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LED based reference for wavelength and relative intensity

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Abstract. Relative emission spectra of LEDs depend on the junction temperature. The high-energy region of the emission spectrum can be modelled with the joint density of states and the Maxwell-Boltzmann distribution as a function of energy and junction temperature. It can be shown that the normalized emission spectra at different junction temperatures intersect at a unique energy value. Thus the wavelength and the relative intensity of the intersection point do not depend on the junction temperature of the LED. The invariant intersection energy exists for all LEDs manufactured using the elements from groups III-V. The wavelength determined by the intersection energy can be used as a temperature invariant wavelength and relative intensity reference in spectral measurements.

1. Introduction

The emission spectrum of an LED is generated by electron-hole recombination and can be modelled as a product of the joint density of states of electrons and holes and the Maxwell-Boltzmann distribution [1,2]. The intensity and the peak wavelength of the light emitted by an LED depend on the junction temperature of the LED. An LED spectrum shows a redshift in the peak energy with increased junction temperature due to the reduced band gap with an increasing temperature [3]. When using LEDs in metrological applications as a wavelength reference, the junction temperature of the device needs to be stabilized in a reproducible way for different ambient temperatures.

It has been shown that the relative LED spectra, normalized to the peak intensity, have an energy value E_B , where the relative intensity is constant, i.e., independent on the junction temperature [1]. This value can be utilized as temperature-invariant wavelength and relative intensity characteristics for the measured LED. We have designed and built a device utilizing the temperature independent energy value as a wavelength and relative intensity reference.

2. LED spectrum model

The emission spectrum of an LED has been mathematically modelled earlier by numerous researchers [2,4,5]. The emission intensity of an LED is proportional to the product of the joint density of states and the exponential Boltzmann distribution of carriers. In [1], the temperature dependent LED spectrum was modelled as

$$I(E, T) \propto (E - (E_B - pkT))^{p-q} \times e^{-\frac{E - (E_B - pkT)}{kT}}, \quad (1)$$



where I is the emission intensity, E is the photon energy, T is the temperature of the LED p-n junction, E_B is the temperature-invariant intersection energy, p is a parameter defining the band gap energy shift as a function of temperature, q is a parameter defining the shift of the peak energy as a function of temperature, and k is the Boltzmann constant.

Equation (1) can be normalized by dividing with the intensity at the peak energy

$$E_{\max}(T) = E_B - qkT. \quad (2)$$

From Eqs. (1) and (2), we can conclude that at the photon energy E_B the relative intensity does not depend on temperature [1]

$$\frac{I(E_B, T)}{I(E_{\max}, T)} = \left(\frac{p}{p-q} \right)^{p-q} e^{-q}. \quad (3)$$

The temperature dependence of the emission intensity of LEDs can be measured with a spectroradiometer and a temperature adjustable mounting base for the LED under study. The temperature of the mounting base was controlled using a Peltier element based temperature controlled copper plate. A temperature sensor of type PT-100 was used to measure the temperature of the mounting plate, and the current through the Peltier element was controlled to stabilize the temperature of the mounting plate. A QE65 Pro spectroradiometer from Ocean Optics was used to measure the spectral distribution of the emission intensity of the LEDs in the wavelength range between 300 nm and 1090 nm. The distance between the LEDs and the measuring head of the spectroradiometer was 150 mm. The intensity calibration of the spectroradiometer was carried out using a calibrated FEL lamp which is traceable to the spectral irradiance scale of the National Metrology Institute of Finland [6]. The wavelength scale of the spectroradiometer was calibrated against spectral lines of a mercury-argon calibration source.

Figure 1 shows measured and modelled spectra of a GaAs infrared LED and a close-up of the temperature-invariant intersection point E_B . The modeling parameters in Eq. (1) can be determined from the LED spectral measurements carried out at different temperatures. The energy E_B is located at the intersection point of the normalized spectra, and the peak shift parameter q can be determined by measuring the shift of the peak of the spectra at different temperatures. The band gap temperature shift parameter p can be found by fitting the model to the normalized spectra. For a typical infrared LED the modeling parameters are $E_B = 1.54$ eV, $p = 4.85$, and $q = 4.55$.

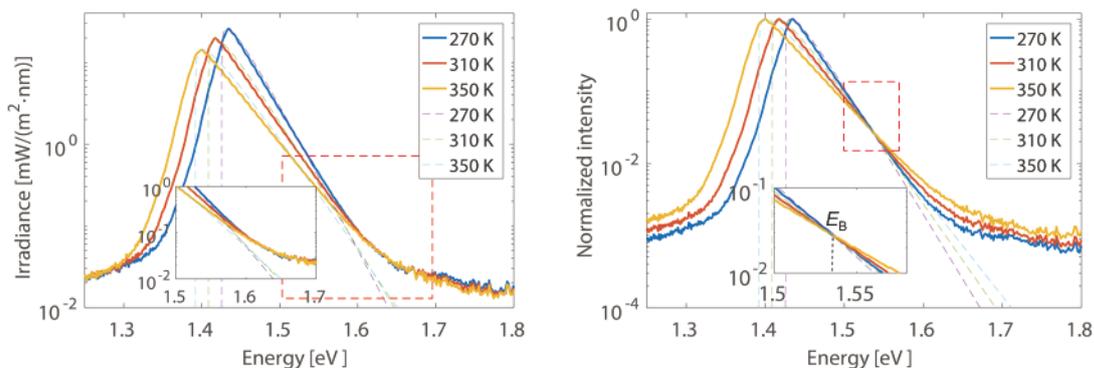


Figure 1. Measured (solid lines) and modelled (dashed lines) spectra of a GaAs LED between 270 K and 350 K and close-ups around the energy E_B . Left figure shows the absolute spectra and the right figure shows the peak normalized spectra.

As seen in Figure 1, the spectral model described by dashed lines is valid only close to the peak intensity and the intersection points [1,7]. However, despite the limitations of the model at the low-energy side of the spectrum, the model predicts reasonably well the relative intensity between the peak

and the intersection energies of the normalized spectra. Figure 1 also demonstrates that the intersection point only exists in normalized spectra.

The optical characteristics such as the peak energy, intersection energy, and the emission intensity of semiconductor devices manufactured using the same process typically differ slightly between different samples. We have measured InGaN/GaN ultraviolet light emitting diodes cut from different parts of a semiconductor wafer and compared the optical properties of the samples. The LEDs were manufactured at Aalto University, grown by metalorganic chemical vapor deposition, thus the location of the samples in the wafer was known [8]. According to our studies, the standard deviation of the intersection energies is 0.007 eV if the samples are cut within 10 mm distance from each other and 0.02 eV if the samples are cut 100 mm from each other. Similar variations can be seen in the corresponding peak energies. The differences in the optical characteristics are presumed to be due to the nonideal growth process leading to crystal dislocations in the semiconductor wafer [9].

The temperature-invariant energy value E_B is a general feature of all LEDs. In Figure 1, the spectra were measured at known heat sink temperatures of 270 K, 310 K, and 350 K. However, determination of E_B does not require knowledge of the absolute temperature, but it is sufficient to vary the temperature and to determine the invariant crossing point in the relative spectra. The temperature dependent LED spectra of Eq. (1) have three modelling parameters E_B , p , and q . As seen in Eq. (2), parameter q defines the shift of the spectral peak as a function of temperature. Modeling parameter p defines the shift of the band gap energy as a function of temperature, thus after the peak shift parameter q has been determined from the measurement results, the value of p can be solved from the intensity of the intersection point using Eq. (3).

3. Reference device

An LED-based wavelength and relative intensity reference device was built utilizing the temperature-invariant energy value E_B . The device comprises a separate control unit and a temperature controlled heat sink for seven LEDs. The LEDs are attached on an aluminium heat sink equipped with a PT100 temperature sensor. The temperature value of the aluminium LED circuit board is sent to the external control unit that controls the temperature of the heat sink with a Peltier element. The temperature of the aluminium circuit board is controlled using a PI (Proportional-Integral) control algorithm. The temperature of the circuit board can be adjusted to three different values selected using a rotary switch on the front panel of the control unit. The external control unit also feeds a constant driving current of 100 mA to the LEDs and is capable of switching each LED on and off separately. Figure 2 shows a photograph of the developed LED-based reference device.



Figure 2. The LED based reference device comprises separate control and heat sink units.

The temperature-invariant reference point of each LED can be measured by varying the temperature of the heat sink and by measuring the emission spectra at different temperatures. Figure 3 shows the

spectra of five different types of LEDs at three different temperatures. The measurement temperatures vary between 270 K and 398 K depending on the LED used.

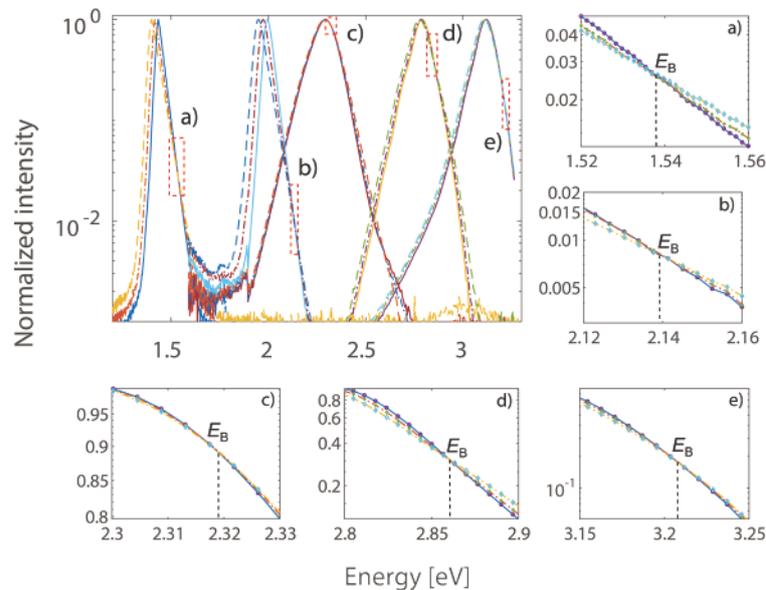


Figure 3. Normalized spectra of five LEDs measured at different temperatures. The intersection energies E_B are inside the red rectangles of dashed lines (a-e). Markers in the close-up figures indicate the measurement points.

The intersection points in Figure 3 are located at the energies (vacuum wavelengths) of 1.537 eV (806.7 nm), 2.140 eV (579.4 nm), 2.319 eV (534.7 nm), 2.860 eV (433.5 nm), and 3.209 eV (386.4 nm). The intersection energies can be used as constant reference wavelengths after calibration with a master spectroradiometer. The normalized intensities for the respective intersection points are 2.7%, 0.75%, 89.5%, 31.5%, and 17.0% of the peak intensity, and these are similarly determined by a linear master spectroradiometer.

The standard uncertainties of the energy values of the intersection points in Figure 3 are 0.005 eV, 0.008 eV, 0.003 eV, 0.005 eV, and 0.008 eV for the intersection points a)-e), respectively. The uncertainties were obtained by studying the standard deviations of the intersection points of individual pairs of curves [1]. The resolution of the spectroradiometer was 0.7 nm, leading to an energy resolution of 0.01 eV at 4.1 eV and 0.0009 eV at 1.1 eV. The standard deviation of the intensity values of the intersection points of individual pairs of curves was found to be 0.2% - 4.0% of the peak intensity.

The non-linearity of CCD (Charge-Coupled Device) array spectroradiometers has been found to be as high as 5% or more [10,11]. Excluding saturation effects, non-linearities of several per cents have been found when measuring intensity levels that are smaller than 30% of the maximum intensity [11]. We introduced an artificial non-linearity to the measurement results in Figure 3 in such a way that at the minimum intensity the non-linearity was 5% and at the maximum intensity the non-linearity was 0%, varying linearly in between. According to these analysis results, the intersection energies varied less than 0.012 eV. At low intensity intersection points a) and b) in Figure 3, the changes of the normalized intensities of the intersection points were +4.9% and +3.9% of the peak intensity, respectively. For the high intensity intersection points c)-e), the changes of the intensities of the intersection energies were +0.41%, +1.1%, and -13.6% of the peak intensity, respectively. For the ultraviolet LED e), the large change of the intensity may be mainly due to the low intensity and energy resolution. As the uncertainties of the energy and intensity values would be substantially the same as the resolution of the master spectroradiometer, the performance of a CCD array spectroradiometer could be studied with the proposed method.

4. Discussion and conclusions

Comprehensive investigation of the stability of spectroradiometers and their suitability for absolute calibrations has been carried out in [10]. Due to the aging, the drift of the wavelength scale of a spectroradiometer can be more than 1 nm and the nonlinearity can be several per cents [11]. It has been suggested that a thorough characterization is needed to verify the suitability of a spectroradiometer for absolute calibration [10]. Full verification of the linearity and the wavelength scale of a spectroradiometer will require non-portable, laboratory grade equipment. Typically the wavelength scale of a spectroradiometer is verified using pencil type gas discharge lamps with discrete emission spectral lines. As the intensities of the spectral peaks of a pencil lamp are normally not controlled, a separate facility for the linearity measurement is needed [11].

Our new type of intensity and wavelength reference can be utilized to carry out a fast verification measurement of array spectroradiometers using a single instrument only. The uncertainty of such a verification is higher as compared to the laboratory grade verification described above, but the cost is less for the cases where the slightly higher uncertainty is enough. The intersection points seen in Figure 3 can be used as temperature-invariant reference values of relative intensity and wavelength in LED spectra. It is sufficient that the LED control unit allows measurements at a few different temperatures without accurate and reproducible temperature stabilization. In addition to wavelength reference, the intersection points give information about the linearity of the spectrometer through the relative intensities at the intersection energies E_B . The wavelength uncertainty of the method is smaller than the 0.7 nm resolution of the spectroradiometer used in our test measurements. The uncertainty of the relative intensity scale was found to be 0.2% - 4.0% of the peak intensity, depending on the LED used.

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