Vilnius University

Lab instructions

Temperature characteristics of LEDs

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Contents

1 The aim of the lab

The aim of the lab is to examine the influence of temperature on the performance of light emitting diodes (LEDs).

2 The tasks of the lab

- Measure current-versus-voltage characteristics $(I - V)$ of LEDs operating in a pulsed mode at different ambient temperatures.
- Measure $I - V$ of LEDs operating in a continuous mode at room temperature.
- Measure spectral power distributions (SPDs) of LEDs for the same driving current, but at different ambient temperatures.
- Calculate the temperature coefficient of the forward voltage.
- Calculate the temperature coefficients for peak wavelength, spectral width and emission power.
- Determine the junction temperature for LED, driven by DC operating at the room temperature.

3 Theory

Since this lab is performed after the laboratory exercise "The electric properties of LEDs", the detailed explanation of electrical properties of LEDs is omitted in "Theory" and "Experiment" sections. For Lithuanian material students are referred to [1]. English speakers more information can find in [2]. In this lab manual a short summary of [1] and [2] is presented.

3.1 Junction temperature

The temperature of the active region crystal lattice, frequently referred to as the junction temperature, is a critical parameter. The junction temperature is relevant for several reasons. Firstly, the internal quantum efficiency depends on the junction temperature. Secondly, high-temperature operation shortens the device lifetime. Thirdly, a high device temperature can lead to degradation of the encapsulant. It is therefore desirable to know the junction temperature as a function of the drive current.

Heat can be generated in the contacts, cladding layers, and the active region. At low current levels, heat generation in the parasitic resistances of contacts and cladding layers is small due to the I^2R dependence of Joule heating. The dominant heat source at low current levels is the active region, where heat is created by non-radiative recombination. At high current levels, the contribution of parasitics becomes increasingly important and can even dominate.

There are several different ways to measure the junction temperature, in this lab manual a method based on the shift of the peak emission wavelength with the temperature and a method based on the shift of the diode forward voltage with temperature are discussed.

3.2 Junction temperature and LED emission

The emission intensity of LEDs decreases with increasing temperature. This decrease of the emission intensity is due to several temperature-dependent factors including:

- non-radiative recombination via deep levels;
- surface recombination;
- carrier loss over heterostructure barriers.

Near room temperature, the temperature dependence of the LED emission intensity is frequently described by the phenomenological equation:

$$I = I \,|_{300\mathrm{K}} \exp \frac{T - 300\mathrm{K}}{T_1}, \tag{1}$$

where T_1 is the **characteristic temperature**. A high T_1, implying a weak temperature dependence, is desirable.

As the temperature increases, the energy gap of semiconductors generally decreases. The temperature dependence of the energy gap of a semiconductor can be expressed by the **Varshni formula**:

$$E_g = E_g \mid_{T=0\mathrm{K}} - \frac{\alpha T^2}{\alpha + \beta}, \tag{2}$$

where α and β are fitting parameters, frequently called the Varshni parameters.

3.3 Temperature dependence of diode forward voltage

In the most simple way, under forward bias, for a fixed current one can obtain temperature coefficient using the following equation:

$$\frac{\partial V_F}{\partial T} = \frac{\partial}{\partial T}\left[2V_T \ln(\frac{I_F}{I_{r0}})\right] + I_F \frac{\partial R_S}{\partial T}. \tag{3}$$

Here it is assumed, that $I_F \gg I_{r0}$. Knowing, that $I_{r0} = qAwn_i/\tau_r$ and that for the nominal current $V_F - I_{F0}R_S \approx V_b$ one obtains:

$$\frac{\partial V_F}{\partial T} = \frac{1}{q}\frac{\partial E_g}{\partial T} - \frac{3k_B}{q} + \frac{2k_B T}{q\tau_r}\frac{\partial \tau_r}{\partial T} - \frac{k_B}{q}\ln\left(\frac{N_{\mathrm{C}}N_{\mathrm{V}}}{N_{\mathrm{D}}^{+}N_{\mathrm{A}}^{-}}\right) + I_F\frac{\partial R_S}{\partial T}. \tag{4}$$

This equation is a very useful expression for the temperature coefficient of the forward voltage. The first summand on the right hand side of the equation 4 is due to the temperature dependence of bandgap energy. At room temperature for AlGaAs, AlGaInP and AlInGaN the value is about -0.4 mV/°C. The second summand is due to the increase of effective density of states with temperature as $T^{3/2}$; its value is approx. $-0{,}25$ mV/°C. The third term is due to the temperature dependence of recombination lifetime and its value is $\sim \pm 1$ mV/°C (positive value is obtained if radiative recombination is dominant). The fourth summand is due to the temperature dependence of intrinsic carrier concentration and it can reach ~ -1 mV/°C at room temperature. And the last term is usually negative due to the fact, that the resistance of capping layers is decreasing when the temperature is raised, this is especially true for p-type nitride semiconductors since acceptors in the room temperature are weakly ionized in nitrides, thus the value of the last summand can reach –10 mV/°C. If all values are summed, one can find, that the temperature coefficient of the forward voltage can vary between –1 mV/°C and – 10 mV/°C.

If the value of injection efficiency is far bellow one, diffuse component is significant in a forward current and $\frac{\partial V_F}{\partial T}$ is slightly influenced by the temperature dependence of diffusion coefficient of minority charge carriers (the contribution is positive but less than 0.1 mV/°C) and less influenced by recombination time. Factors for tunnelling current are not known, thus there are no analytical expressions for $\frac{\partial V_F}{\partial T}$ yet. For InGaN LEDs, where forward current is strongly influenced by the tunnelling components, the temperature coefficients of the forward voltage are in the range of –1 mV/°C.

It is seen that the temperature coefficient of the forward voltage for LEDs is usually negative and determined by chip material innate (e.g. temperature dependence of E_g) and technologically controlled (e.g. doping and conductivity of capping layers) properties. For different brand LEDs the temperature coefficient of the forward voltage can vary between –1 and –20 mV/°C. In the case of high power LEDs, it is desirable to minimize the absolute value of $\frac{\partial V_F}{\partial T}$ due to the fact that the chip temperature is caused not only by the ambient temperature but also by Joule heating.

4 Experiment

4.1 Junction temperature and peak emission wavelength

This method makes use of the dependence of the bandgap energy (and thus the peak emission wavelength) on temperature. The method consists of a calibration measurement and a junction-temperature measurement. In the calibration measurement, the peak energy is measured at different ambient temperatures, typically in the range 20 °C to 120 °C, by placing the device in a temperature-controlled oven. The device is injected with a range of pulsed currents with a duty cycle $\ll 1$ to minimize additional heating. As a consequence, the ambient temperature in the oven and the junction temperature can be assumed to be identical. The calibration measurement establishes the junction-temperature versus emission-peak-energy relation for a range of currents.

Subsequent to the calibration, the peak emission energy is measured as a function of the DC injection current with the device in a room-temperature ambient. The junction temperature for each current level can then be determined by using the calibration data.

The accuracy of the method is limited by the ability to determine the peak wavelength. As a rule of thumb, the error bar of the peak wavelength is about 5–10% of the full-width at half- maximum of the luminescence line. Alloy-broadening effects and $k_B T$ broadening impose a limitation on the accuracy of the method.

Note that band-filling effects should not influence the results as they also enter the calibration measurement. The peak emission energy shifts to higher energies due to band filling occurring at high injection current densities. In contrast, the peak emission energy shifts to lower energies due to bandgap shrinkage. Although it is difficult to clearly separate the junction-temperature-induced shift from the band-filling-induced shift, the former effect dominates under typical experimental conditions.

In order to perform this measurement:

- Turn on the computer, and start the program *Illumia®Pro*.
- Attach LED to Peltier element.
- Connect LED to current supply as described in a lab manual "The electric properties of LEDs". Drive the device with a pulsed nominal current.
- Using lens, focus the emission light to the spectrometer.
- Begin the calibration measurement. Range 0–80 °C, step 20 °C. Figures in the appendix show the screen shots of the software used for the measurements.

- Measure the spectral power distribution of LED as a function of the DC injection current with the device in a room-temperature ambient.

- Draw the junction temperature as a function of injection current curve.

4.2 Measurement of junction temperature using forward voltage

This method consists of a V_f calibration measurement under pulsed-current injection, and a V_f measurement under DC-current injection. In the calibration measurement, the device under test is located in a temperature-controlled oven, so that the temperature of the device and junction is known. The temperature is varied from typically 20 °C to 120 °C. The calibration measurement is performed in a pulsed mode with a very small duty cycle (e.g. 0.1%), so that the heat generated by the injection current becomes negligibly small. The forward voltage is measured at each temperature for the current levels of interest. The calibration measurement establishes the relation between forward voltage and junction temperature for the I_f levels of interest.

Subsequently the device is exposed to room-temperature ambient and subjected to a series of DC currents. Forward voltages are measured once thermal steady state has been reached. The measured DC forward voltages and the calibration measurement data are used to establish the junction temperature for different current levels.

The forward-voltage method is accurate to within a few degrees. The V_f method is more accurate than the peak-wavelength method. The latter method is limited by the uncertainty in the peak wavelength, which is difficult to determine accurately for broadened emission bands.

In order to perform this measurement:

- Read the lab manual "The electric properties of LEDs" first.

- Connect LED to current supply. Drive the device with a pulsed nominal current.

- Begin the calibration measurement. Measure $I-V$ in the range of 0–80 °C with a step of 20 °C.
- Inject LED with a DC. Measure the $I-V$.
- Draw the junction temperature as a function of injection current curve.

A Appendix. *Illumia®Pro* screen shots.

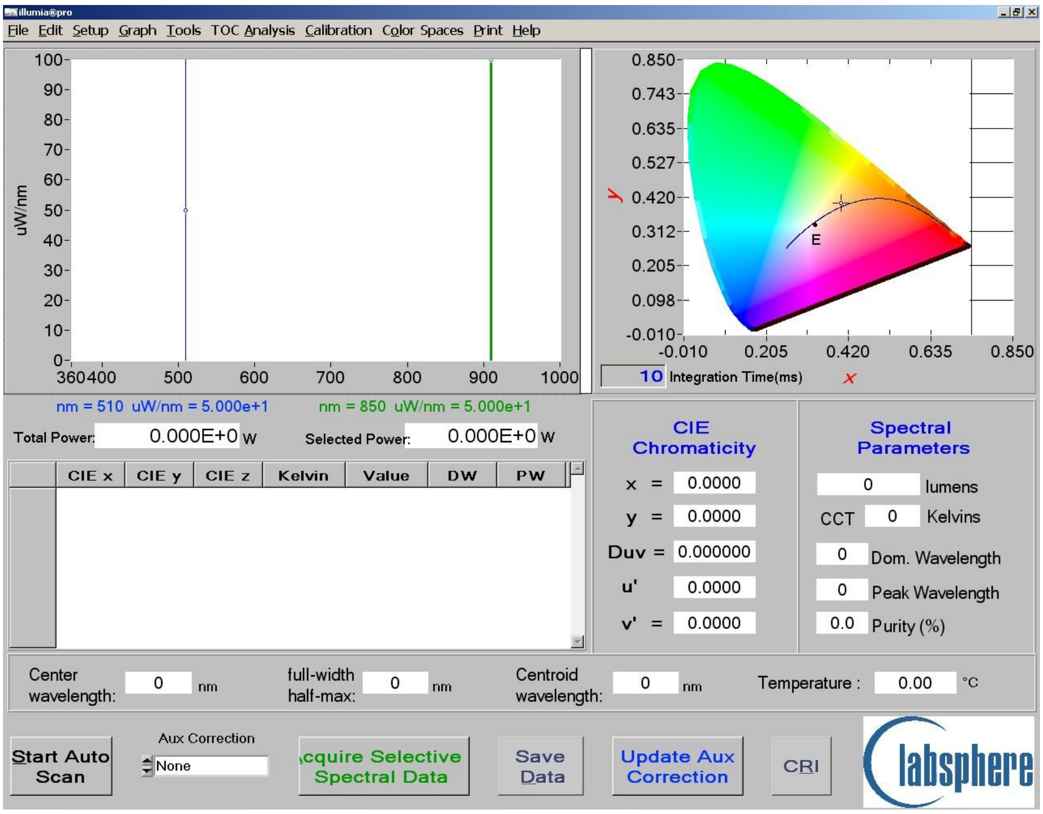

Figure 1: Screenshot of *Illumia®Pro* software.

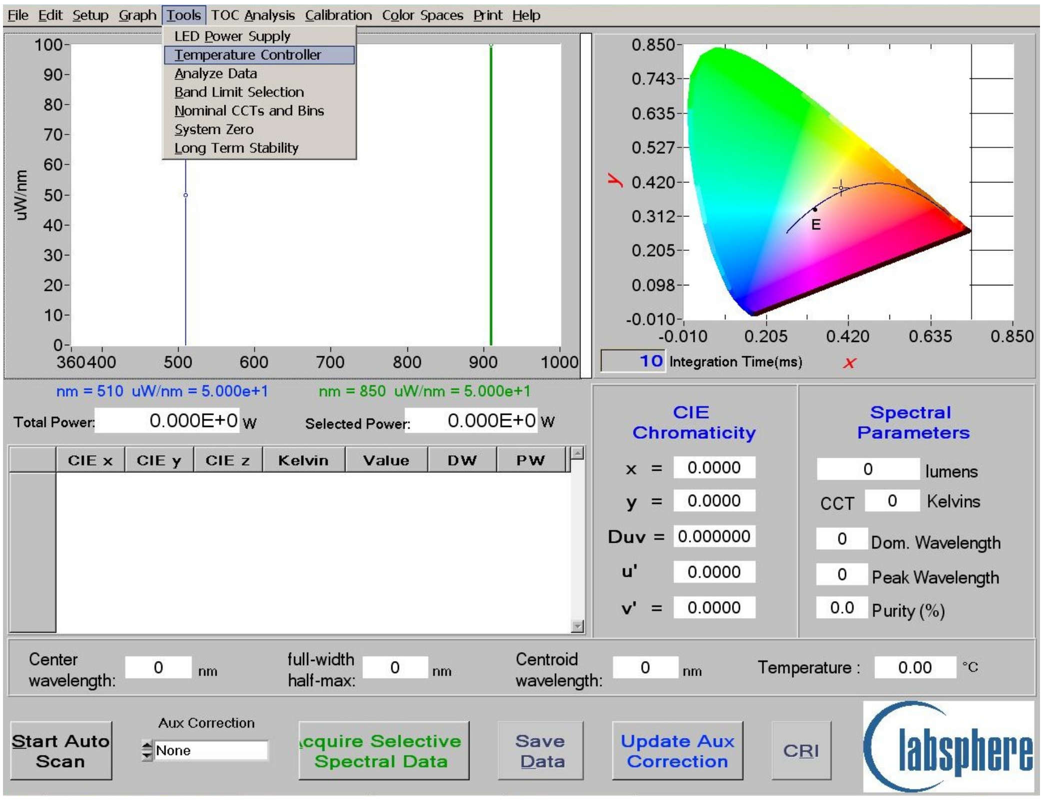

Figure 2: Screenshot of *Illumia®Pro* software. Finding the Peltier element controler.

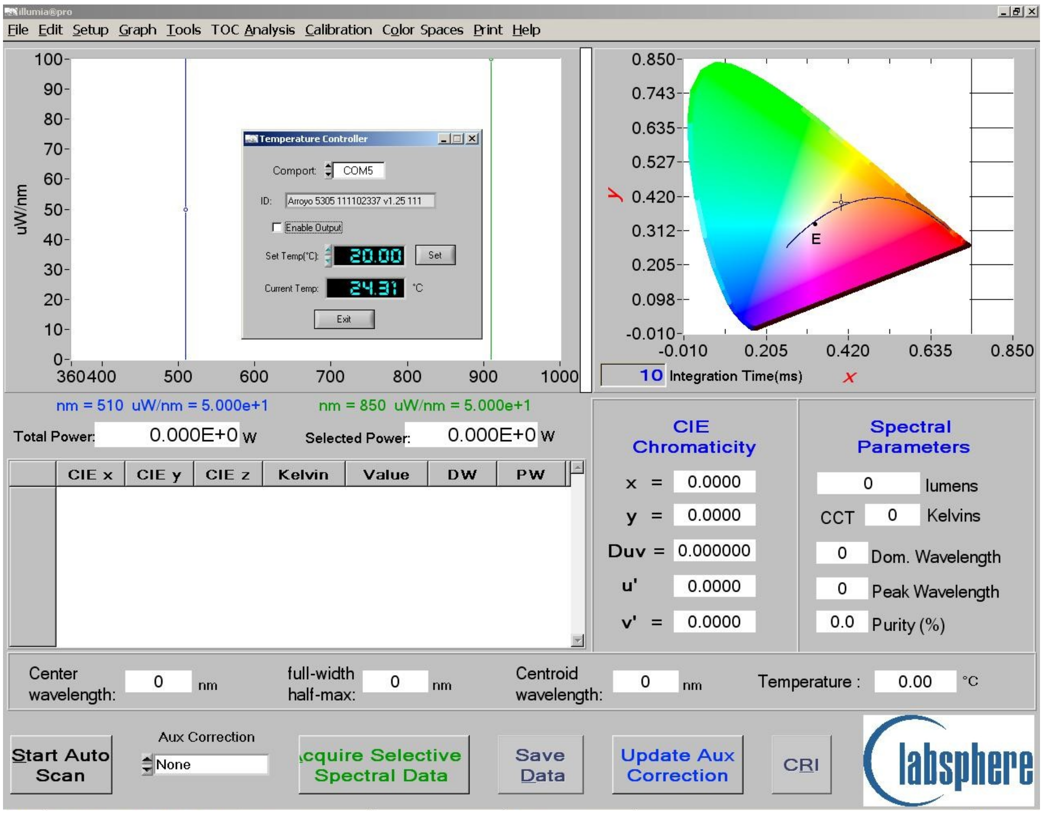

Figure 3: Screenshot of *Illumia®Pro* software. Using the Peltier element controler.

References

[1] A. Žukauskas, *Puslaidininkiniai Šviestukai* (Progretus, Vilnius, 2008).

[2] E. F. Schubert, *Light Emitting Diodes* (Cambridge university press, New York, 2006), second edition.