LED Color

A light-emitting diode (LED) is a semiconductor device that emits light when an electric current flows through it in the forward direction. As current flows across the p-n junction, electrons and holes collide and recombine, emitting energy E_g equal to the semiconductor's bandgap width. The bandgap is the energy range within an ideal crystal that electrons cannot occupy. Its width determines the electrical and optical properties of the crystal. Therefore, the emission spectrum of an LED is a relatively narrow line with wavelength given by $\lambda = 2\pi\hbar c/E_g$, where $\hbar = 1.05 \cdot 10^{-34}\ J \cdot s$.

By using different semiconductor materials, it is possible to fabricate LEDs with varying bandgap widths and emission wavelengths.

There is an empirical formula describing the dependence of the bandgap width E_g on temperature:

$$E_g(T) = E_0 \left(1 - \frac{\alpha T^2}{\theta + T}\right), \tag{1}$$

where E_0 is the bandgap width at zero temperature, α is a constant representing the magnitude of electron-phonon interaction, and θ is the Debye temperature.

The current-voltage characteristic of a semiconductor diode can be expressed as follows:

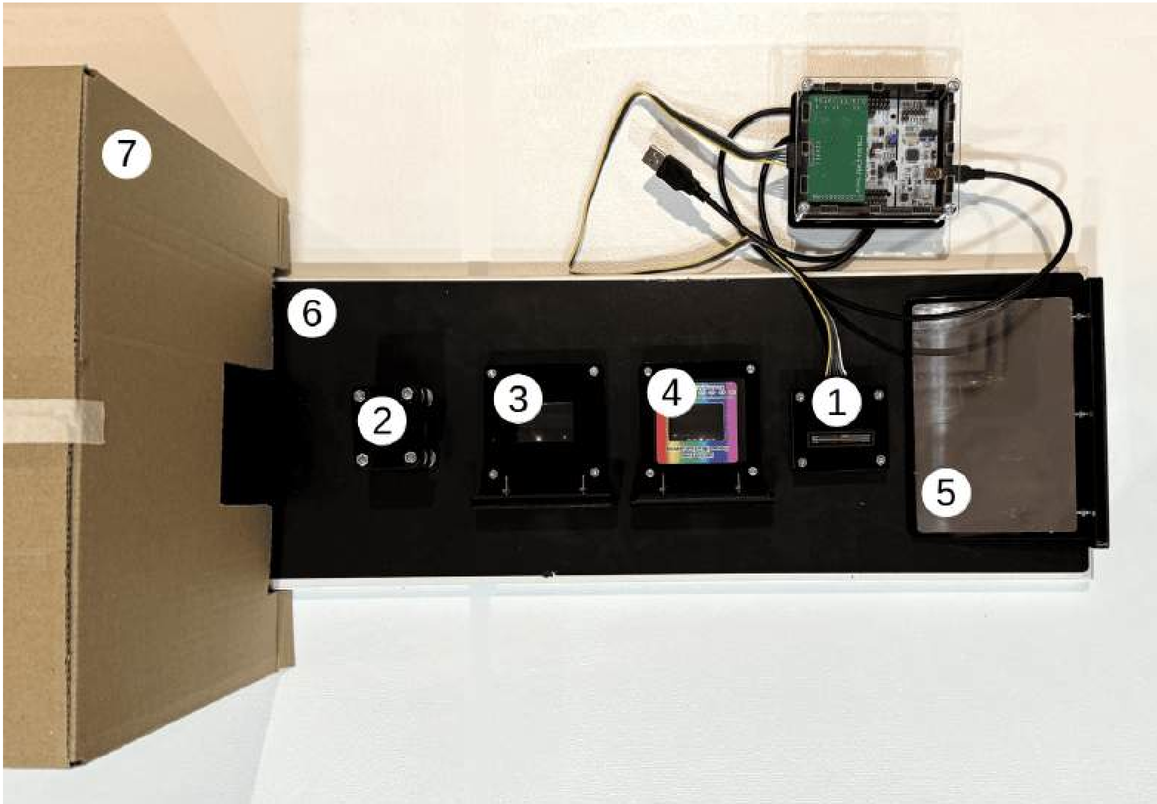
$$I(U) = I_0 \left(\text{exp}\left[\frac{eU}{\eta k_{\mathrm{B}} T}\right] - 1\right). \tag{2}$$

This expression is called the Shockley equation, where I_0 is the saturation current, η is the ideality factor, $k_B = 1.38 \cdot 10^{-23}\ J/K$ is the Boltzmann constant, and T is the temperature of the diode. In this equation, both I_0 and η depend on temperature.

Room temperature is $T_0 = 298\ K$.

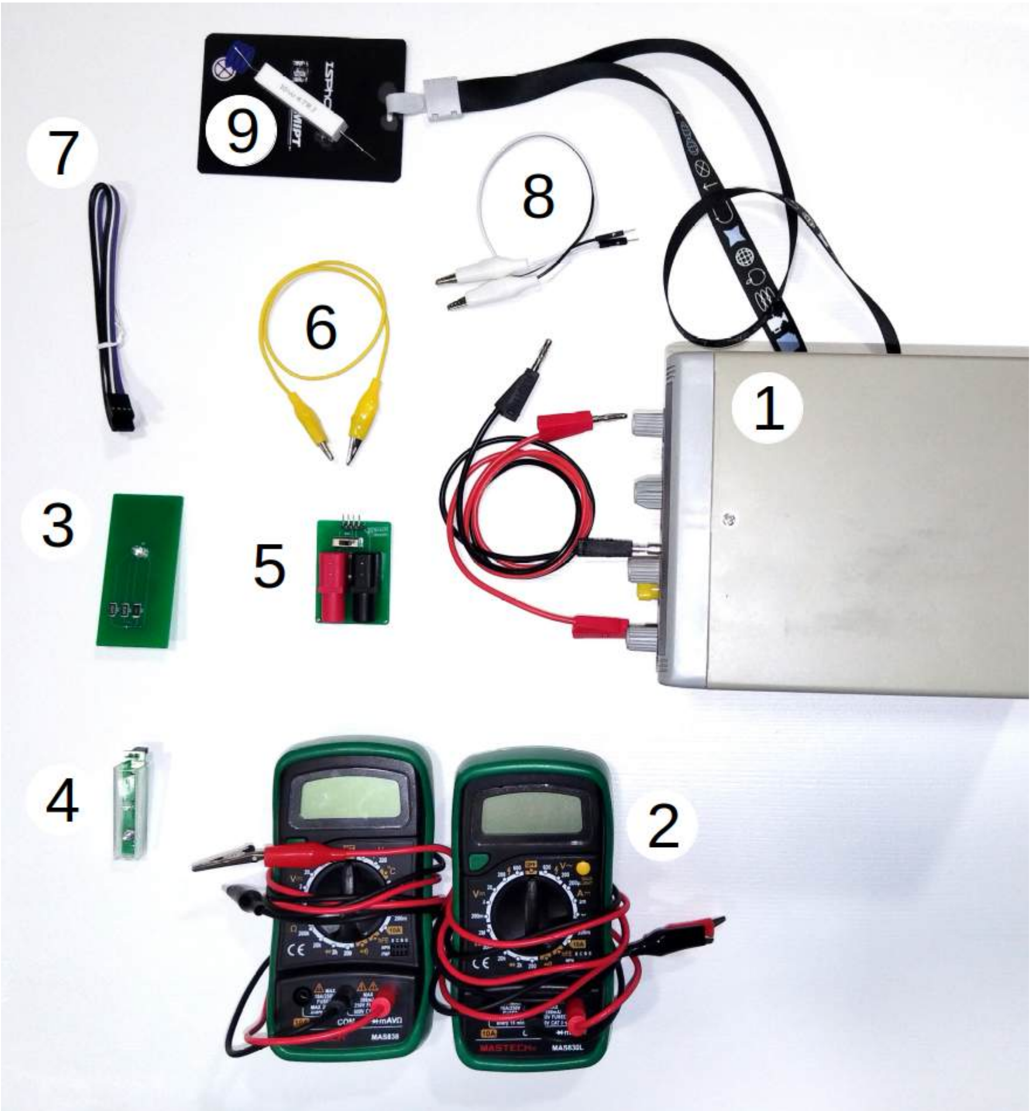
10Equipment (Optical)

1. Photosensitive CCD array connected to a computer (hereafter referred to as the sensor).
2. Stand for LEDs.
3. Lens L_1.
4. Lens L_2 with diffraction grating G mounted on a magnet.
5. Screen.
6. Optical table.
7. Shielding screen to protect against stray light.



10Equipment (Electrical)

1. DC voltage source with wires, up to $15\ V$.
2. Two multimeters with wires.
3. "RGB" LED.
4. "MAIN" LED in a cuvette (second as a reserve).
5. Adapter with a switch.
6. Connecting wire with alligator clips.
7. Ribbon cable with 4 leads.
8. Ribbon cable with 2 leads.
9. Resistor R_0.



10Equipment (Chemical)

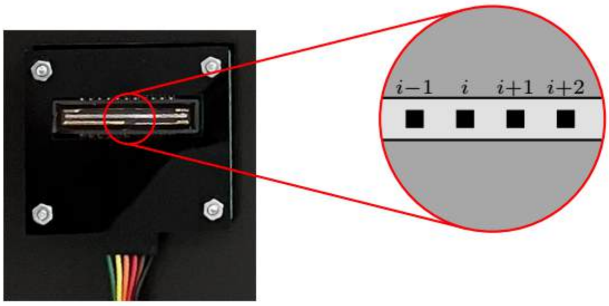
1. Thermos with liquid nitrogen.
2. Special tube suspended on a thread.
3. Container with distilled water.

4. Pasteur pipette.
5. Clamp for manipulation.
6. Waste beaker.

Part A. Calibration (0.6 points)

In this part of the task, you are required to assemble an optical setup according to the scheme provided below and calibrate the sensor.

The photosensitive part of the sensor consists of approximately 3650 identical photodiodes, referred to as pixels (see figure). As a result of computer processing of the sensor data, the dependence of the illumination intensity of each pixel on its number is obtained. The intensity is measured by the sensor in arbitrary units.



Light from any real source consists of a continuous set of components with different wavelengths, called the emission spectrum. Using the proposed optical setup, it is possible to spatially "separate" the components of the spectrum. In this way, it is possible to ensure that almost monochromatic radiation falls on each pixel of the sensor. Calibration consists in matching the pixel number to its corresponding wavelength.

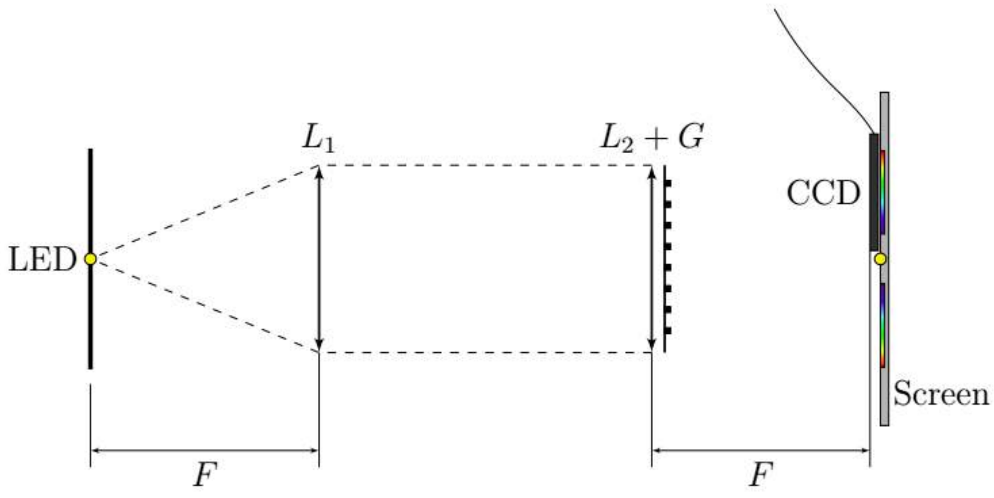
Insert the board with the “RGB” LED into the appropriate slot of the stand. Switching between the colors of the “RGB” LED is performed using the toggle switch on the control board.

Later, the board with the “RGB” LED may be replaced by the cuvette with the “MAIN” LED. The cuvette with the “MAIN” LED and the board with the “RGB” LED should fit tightly into the slots of the stand. Practice removing and inserting the cuvette with the “MAIN” LED and the board with the “RGB” LED so that the stand does **NOT MOVE** relative to the surface of the magnetic table. To achieve this, you may press the stand to the table with your hands.

The wires should be connected in advance to the pins of both the “MAIN” and “RGB” LEDs!

During the measurement series, do not touch the cuvette or the stand! Maintaining the initial position of the optical components is very important for the subsequent steps!

Assemble the setup shown in the figure and adjust it so as to obtain a reliable optical spectrum from the “RGB” LED with the correct characteristic shape for each of its operating modes. The first-order diffraction maxima for each color should be located on the measuring part of the CCD array. The “RGB” LED should be positioned at the focus of lens L_1, and the screen plane should be at the focus of lens L_2 (with the diffraction grating mounted).



A.1	Measure the emission spectra of the "RGB" LED in each operating mode. Use the **Single spectrum** function of the program for this purpose. Save the spectrum files in the A1 folder and name them according to the colors: R.csv (red), G.csv (green), and B.csv (blue).	0.3 pt

A.2	For each saved spectrum, find the pixel number N corresponding to the maximum intensity of the LED emission. As your answer, fill in the table A2-ans.xlsx in A2 folder.	0.1 pt

You will need to convert the pixel number N to the corresponding wavelength λ using the formula:

$$\lambda = \mathrm{slope} \cdot N + \mathrm{shift}.$$

The coefficient values depend on the position of the stand, which is why it was previously strictly prohibited to move it across the surface of the magnetic table between measurements.

To determine the coefficients of the linear dependence $\lambda(N)$, use the data obtained in question A2. The wavelengths of the studied LED are given below:

- Red: $620\ \mathrm{nm}$
- Green: $520\ \mathrm{nm}$
- Blue: $460\ \mathrm{nm}$

A.3	Using the known values of the wavelengths, determine the values of slope and shift. Save the graph of the dependence $\lambda(N)$ in the file A3-sol.xlsx in the A3 folder.	0.2 pt

Part B. LED in air (5.3 points)

B.1	Before starting work with the "MAIN" LED, measure the internal resistance of the voltmeter R_V over all its measurement ranges. The table B1-sol.xlsx in the B1 folder is the answer for this question.	0.1 pt

Attention!

Before connecting the power supply to the circuit, always turn the voltage knob to the far left position to avoid burning out the LED. If you are not sure that the circuit is assembled correctly, test it at a supply voltage $\mathcal{E} < 2.0\ \mathrm{V}$.

The current through the LED must not exceed $100\ \mathrm{mA}$!

If the current through the LED is $I > 100\ \mathrm{mA}$, it may be damaged!

Recommendations for current-voltage characteristics measurements: To measure the current-voltage characteristic of a diode in *low current mode*, you need to use a voltmeter as an ammeter: if its internal resistance is R_V and the readings are V, then the current through it is V/R_V. To measure the volt-ampere characteristic of a diode in *high current mode*, a resistor R_0 with a voltmeter connected in parallel should be used as an ammeter.

B.2	Measure the resistance of the provided resistor R_0. Calculate the voltage $U_{100\ \mathrm{mA}}$ across it in the case when a current of $100\ \mathrm{mA}$ flows through it, and record the obtained value in the answer sheet.	0.1 pt

B.3	Assemble and draw in the answer sheet the electrical circuit for measuring the current-voltage characteristic of the “MAIN” LED in the *low-current mode* using a variable voltage source. Mark the voltmeters V_1 and V_2 on the drawing (the voltages measured by them are denoted accordingly).	0.3 pt

B.4	Measure the dependence of V_1 on V_2 in the *low-current mode*, when current flows through the “MAIN” LED in the forward direction. Perform 10 measurements. The table B4-ans.xlsx in the B4 folder is the answer for this question. Indicate the units for V_1 and V_2.	0.6 pt

B.5	Indicate which figure in the answer sheet shows the correct polarity for the “MAIN” LED.	0.1 pt

B.6	Assemble and draw in the answer sheet the electrical circuit for measuring the current-voltage characteristic of the “MAIN” LED in the *high-current mode* using a variable voltage source. Mark the voltmeters V_1 and V_2 on the drawing (the voltages measured by them are denoted accordingly).	0.3 pt

B.7	Measure the dependence of V_1 on V_2 in the *high-current mode*, when current flows through the "MAIN" LED in the forward direction. Perform 15 measurements. **The current through the LED must not exceed 100 mA!** The table B7-ans.xlsx in B7 folder is the answer for this question. Indicate the units for V_1 and V_2.	0.9 pt

B.8	Convert the values of V_1 and V_2 into the current I (in milliamperes) flowing through the "MAIN" LED and the voltage U (in volts) across the "MAIN" LED for both series. Write the formulas for the conversion in the answer sheet. As your answer, submit the tables B8-low.xlsx (conversion for the *low-current mode*) and B8-high.xlsx (conversion for the *high-current mode*) in the B8 folder.	0.4 pt

B.9	Combine the obtained dependencies into a single table.Plot the current-voltage characteristic of the "MAIN" LED in the forward direction. Use a logarithmic scale for the current. The axes and the units of the quantities must be labeled on the graph. The table B9-ans.xlsx in the B9 folder is the answer for this question.	0.2 pt

B.10	Calculate the value of $\eta_0 k_B T_0 / e$ numerically, using the ideality factor $\eta_0 = 2.0$ and room temperature T_0. Indicate the unit of the calculated value.	0.1 pt

B.11	Determine the value of the ideality factor η_{room} at room temperature. Note that the shape of the current-voltage characteristic of the diode may be affected by its heating (when significant currents flow). The region of very low currents may also be distorted due to the absorption of EM radiation by the LED. Be sure you have documented the solution!	0.3 pt

Proceed to optical measurements. Place the cuvette with the "MAIN" LED into the stand. Using the setup prepared in Part A, make sure that you obtain a correct characteristic optical spectrum of the "MAIN" LED.

If you are unable to obtain the spectrum, repeat the adjustment procedure described in Part A. In this case, you will need to recalibrate. Files obtained in Part A do not need to be overwritten.

Remember, the stand must not be moved during measurements!

B.12	For 7 different currents I flowing through the LED, measure the emission spectrum of the LED in the first diffraction order (the sensitivity can be adjusted). When taking measurements, wait for thermal equilibrium to be established (about 20 s). Save the spectrum files in the B12 folder and name them air-x.csv, where x is the current through the LED in milliamperes. **The maximum current through the LED is $100\ \mathrm{mA}$!**	0.8 pt

In the next step, you will need to perform a series of measurements over a specified period of time. For this, you must use the **Time Series** mode, which can only be activated after pressing the **Launch** button. To stop recording, press the **Pause** button. To save the results to a file, press **Save time series**.

The saved file can be used to analyze quantities that change over time, such as the wavelength of the spectrum maximum.

B.13	Connect the LED to the power source and adjust the circuit so that the maximum current $I = 100\ \mathrm{mA}$ flows through the LED. Then disconnect the LED from the source **without changing the adjustment settings** and wait for it to cool to room temperature (about 2 minutes). Start the **Time Series** mode. Quickly reconnect the LED to the power source and record the spectra until thermal equilibrium is reached. In this way, you will obtain the dependence of the LED spectrum on time as it heats up in air. The file air-TS.csv in the B13 folder is the answer for this question.	0.8 pt

After completing the measurements, do not touch the cuvette!

B.14	Using the data measured in B13, obtain the dependence of the wavelength λ on the time t elapsed since the LED was turned on in the circuit with current. Plot the obtained dependence. The table B14-ans.xlsx in B14 folder is the answer for this question. Be sure you have documented the solution!	0.3 pt

Part C. LED in water (3.5 points)

Using a pipette, carefully fill the cuvette with the "MAIN" LED with distilled water, **making sure not to move the stand**.

C.1	Assemble the electrical circuit for measuring the current-voltage characteristic of the “MAIN” LED in the *high-current mode* in distilled water. Measure the dependence of V_1 on V_2 when current flows through the “MAIN” LED in the forward direction. Perform 15 measurements. The table C1-ans.xlsx in the C1 folder is the answer for this question. Indicate the units for V_1 and V_2.	0.9 pt

C.2	For the series measured in C1, convert the values of V_1 and V_2 into the current I (in milliamperes) flowing through the “MAIN” LED and the voltage U (in volts) across the “MAIN” LED. Write the conversion formula in the answer sheet. The table C2-ans.xlsx in the C2 folder is the answer for this question.	0.2 pt

The current-voltage characteristic of the LED in water and in air differ only in the high-current mode.

C.3	On the same graph, plot the current-voltage characteristic of the LED in air (see B9) and in water (see C2). Use a logarithmic scale for the current. The axes and units of the quantities must be labeled on the graph. The table C3-ans.xlsx in C3 folder is the answer for this question.	0.5 pt

C.4	For 7 different currents I flowing through the LED, measure the emission spectrum of the LED (the sensitivity can be adjusted). When taking measurements, wait for thermal equilibrium to be established (about 10 s). Save the spectrum files in the C4 folder and name them water-x.csv, where x is the current through the LED in milliamperes. **Reminder: The maximum current through the LED is $100\ \mathrm{mA}$!**	0.8 pt

C.5	Connect the LED to the power source and adjust the circuit so that a current $I = 100\ \mathrm{mA}$ flows through the LED. Then disconnect the LED from the source **without changing the adjustment settings** and wait for it to cool to room temperature (about 2 minutes). Start the **Time Series** mode. Quickly reconnect the LED to the power source and record the spectra until thermal equilibrium is reached. In this way, you will obtain the dependence of the LED spectrum on time as it heats up. The measurement results file water-TS.csv in the C5 folder is the answer for this question.	0.8 pt

C.6	Using the data measured in C5, obtain the dependence of the wavelength λ on the time t. The table C6-ans.xlsx in C6 folder is the answer for this question. Be sure you have documented the solution!	0.3 pt

Part D. LED in liquid nitrogen (6.1 points)

In this section, you will need to cool the cuvette and its contents using liquid nitrogen ($T_{\mathrm{N}_2} = 77\ \mathrm{K}$), so it is essential to carefully read the following instructions.

The provided thermos flask with liquid nitrogen is fixed to the table. **Do not lift the thermos, tilt it, or attempt to interfere with its mounting mechanism.** To access the liquid nitrogen, use the special tube attached to a string, which allows you to scoop a small volume of the liquid. To hold special tube **use a clip**.

Do not immerse warm objects abruptly into liquid nitrogen — this will cause violent boiling. After lowering the tube into the thermos with liquid nitrogen, wait for some time before removing it to allow cooling. **Do not carry containers of liquid nitrogen over yourself, and avoid spilling liquid nitrogen on your skin, clothing, or footwear.**

During measurements in this part of the task, you must monitor the level of liquid nitrogen in the cuvette and periodically refill it. The LED must remain fully submerged in liquid nitrogen at all times.

Carefully remove the cuvette from its stand (ensuring minimal or no displacement). Pour out the water from the cuvette and then carefully place it back. Note that the position of the LED may still shift slightly, so subsequent data processing must account for this.

When performing measurements with liquid nitrogen, **always wipe the front surface of the cuvette** to remove any frost buildup (you can use your finger). Even a small amount of frost can significantly distort your measurements.

D.1	Measure the spectrum of the LED in air when a current of approximately $1\ \mathrm{mA}$ is flowing through it. The file D1-ans.csv in D1 folder is the answer for the question . No recalibration is needed, as we are only interested in relative changes in wavelength values.	0.1 pt

Using the special tube, you can pour liquid nitrogen into the cuvette containing the "MAIN" LED.

D.2	Assemble an electrical circuit to measure the current-voltage characteristics of the "MAIN" LED in *low-current mode* using an adjustable voltage source. Measure the dependence of V_1 on V_2 when current flows through the "MAIN" LED in forward direction, while it is immersed in liquid nitrogen. Perform 10 measurements. The table D2-ans.xlsx in D2 folder is the answer for the question. Specify units for both V_1 and V_2.	0.6 pt

D.3	Assemble an electrical circuit to measure the current-voltage characteristics of the "MAIN" LED in *high-current mode* using an adjustable voltage source. Measure the dependence of V_1 on V_2 when current flows through the "MAIN" LED in forward direction, while it is immersed in liquid nitrogen. Perform 15 measurements. The expected output is table D3-ans.xlsx in folder D3. Specify units for both V_1 and V_2.	0.9 pt

D.4	Convert the values of V_1 and V_2 into the current I (in milliamperes) flowing through the "MAIN" LED and the voltage U (in volts) across the "MAIN" LED for both dependencies measured in sections D2-D3. The tables D4-low.xlsx (conversion for low-current mode) and D4-high.xlsx (conversion for high-current mode) in folder D4 form the answer for this question.	0.2 pt

D.5	Combine the obtained $I(U)$ dependencies from the previous question into a single table. Plot the current-voltage characteristic of the "MAIN" LED in forward direction at liquid nitrogen temperature. Use a logarithmic scale for current. The graph must include labeled axes with units. The table D5-ans.xlsx in folder D5 is the answer for this question.	0.2 pt

D.6	Determine the value of the ideality factor η_{N2} at liquid nitrogen temperature. Document the complete solution including all calculations!	0.3 pt

D.7	Measure the emission spectrum of the LED for 7 different current values I flowing through the diode (the sensitivity could be adjusted). Allow approximately 10 seconds for thermal equilibrium to be established before each measurement. During measurements, monitor the liquid nitrogen level in the cuvette and replenish it periodically. Condensation and ice formation occur on the outer surface of the liquid nitrogen-filled cuvette. This layer of ice and water affects spectral measurements. Remember to regularly and promptly remove it by hand. The answer consists of measurement files in folder D7. Name the files N2-x.csv, where x represents the LED current in milliamperes.	1.0 pt

D.8	For each saved spectrum from section D7, determine the wavelength λ corresponding to the maximum emission intensity of the LED. The table D8-ans.xlsx in folder D8 is the answer for this question. Note that a wavelength shift λ may occur for the LED in air due to stand displacement. Account for this as a constant wavelength shift applied to all measurements from section D7.	0.5 pt

D.9	Plot all three $\lambda(I)$ dependencies under different conditions (LED in air, water, and liquid nitrogen) on a single graph. The table D9-ans.xlsx in D9 folder is the answer for the question.	1.0 pt

The spectral peak wavelength shift directly correlates with LED junction heating during current flow.

D.10	By extrapolating the graphs from section D9 to $I = 0$, determine $\lambda_{\mathrm{N_2}}$ — the spectral peak wavelength at temperature $T_{\mathrm{N_2}}$ and λ_{room} — the spectral peak wavelength at temperature T_0.	0.6 pt

D.11	Using the results from section D10 and the theoretical expression for the temperature dependence of the band gap (1), determine the values of the parameters E_0 and α The value of Debye temperature θ is $500\ K$.	0.7 pt

Part E. Calculation of calorimetric parameters (3.1 points)

In the vicinity of room temperature T_0, formula (1) can be approximately represented in linear form as

$$\lambda(T) = \lambda_{\mathrm{room}} - \chi \cdot (T - T_0).$$

E.1	Write the expression for χ and calculate its value.	0.5 pt

Establishment of thermodynamic equilibrium is associated with heat transfer from the LED to the external environment at temperature T_0:

$$UI = \varkappa(T - T_0)$$

where U and I are the voltage across the LED and the current through it, respectively, and $\varkappa$ is the effective heat loss coefficient.

E.2	Determine the ratio $\varkappa^{\mathrm{air}}/\varkappa^{\mathrm{water}}$ of the effective heat loss coefficients in air and water.	0.5 pt

If LED is initially at room temperature T_0 and the current is suddenly starts to path through it, it begins to heat up until thermal equilibrium is reached.

This dynamics can be described by the following equation:

$$CdT = \varkappa(T_\infty - T)dt,$$

where C is the effective heat capacity of the LED in its environment (may depend on environment), T_∞ is the temperature of the LED in thermal equilibrium mode.

E.3	Derive an expression for the LED temperature T as a function of time t after the LED is turned on. Express your answer in terms of $\varkappa$, C, T_0, and T_∞.	0.3 pt

E.4	Using the data obtained in sections B13 and C6, derive the dependence of the LED temperature T on time t for each heating process. The answer for this question consists of tables E4-air.xlsx and E4-water.xlsx in E4 folder.	1.0 pt

E.5	Linearize the dependencies obtained in section E4 and plot the linear graphs. The table E5.xlsx in the folder E5 containing two graphs: one for air, the other for water is the answer for the question. The graphs must be labeled.	0.5 pt

E.6	Determine the ratio $C^{\mathrm{air}}/C^{\mathrm{water}}$ of the effective heat capacities of the LED in air and water, respectively.	0.3 pt

Part F. Temperature dependence of saturation current (1.4 points)

In the previous section, we utilized the temperature dependence of the LED's emission spectrum to determine calorimetric parameters. Now, we propose to investigate the influence of temperature on the current-voltage characteristic of the LED. In parts B-D, we observed that the LED's current-voltage characteristic deviates from the Shockley equation (at fixed temperature of p-n junction) at high currents, which is associated with its heating.

The obtained data can be used to determine the dependence of I_0 on temperature. Here, we will neglect the temperature dependence of the ideality factor η.

F.1	Using the results from part B, determine the dependence of ln(I_0/mA) on temperature T for measurements in air. As your answer, fill in table F1-ans.xlsx in folder F1 and plot the graph of this dependence.	0.6 pt

F.2	Using the results from part C, determine the dependence of ln(I_0/mA) on temperature T for measurements in water. As your answer, fill in table F2-ans.xlsx in folder F2 and plot the graph of this dependence.	0.6 pt

F.3	By what factor does the current I_0 change when the temperature increases by $10\ K$?	0.2 pt