Non-ideal capacitors (10 points)

Capacitance measurement method:

First, measure the highest voltage the capacitor can reach by connecting it to the voltage source via jumper wire W2. Before each measurement, connect capacitor to starting voltage source with jumper wire W2 and to a final voltage source (U_f) with jumper wire W1 via the resistor R1. Capacitor C2 should be prepared that way for at least 10 s, while C1 measurement can be started immediately by disconnecting jumper wire W2 from the starting voltage source. To determine a precise value of the final voltage U_f, it should be measured after capacitor has been connected to final source via R1 for a long time (at least 3 minutes). Then, the capacitance can be calculated from:

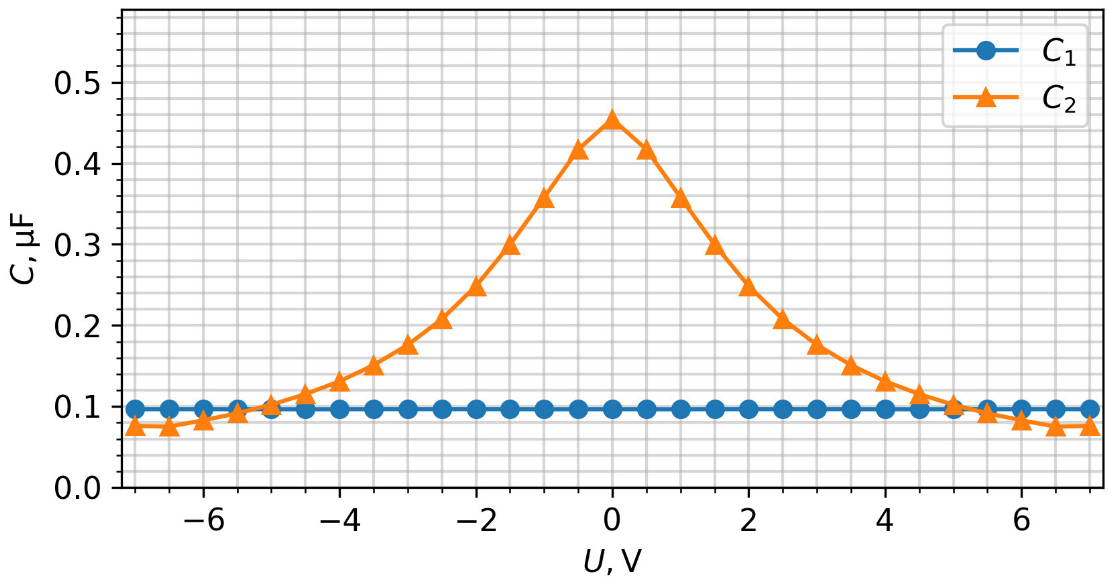
$$C(U) = \frac{U_f - U(t)}{R1} \bigg/ \frac{\mathrm{d}U}{\mathrm{d}t}$$

When measuring C2, to ensure minimal change in charging current, capacitance should only be calculated in conditions where U_f and $U(t)$ have different polarities. This way, capacitance dependence on voltage should be symmetrical around 0 V.

Part A: Capacitors at room temperature (4 points)

A.1 (2.3 pt)

Graph $C_1(U)$ should be constant, $C_2(U)$ must be highest at 0 V.
Example results measured at room temperature of 29 °C.



	C_1	C_2
0 V	0.100 μF	0.473 μF
3 V	0.100 μF	0.183 μF
6 V	0.100 μF	0.086 μF

$$C(U) = \frac{U_f - U(t)}{R1} \Big/ \frac{\mathrm{d}U}{\mathrm{d}t}.$$

A.2 (0.5 pt)

$U_{\text{max change}} = 4.5$ V at capacitor C2

A.3 (1.2 pt)

It's important to calculate $\int_{0V}^{6V} C(U)dU$, not just attempt to multiply $C(6\text{ V}) \cdot 6\text{ V}$

$$q_1 = 0.60\ \mu\text{C}; \quad q_2 = 1.3\ \mu\text{C}$$

Part B: Calibrating NCT thermistor (1 point)

B.1 (1.0 pt)

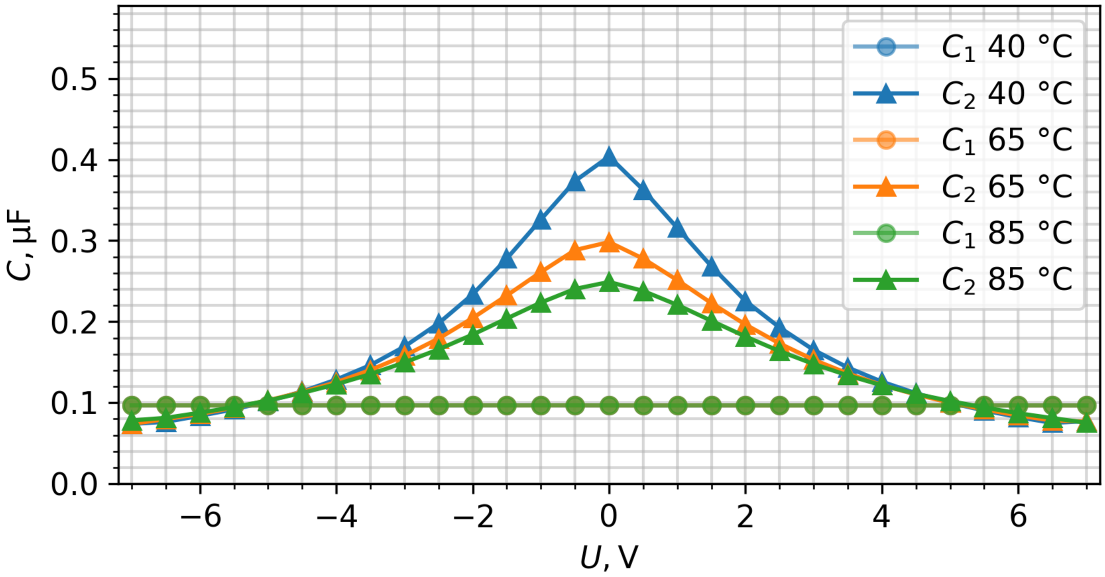
$R_0 = \frac{U_{T0} R_3}{U - U_{T0}} \mathrm{e}^{-B/T}$,
where $U = 3.3$ V, U_{T0} – uT at room temperature, T – room temperature in kelvins

$R_0 = 0.0341\ \Omega$.

Part C: Capacitors at different temperatures (3 points)

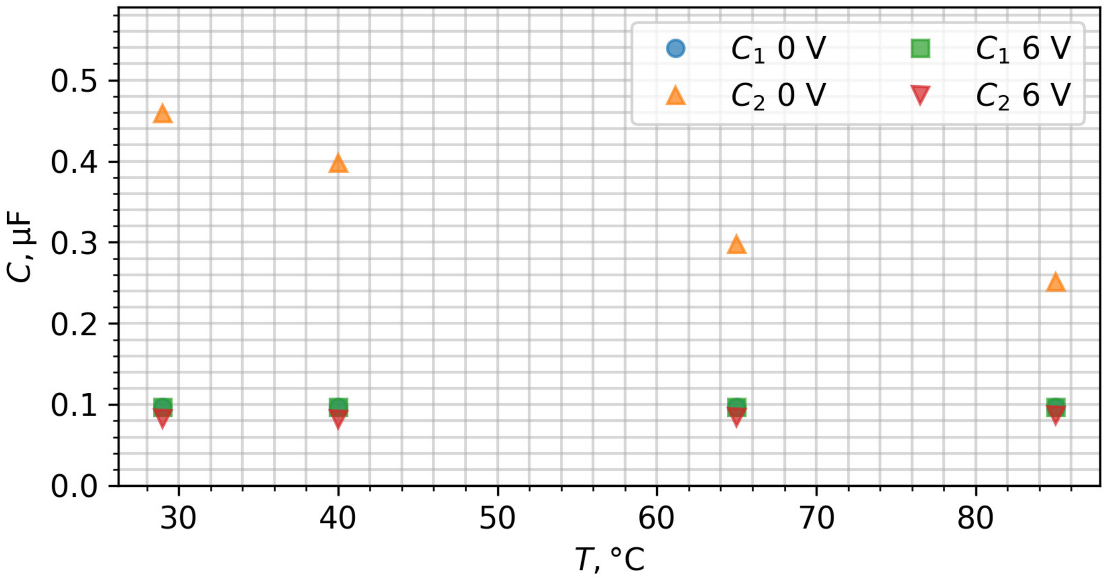
C.1 (1.3 pt)

Graphs $C_1(U,T)$ should always stay constant, $C_2(U)$ must be highest at 0 V



C.2 (0.5 pt)

Graph $C_1(T)$ should always stay constant



C.3 (1.2 pt)

$C_1(85\ °C)/C_1(40\ °C)\ |_{0V} = 1.00$

$C_1(85\ °C)/C_1(40\ °C)\ |_{6V} = 1.00$

$C_2(85\ °C)/C_2(40\ °C)\ |_{0V} = 0.63$

$C_2(85\ °C)/C_2(40\ °C)\ |_{6V} = 1.06$

Part D: Sources of measurement errors (2 points)

D.1 (1.0 pt)

Initial settings:

S1 position	IN connection
C1	-9V or GND

Process:

Step number	S1 position	IN connection	Duration, s	Measured variable
1	C1	+9V	0.2 s (any short time is good)	
2	C1	Free		$\lvert du_C(t)\rvert/dt$
3	C1	+9V	5 s (has to be much longer than first)	
4	C1	Free		$\lvert du_C(t)\rvert/dt$

Verification: $\lvert du_C(t)\rvert/dt\rvert_2 = \lvert du_C(t)\rvert/dt\rvert_4$

Main source of error: 1 (Leakage current.)

D.2 (1.0 pt)

Initial settings:

S1 position	IN connection
C2	-9V or GND

Process:

Step number	S1 position	IN connection	Duration, s	Measured variable
1	C2	+9V	0.2 s (any short time is good)	
2	C2	Free		$\lvert duC(t)\rvert/dt$
3	C2	+9V	5 s (has to be much longer than first)	
4	C2	Free		$\lvert duC(t)\rvert/dt$

Verification: $\lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t\rvert_2 \gg \lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t\rvert_4$

Alternatively,

$$\frac{\lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t\rvert_2}{\lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t\rvert_4} > 2.$$

Main source of error: 2 (Polarization properties of the capacitor’s dielectric media)

Non-ideal capacitors

Depending on how far participant's measurements are from the correct ones, an extra multiplier η is applied to reduce the points for the task.

For each task (for example, A1, A2, B1, ...) the final score has to be rounded up to a single decimal digit.

Part A: Capacitors at room temperature (4 points)

A.1 (2.3 pt)	Graphs are plotted with correct axes, units and reasonable ranges (data fills most of the graph)	0.1 pt
	Graph $C_1(U)$ 0.3 points only if it is from -7 V to 7 V and its magnitude changes no more than 0.5% 0.1 points if its magnitude changes more than 0.5% or is plotted within a more limited range (f.e. 0 V to 7 V)	0.3 pt
	Graph $C_2(U)$. 0.5 points only if it is from -7 V to 7 V and its highest at 0 V. 0.2 points if it is from -7 V to 7 V, but its highest not at 0 V or if it increases with magnitude of voltage 0 points if it's only shown between 0 V and ± 7 V	0.5 pt
	Correct C_1 value (error under 10%) These points are void if $C_1(U)$ magnitude changes more than 0.5% η = 0.3, if error within 10–15%	0.2 pt
	Correct C_2 values (error under 20%) η = 0.7, if error within 20–30% η = 0.5, if error within 30–40% η = 0.2, if error within 40–50%	1.0 pt
	Correct $C(U)$ formula	0.2 pt

A.2 (0.5 pt)	Correct voltage (within 10%) and capacitor η = 0.7, if error within 10–15% η = 0.5, if error within 15–20% η = 0.2, if error within 20–25%	0.5 pt

A.3 (1.2 pt)	Correct q_1 value (within 0.5% from $C_1 \cdot 6\,V$)	0.2 pt
	Correct q_2 value (within 10%) η = 0.7, if error within 10–15% η = 0.5, if error within 15–20% η = 0.2, if error within 20–25%	1.0 pt

Part B: Calibrating NCT thermistor (1 point)

B.1 (1.0 pt)	Correct R_0 formula	0.7 pt
	Correct R_0 value (within 10%) η = 0.7, if error within 10–15% η = 0.4, if error within 15–25%	0.3 pt

Part C: Capacitors at different temperatures (3 points)

C.1 (1.3 pt)	Graphs are plotted with correct axes, units and reasonable ranges (data fills most of the graph)	0.1 pt
	Graphs $C_1(U)$ at different temperatures. To get these points C_1 must not depend on voltage or temperature at all	0.3 pt
	Graphs $C_2(U)$ at different temperatures. 0.3 pt given per temperature if $C_2(U)$ is highest at 0 V and its capacitance doesn't increase with the magnitude of voltage	0.9 pt

C.2 (0.5 pt)	Graphs are plotted with correct axes, units and reasonable ranges (data fills most of the graph)	0.1 pt
	Graphs $C_1(T)$ and $C_2(T)$ at 0 V and 6 V versus the temperature. −0.2 pt penalty if C_1 clearly depends on voltage or temperature −0.2 pt penalty if no points at room temperature	0.4 pt

C.3 (1.2 pt)	Correct $C_1(85\,°C)/C_1(40\,°C)$ ratio values (within 0.5%) 0.2 pt for correct values at 0 V and 0.2 pt for correct values at 6 V	0.4 pt
	Correct $C_2(85\,°C)/C_2(40\,°C)$ ratio values (within 10%) 0.4 pt for correct values at 0 V and 0.4 pt for correct values at 6 V η = 0.7, if error within 10–15% η = 0.5, if error within 15–20% η = 0.2, if error within 20–25%	0.8 pt

Part D: Sources of measurement errors (2 points)

D.1 (1.0 pt)	Correct answer for main source of error for $C_1(9\ V)$ measurement.	0.2 pt
	Given reasoning for the answer	0.5 pt
	The answer table has been filled correctly	0.3 pt

D.2 (1.0 pt)	Correctly determined main source of error for $C_2(9\ V)$ measurement.	0.2 pt
	Given reasoning for the answer: wrote $\lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t\rvert_2 \gg \lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t\rvert_4$ or $\lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t\rvert_2 > K \cdot \lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t\rvert_4$, where $K \geq 2$ is any multiplier 0.3 pt, if just inequality $\lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t\rvert_2 > \lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t\rvert_4$ is given	0.5 pt
	The answer table has been filled correctly	0.3 pt

Light Emitting Diodes (LEDs)

Volt-Ampere characteristics of the LED have to be measured in two modes: pulsed (part A) and continuous (part B). Running LED continuously produces a noticeable amount of heat, while running it in the pulsed mode allows minimizing and neglecting self-heating effect.

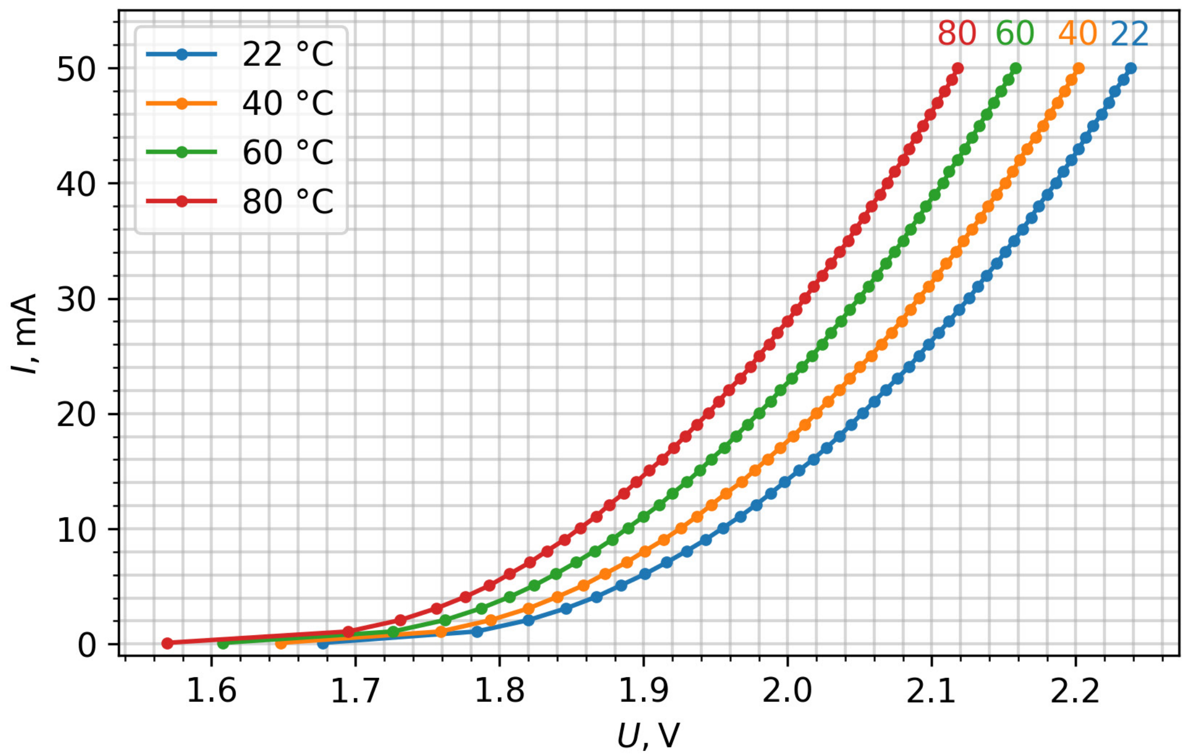
Students have to be able to run the automated $I_{LED}(U_{LED})$ measurement procedure and extract the required point by visually interpolating data for required values of I_{LED}.

The temperature of PCB is controlled by changing the current of the heating circuit. The heating and temperature measurement parts of this Experiment are identical to the Experiment 1.

Part A: Volt-ampere characteristics at different temperatures (5.0 points)

A.1 (2.5 pt.)

Graph $I_{LED}(U_{LED})$ has to be accurate (in right range) and smooth.



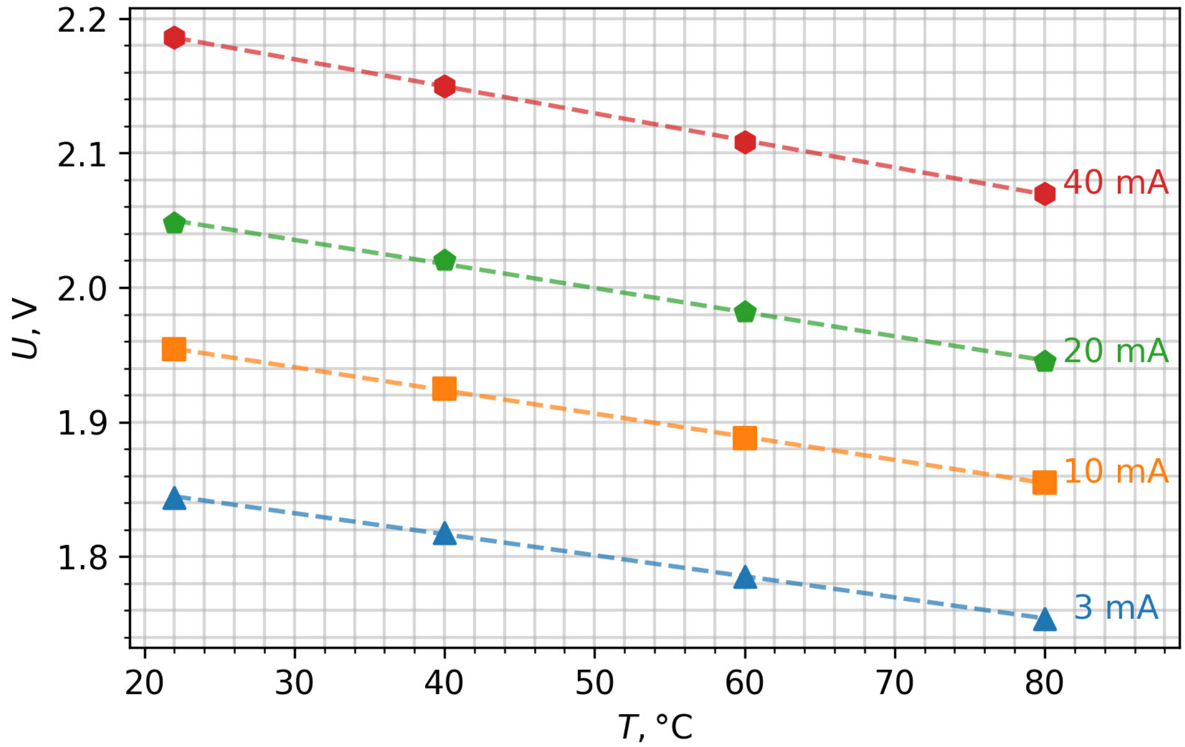
A.2 (1.0 pt.)

$U_{\text{LED}}(I_{\text{LED}}, T)$:

I_{LED} \ T	"Room" 22 °C	40 °C	60°C	80°C
3 mA	1.844 V	1.818	1.785	1.754
10 mA	1.954	1.925	1.888	1.855
20 mA	2.048	2.02	1.982	1.945
40 mA	2.186	2.15	2.108	2.07

A.3 (1.5 pt.)

Graphed $U_{\text{LED}}(I_{\text{LED}}, T)$ from A.2 data. $U_{\text{LED}}(T)$ should show clear linear trend and be approximated graphically. The slope $\left(\frac{\Delta U(I,T)}{\Delta T}\right)$ should also be calculated.

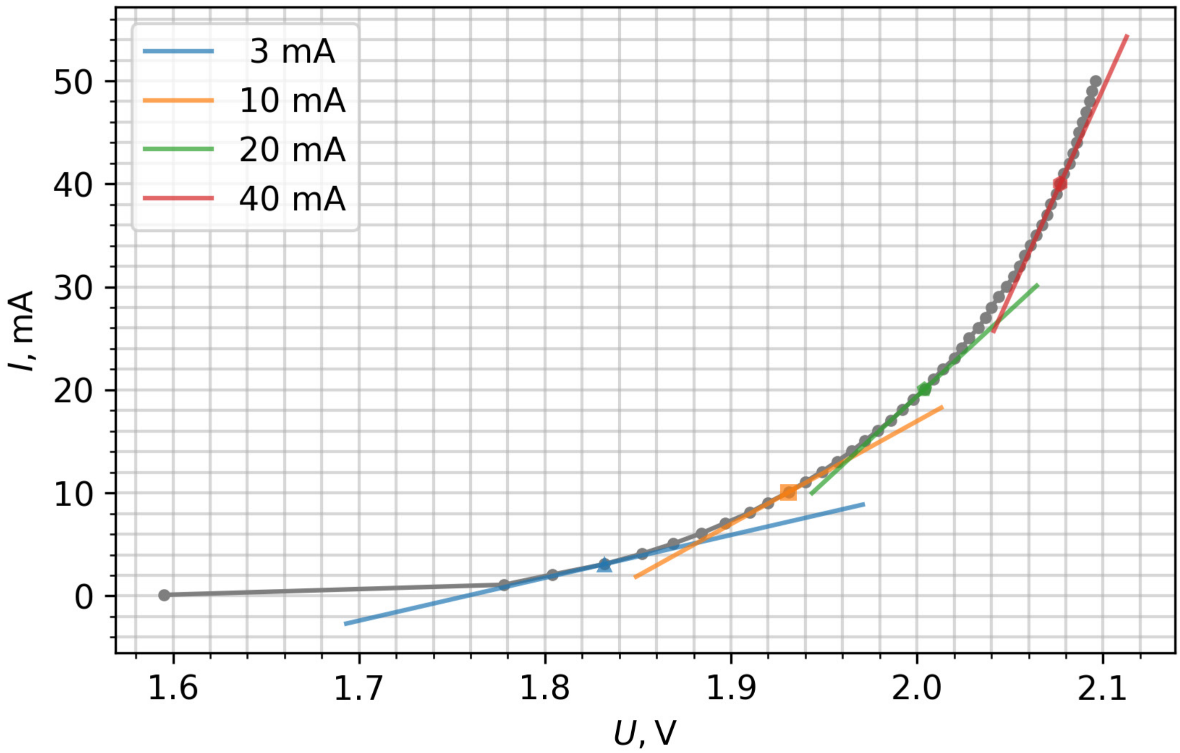


I_{LED}	3 mA	10 mA	20 mA	40 mA
$\left(\frac{\Delta U(I,T)}{\Delta T}\right)$	-1.55 mV/K	-1.7 mV/K	-1.8 mV/K	-2.0 mV/K

Part B: Measurement of the LED Volt-Ampere characteristics at continuous driving current (3.5 points)

B.1 (1.5 pt.)

Graph $I_{\text{LED}}(U_{\text{LED}})$ has to be accurate (in right range) and smooth.



I_{LED}	3 mA	10 mA	20 mA	40 mA
U_{LED}	1.83 V	1.93 V	2.00 V	2.08 V
ΔU	0.014 V	0.024 V	0.048 V	0.106 V
T_{J}	~ 32.3 °C	~43 °C	~49 °C	~76.5 °C
T_{PCB}	~ 25–30 °C	~ 30–35 °C	~ 33–37 °C	~ 35–40 °C

B.2 (0.5 pt.)

The dynamic resistance of the LED has to be calculated as derivative at the asked values of I_{LED}.

I_{LED}	3 mA	10 mA	20 mA	40 mA
$\frac{dI}{dU}$	41.6 mA/V	100 mA/V	166.7 mA/V	400 mA/V

B.3 (1.5 pt.)

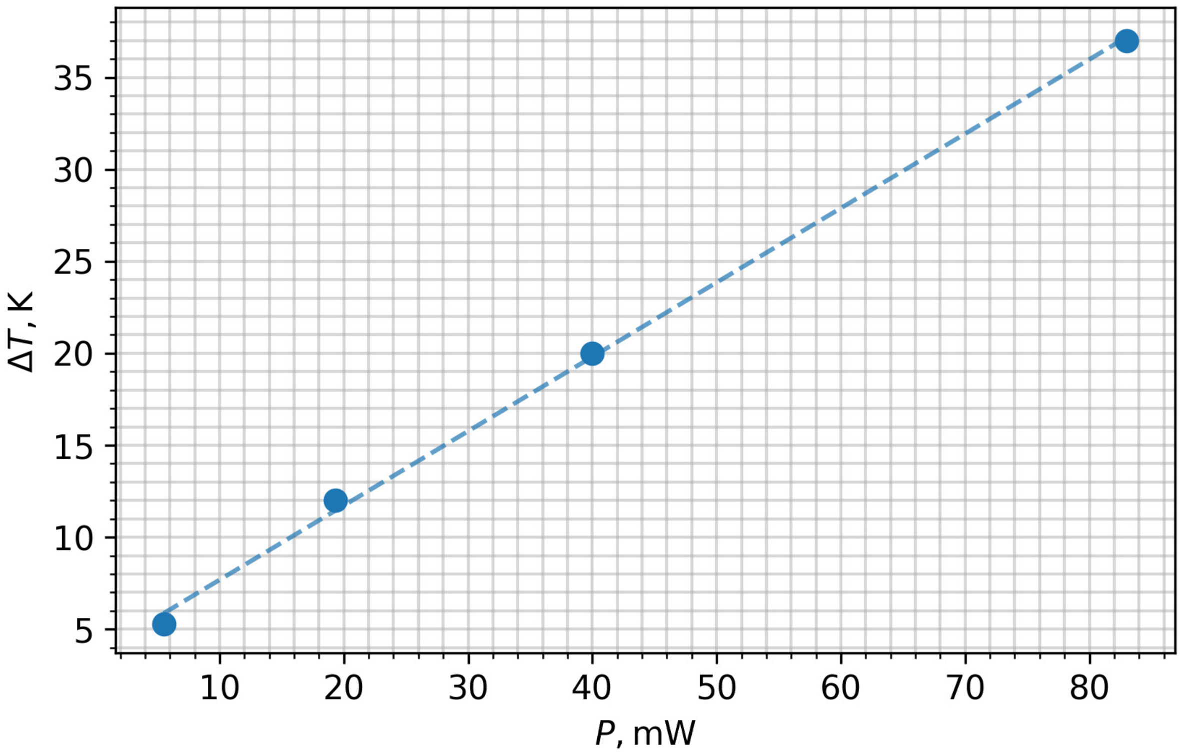
Graphed $\Delta T(P)$.

ΔT for each I_{LED} has to be calculated as $\Delta T = \frac{U(\text{pulsed}) - U(\text{CW})}{\left(\frac{\Delta U(I,T)}{\Delta T}\right)} - \left(T_{\mathrm{PCB}}(\text{CW}) - T_{\mathrm{PCB}}(\text{pulsed})\right)$ from the data of A.2, B.1 and A.3.

Caution: during the measurement of B.1, the temperature of the PCB is not constant and rises up to 7 °C above the "room' temperature at higher currents. This has to be taken into account when calculating ΔT.

The generated heat is taken as electrical power: $P = I_{\mathrm{LED}} \times U_{\mathrm{LED}}$. The energy emitted by the escaping light is neglected.

The graph should have a clear linear trend and approximated graphically. Thermal resistance is calculated as linear slope $\frac{\mathrm{d}}{\mathrm{d}P}\left(\Delta T(P)\right) = 400\ K/\mathrm{W}$.



I_{LED}	3 mA	10 mA	20 mA	40 mA
ΔT	5.0 K	12 K	20 K	37 K

Part C: Calculation of the LED current drift due to the temperature (1.5 points).

C.1 (1.5 pt)

The I_{LED} under constant $U_{\mathrm{LED}} = U_{\mathrm{20mA}}$ is calculated:

$$I_{LED}(U_{\mathrm{20mA}}, \mathrm{T}) = 20\ \mathrm{mA} - (T - T_{\mathrm{room}}) \times \left(\frac{\Delta U(20\ \mathrm{mA}, T)}{\Delta T}\right) \times \frac{\mathrm{d}I(20\ \mathrm{mA}, U)}{\mathrm{d}U}.$$

$I_{LED}(U_{\mathrm{20mA}}, 0°\mathrm{C}) = 13.3\ \mathrm{mA}$, $I_{LED}(U_{\mathrm{20mA}}, 40°\mathrm{C}) = 25.7\ \mathrm{mA}$.

Light Emitting Diodes (LEDs)

Depending on how far participant's measurements are from the correct ones, an extra multiplier **η** is applied to reduce the points for the task.

For each task (for example, A1, A2, B2, ...) the final score has to be rounded up to a single decimal digit.

Part A: Volt-ampere characteristics at different temperatures (5.0 points)

A.1 (2.5 pt)	Graph $I_{\mathrm{LED}}(U_{\mathrm{LED}})$, 4 curves at different temperatures. 0.1 pt. for the axis and ranges correctly marked; 0.6 pt for each curve (4 × 0.6 max). **−1** pt penalty if $I_{\mathrm{LED}}(U_{\mathrm{LED}})$ curves are not smooth and have less than 15 points per curve.	2.5 pt

A.2 (1.0 pt)	Table 4 × 4 cells. Each cell is worth of 1/16 pt = 0.0625 pt. Marking is based on the average of five biggest errors of all U values. Correct if within 3%; η = 0.7, if error within 4–7% η = 0.5, if error within 8–10% η = 0.2, if error within 11–12% At final step, the sum of cell points multiplied by **η** has to be averaged to a single decimal digit by general averaging rules.	1.0 pt

A.3 (1.5 pt)	Graph $U_{\mathrm{LED}}(I_{\mathrm{LED}}, T)$: 4 curves with linear approximations; 0.2 pt for the axis and ranges correctly marked; 0.2 pt for each curve (4 × 0.2 max). −0.25 pt penalty if $U_{\mathrm{LED}}(I_{\mathrm{LED}}, T)$ if linear approximations not shown.	1.0 pt
	Table 1 × 4 cells. Each cell is worth of 0.5/4 pt = 0.125 pt. Correct $\frac{\Delta U(I,T)}{\Delta T}$ value (within 5%). Marking is based only on the biggest error of all four values. η = 0.7, if error within 6–10% η = 0.5, if error within 11–15% η = 0.2, if error within 16–20%	0.5 pt

Part B: Measurement of the LED Volt-Ampere characteristics at continuous driving current (3.5 points)

B.1 (1.5 pt)	Graph $I_{\text{LED}}(U_{\text{LED}})$: single curve with derivatives at certain points: 0.15 pt for the axis and ranges correctly marked; 0.6 pt for the smooth graph with at least 15 points. −0.25 pt penalty if $I_{LED}(U_{LED})$ curves are not smooth and have less than 15 points.	0.5 pt
	Only U_{LED} and T_{PCB} are required and. Each cell is worth of 1/8 pt. = 0.125 pt. T_{J} and ΔU are not evaluated. Correct $I_{\text{LED}}(U_{\text{LED}})$ values (error under 5%) Marking is based only on the biggest error of U_{LED} (other values are not evaluated at this point since they can depend on room temperature etc.) η = 0.7, if error within 6–10% η = 0.5, if error within 11–15% η = 0.2, if error within 16–20%	1.0 pt

B.2 (0.5 pt)	Table 1 x 4 cells. Each cell is worth of 0.4/4 pt. = 0.1 pt. 0.1 pr for the graphical representation of the derivatives on B.1 graph. Correct $\frac{dI}{dU}$ values (within 5%). Marking is based only on the biggest error of all four values. η = 0.7, if error within 6–10% η = 0.5, if error within 11–15% η = 0.2, if error within 16–20%	0.5 pt

B.3 (1.5 pt)	Graph $\Delta T(P)$: 4 points with linear approximation. 0.1 pt for the axis and ranges correctly marked; 0.2 pt for the correct P points on X axis (~6, ~20, ~40 and ~83 mW); 0.2 pt for the linear approximation visually correctly shown.	0.5 pt
	Table 1 × 4 cells. Each cell is worth of 0.5/4 pt = 0.125 pt. Marking is based only on the biggest error of all four values. Correct ΔT values (error under 10%). η = 0.7, if error within 11–15% η = 0.5, if error within 16–20% η = 0.2, if error within 20–30%	0.5 pt
	Correct $\Delta T(P)/P$: value (within 10%) η = 0.7, if error within 11–15% η = 0.5, if error within 16–20% η = 0.2, if error within 20–30%	0.5 pt

Part C: Calculation of the LED current drift due to the temperature (1.5 points)

C.1 (1.5 pt)	Correct I_{LED} values (within 5%) η = 0.7, if error within 6–10% η = 0.5, if error within 11–15% η = 0.2, if error within 16–20%	1.5 pt