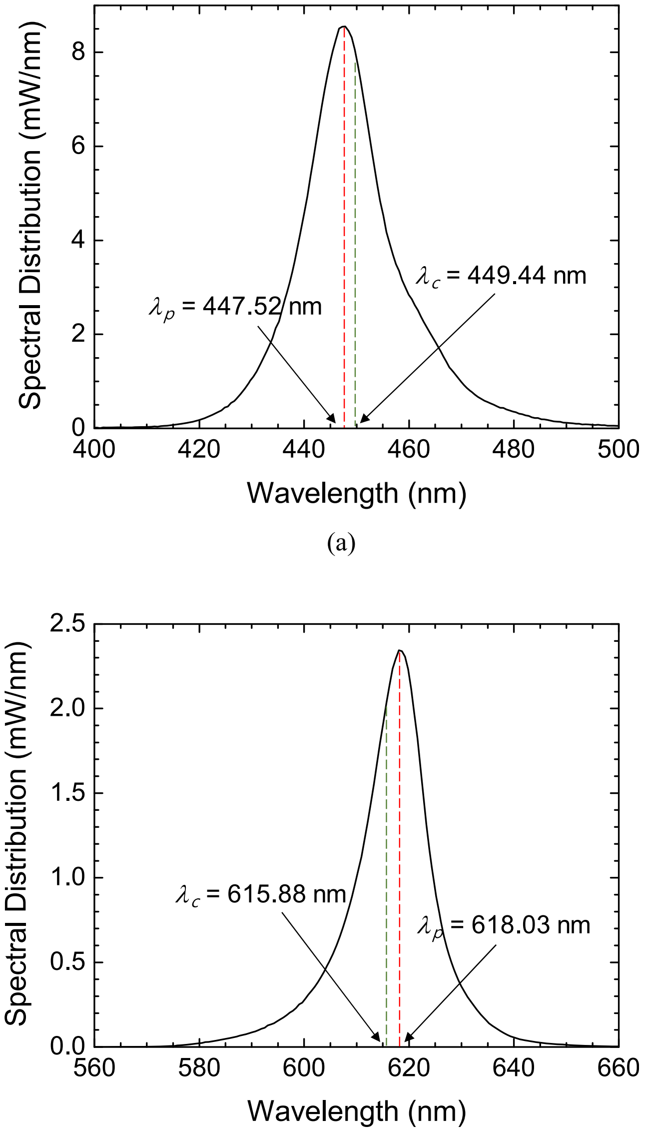
Then, the PE can be expressed as a product of the VE and the EQE:

$$\eta_{\text{PE}} \equiv \frac{\Phi_e}{V \cdot I} = \eta_{\text{VE}} \cdot \eta_{\text{EQE}}. \tag{12}$$

One can see the importance of the mean photon energy in connecting the VE and the EQE as seen in Equations (10) and (11). The definition of the mean photon energy given in Equation (5) is crucial in decomposing the PE into its constituent efficiencies, the VE and the EQE [Equation (12)].

3 | EXPERIMENTS

To evaluate the mean photon energy by Equation (5) and subsequently the EQE values by Equation (10), we utilised two commercial LED samples, namely a GaN-based blue LED (chip size: 1160 × 650 μm^2) and a GaAs-based red LED (chip size: 940 × 940 μm^2). The radiant power from the LED was measured by an integrating sphere (Instrument Systems ISP 500) while the injection current to the LED was supplied by a Keithley 2601 source metre in the pulse mode (period: 1000 ms, duty cycle: 1%). Being commercial samples, the detailed epitaxial structures of the samples were unknown. However, the optoelectronic performances including the *L-I-V* characteristics and the spectra were considered typical for the blue and red LEDs, respectively.

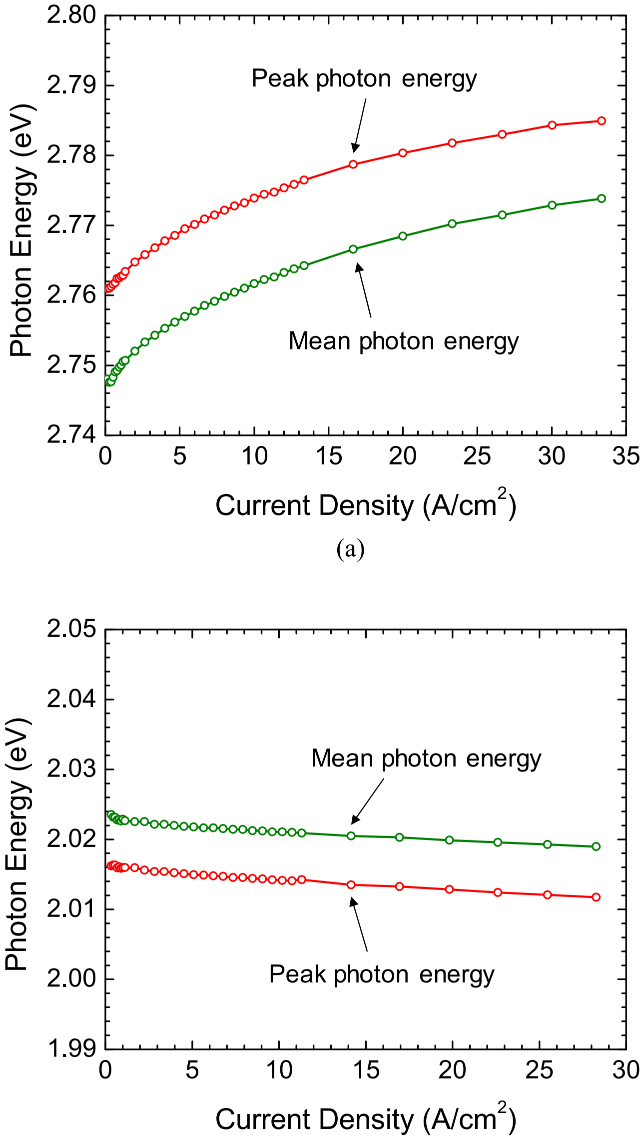


(a)

(b)

FIGURE 1 Emission spectra from (a) blue and (b) red light-emitting diode samples at 150 mA. Both the peak wavelength λ_p and the centroid wavelength λ_c are shown.

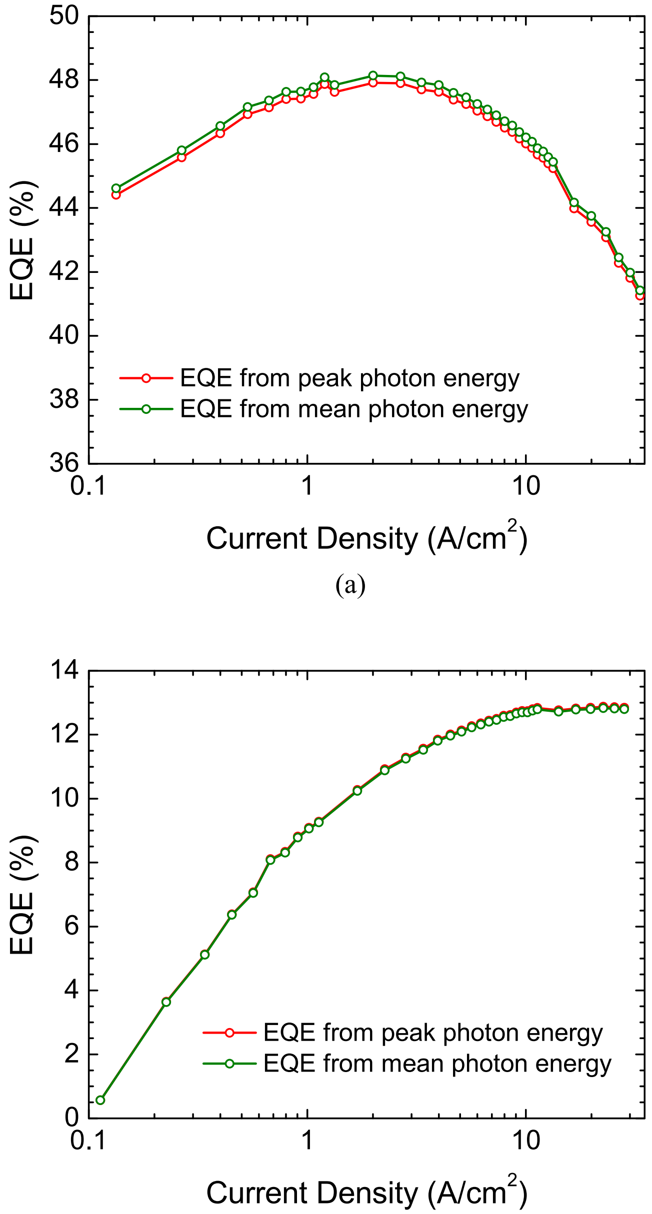
Figure 1a,b shows the measured spectra of both the blue and red LED samples. The spectra shown in Figure 1 represent the typical characteristics of blue and red LEDs based on different material systems [2]. The spectrum of the blue LED shown in Figure 1a has a longer tail on the long-wavelength (low-energy) side from the peak, while that of the red LED in Figure 1b shows the opposite trend. Judging from the typical optoelectronic performances, for the blue LED, a very large piezoelectric field in the quantum well (QW) and the local potential fluctuation are considered playing roles on the longer tail on the long-wavelength side [10, 11]. On the other hand, for the red LED, relatively low barrier height in the QW seems to cause the longer tail in the short-wavelength (high-energy) side in the spectrum [2]. This difference in the spectral shape of the LED causes the centroid wavelengths, calculated by Equation (7), related to the mean photon energies, to be located at the opposite sides from the peaks: For the blue LED, the centroid wavelength (λ_c = 449.44 nm) is



(a)

(b)

FIGURE 2 Mean and peak photon energies as functions of current density for (a) blue and (b) red light-emitting diodes



(a)

(b)

FIGURE 3 EQE values as functions of current density for (a) blue and (b) red LEDs. EQE, external quantum efficiency; LED, light-emitting diode

located at the long-wavelength side from the peak wavelength (λ_p = 447.52 nm), while for the red LED, it is located on the short-wavelength side (λ_c = 615.88 nm) from the peak wavelength (λ_p = 618.03 nm).

Figure 2a,b depicts the mean photon energies as functions of current density, evaluated from the spectra by using Equation (5) for blue and red LEDs. Also shown in Figure 2 are the *peak* photon energies, that is, the photon energies evaluated from the peak wavelengths (hc/λ_p). It is seen in Figure 2a that for the blue LED, both the mean photon energy and the peak photon energy show a blueshift with the current density, which is mainly the consequence of the piezoelectric-field screening by the injected charge carriers and the subsequent quantum-energy shift, a phenomenon called the quantum-confined Stark effect [12]. The mean photon energy in Figure 2a is consistently smaller than the peak photon energy, whose differences are kept almost constant at ~14 meV. On the other hand, the photon energies for red LEDs in Figure 2b show a slight redshift with the current density, mainly caused by the bandgap narrowing due to the heat generation from the injected charge carriers. Contrary to the blue LED case, the mean photon energy of the red LED in Figure 2b is consistently larger than the peak photon energy and the differences are smaller than that of the blue LED at ~8 meV.

TABLE 1 Mean and peak photon energies at maximum EQEs for blue and red LEDs and subsequent EQEs using the respective photon energies

Sample	Mean photon energy at max EQE (eV)	Peak photon energy at max EQE (eV)	Max EQE by mean photon energy (%)	Max EQE by peak photon energy (%)	Error from the peak photon energy (%p)
Blue LED	2.752	2.765	48.14	47.91	−0.23
Red LED	2.020	2.012	12.83	12.88	0.05

Note: Error from the peak photon energy is defined as the maximum EQE by peak photon energy subtracted by the maximum EQE by mean photon energy.

Abbreviations: EQE, external quantum efficiency; LED, light-emitting diode.

This difference between the peak photon energy and the mean photon energy leads to the EQE values being different depending on the energies used. For its simplicity and ease of use without any integration, the peak photon energy is often used in the LED community. However, for more accurate evaluation, the mean photon energy must be used. Shown in Figure 3a,b are the EQE values evaluated for blue and red LEDs with the mean and peak photon energies. The EQE of the blue LED shown in Figure 3a demonstrates that using the peak photon energy *underestimates* the EQE value over all current densities. The *maximum* EQE value of the blue LED sample is underestimated by 0.23%p. On the other hand, in the case of the red LED as depicted in Figure 3b, using the peak photon energy tends to *overestimate* the EQE over all current ranges. The maximum EQE value of the red LED sample is overestimated by 0.05%p. Although the general trends are different in terms of under- and overestimating, the errors involved with using the peak photon energy instead of the more accurate mean photon energy are consistently smaller than 0.5%p. Table 1 summarises the results of the mean and peak photon energies at maximum EQEs and the subsequent EQE values using the respective photon energy values for blue and red LEDs. While the current study used only a limited number of LED samples, the cases considered here give a clear idea about whether replacing the mean photon energy with the peak photon energy under- or overestimates the EQE depending on blue/red LEDs and the error levels involved with the replacement.

4 | CONCLUSION

We have theoretically examined how the mean photon energy is defined for the broad spectrum of an LED. Only when the mean photon energy is defined as the arithmetic mean of photon energies in the emission spectrum, the PE can be decomposed into the VE and the EQE. It has been demonstrated how the mean photon energy and the peak photon energy differ from each other for blue and red LEDs. In case of the blue LED, replacing the mean photon energy with the peak photon energy typically underestimates the EQE, while the trend is opposite for the red LED, which is caused by the difference in emission spectra. Although the precise evaluation of the EQE requires an integration over the entire spectrum to obtain the mean photon energy, one can replace the mean photon energy with the peak photon energy with relatively small errors involved. The current work can serve as a useful guide when evaluating the EQE of blue or red LEDs for possible errors associated with using the peak photon energy instead of the mean photon energy.

AUTHOR CONTRIBUTIONS

Ilgyu Choi: data curation; investigation; writing – original draft; formal analysis. **Sangjin Min:** methodology; validation. **Jong-In Shim:** funding acquisition; review and editing. **Dong-Soo Shin:** conceptualisation; writing – review and editing.

ACKNOWLEDGEMENT

This work was supported by the Korea Institute for Advancement of Technology under grant P0016250.

CONFLICT OF INTEREST

The authors do not have any conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Jong-In Shim https://orcid.org/0000-0002-1305-074X
Dong-Soo Shin https://orcid.org/0000-0002-0863-9138

REFERENCES

1. Schubert, E.F.: Light-Emitting Diodes, 2nd ed, pp. 86–87. Cambridge University Press (2006).
2. Oh, C.-H., Shim, J.-I., Shin, D.-S.: Current- and temperature-dependent efficiency droops in InGaN-based blue and AlGaInP-based red light-emitting diodes. Jpn. J. Appl. Phys. 58(SC), SCCC08-1–SCCC08-7 (2019). https://doi.org/10.7567/1347-4065/ab09db
3. Islam, A.B.M.H., Shim, J.-I., Shin, D.-S.: Measurement of the piezoelectric field in InGaN/AlGaN multiple-quantum-well near-ultraviolet light-emitting diodes by electroreflectance spectroscopy. IEEE J. Quant. Electron. 55(5), 3200307-1–3200307-7 (2019). https://doi.org/10.1109/jqe.2019.2928370
4. Shim, J.-I., Shin, D.-S.: Measuring the internal quantum efficiency of light-emitting diodes: towards accurate and reliable room-temperature characterization. Nanophotonics 7(10), 1601–1615 (2018). https://doi.org/10.1515/nanoph-2018-0094
5. Shim, J.-I., et al.: Measuring the internal quantum efficiency of light-emitting diodes at an arbitrary temperature. IEEE J. Quant. Electron. 54(2), 8000106-1–8000106-6 (2018). https://doi.org/10.1109/jqe.2018.2795044
6. IEC 60747-5-8: Test method of optoelectronic efficiencies of light emitting diodes (2019)
7. Shin, D.-S., Han, D.-P., Shim, J.-I.: Study of droop phenomena in InGaN-based blue and green light-emitting diodes by temperature dependent

electroluminescence. Appl. Phys. Lett. 100(15), 153506-1–153506-4 (2012). https://doi.org/10.1063/1.3703313

8. Oh, C.-H., Shin, D.-S., Shim, J.-I.: Interrelation between the internal quantum efficiency and forward voltage of blue LEDs. IEEE Photon. Technol. Lett. 31(17), 1441–1444 (2019). https://doi.org/10.1109/lpt.2019.2930756
9. CIE 127: Measurement of LEDs (1997)
10. Park, S.-I., et al.: Measurement of internal electric field in GaN-based light-emitting diodes. IEEE J. Quant. Electron. 48(4), 500–506 (2012). https://doi.org/10.1109/jqe.2012.2186610
11. Kawakami, Y., et al.: In inhomogeneity and emission characteristics of InGaN. J. Phys. Condens. Matter. 13(32), 6993–7010 (2001). https://doi.org/10.1088/0953-8984/13/32/308
12. Takeuchi, T., et al.: Quantum-confined Stark effect due to piezoelectric fields in GaInN strained quantum wells. Jpn. J. Appl. Phys. 36(4A), L382–L385 (1997). https://doi.org/10.1143/jjap.36.l382

How to cite this article: Choi, I., et al.: Understanding and evaluating the mean photon energy and the external quantum efficiency of light-emitting diodes. IET Optoelectron. 17(1), 32–37 (2023). https://doi.org/10.1049/ote2.12083