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:

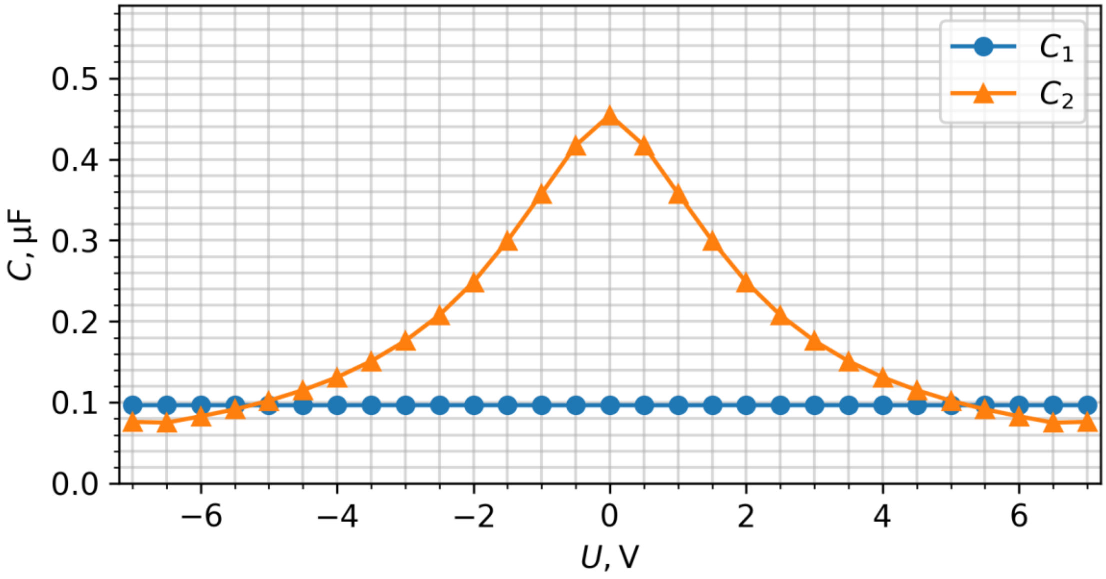
$$C(U) = \frac{U_f - U(t)}{R1} \Big/ \frac{\mathrm{d}U}{\mathrm{d}t}$$

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)

$U_{\text{max change}} = 1.6$ 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 $C(6\ \mathrm{V}) \cdot 6\ \mathrm{V}$

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

Part B: Calibrating NCT thermistor (1 point)

B.1 (1.0 pt)

$R_0 = \frac{U_{T0} R_3}{U - U_{T0}} \mathrm{e}^{-B/T}$,

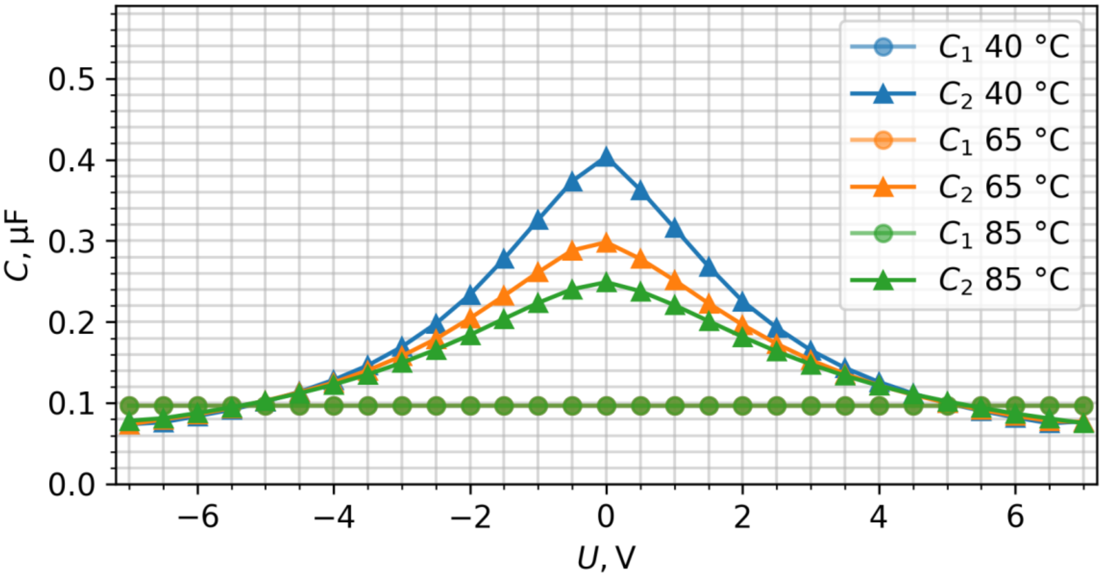
where $U = 3.3$ V, U_{T0} – uT at room temperature, T – room temperature in kelvins

$R_0 = 0.0341\ \Omega$.

Part C: Capacitors at different temperatures (3 points)

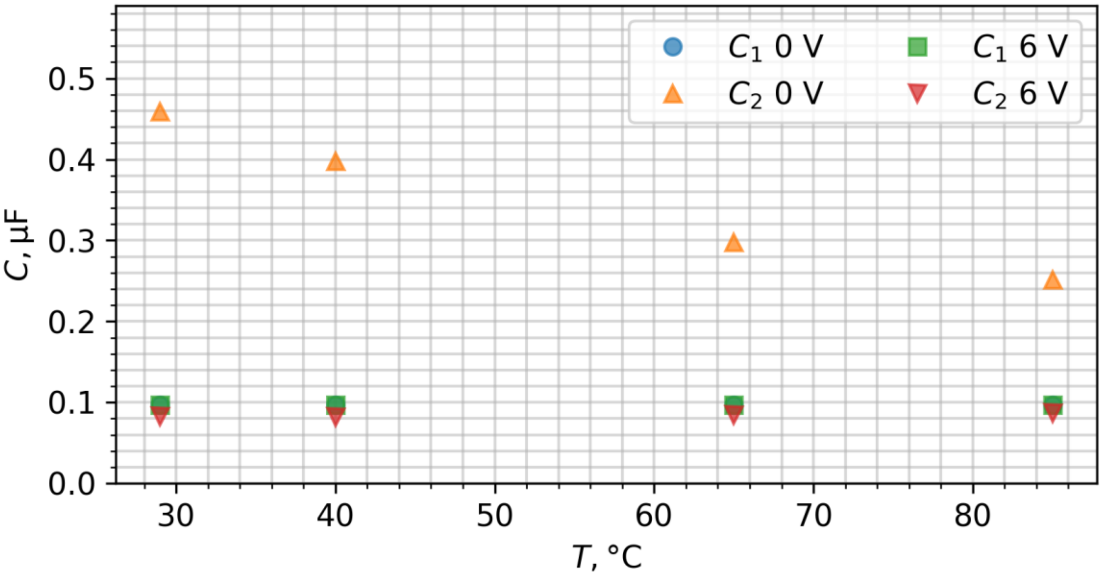
C.1 (1.3 pt)

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)

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

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

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

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

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		$\lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t$
3	C1	+9V	5 s (has to be much longer than first)	
4	C1	Free		$\lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t$

Verification: $\lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t|_2 = \lvert \mathrm{d}uC(t)\rvert/\mathrm{d}t|_4$

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		$\|duC(t)\|/dt$
3	C2	+9V	5 s (has to be much longer than first)	
4	C2	Free		$\|duC(t)\|/dt$

Verification: $|\mathrm{d}uC(t)|/\mathrm{d}t|_2 \gg |\mathrm{d}uC(t)|/\mathrm{d}t|_4$

Alternatively,

$$\frac{|\mathrm{d}uC(t)|/\mathrm{d}t|_2}{|\mathrm{d}uC(t)|/\mathrm{d}t|_4} > 2.$$

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

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.

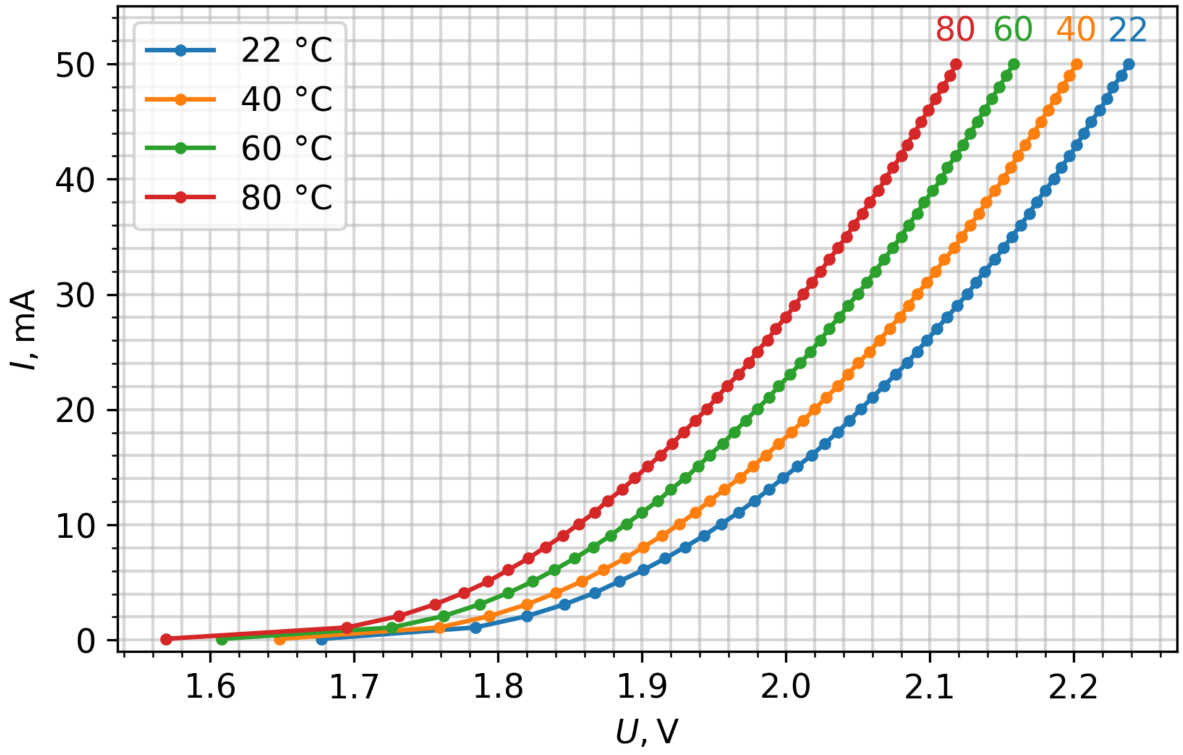
Students have to be able to run the automated $I_{\mathrm{LED}}(U_{\mathrm{LED}})$ measurement procedure and extract the required point by visually interpolating data for required values of I_{LED}.

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



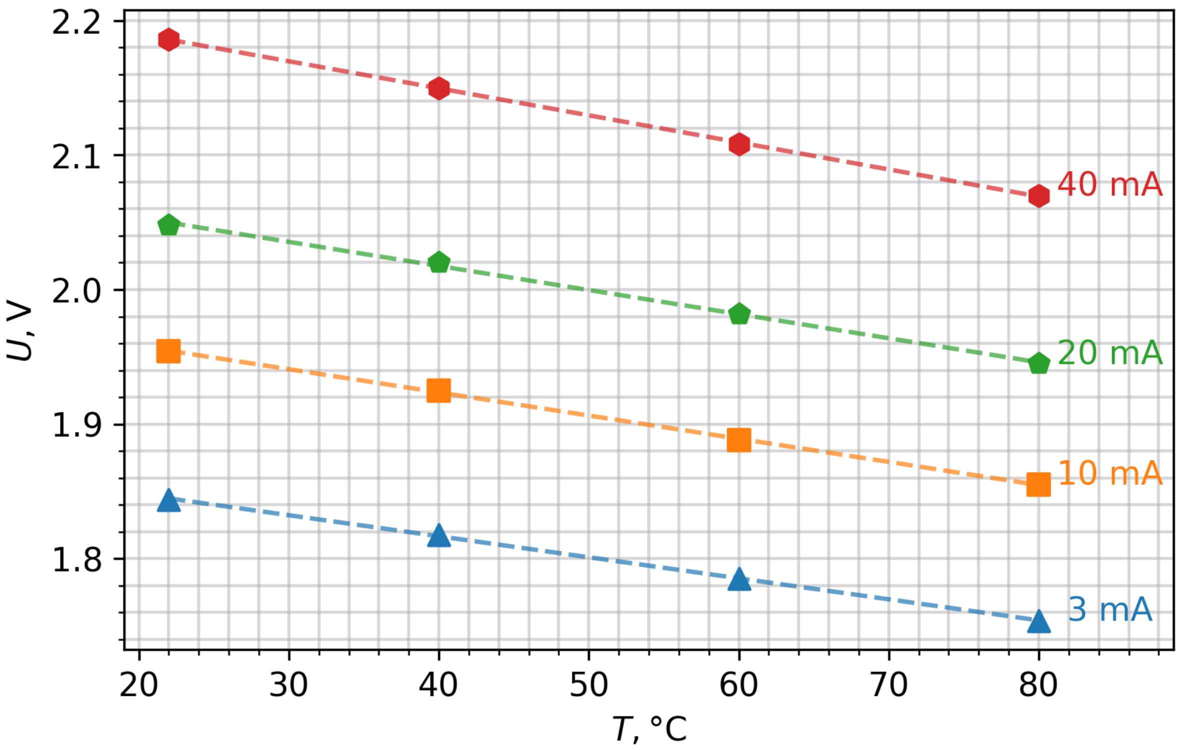
A.2 (1.0 pt.)

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

T / I_{LED}	“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.

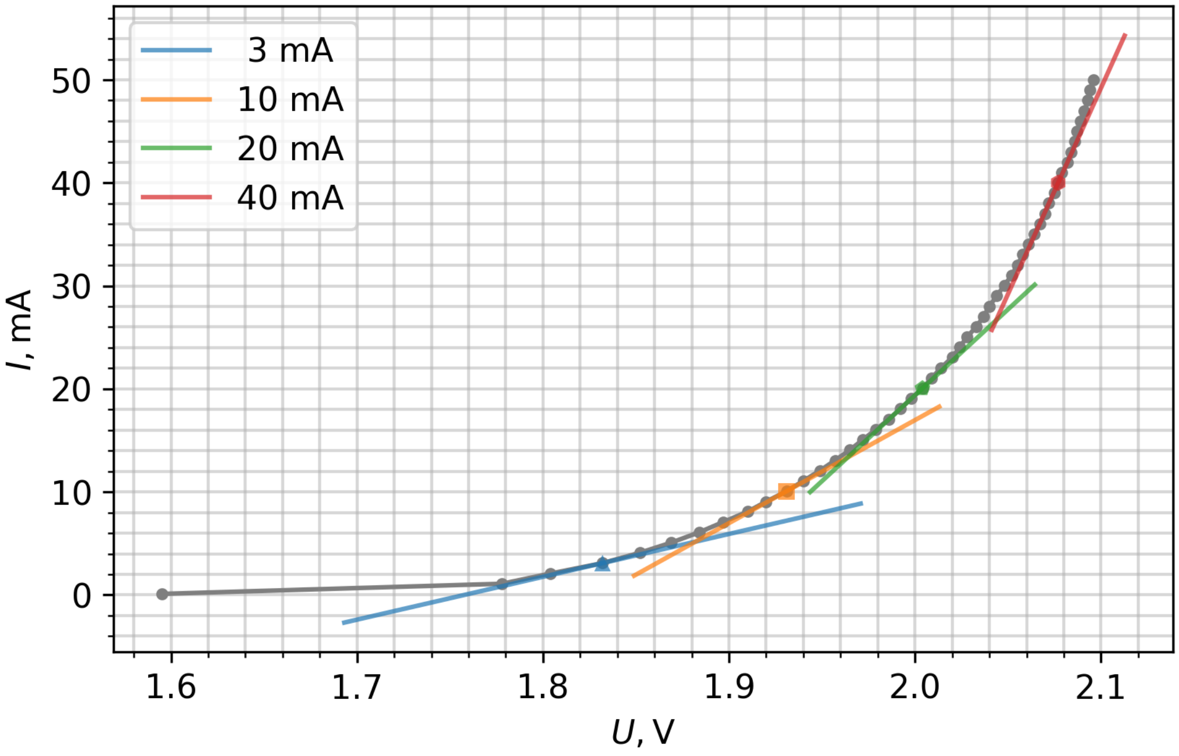


I_{LED}	3 mA	10 mA	20 mA	40 mA
$\left(\frac{\Delta U(I,T)}{\Delta T}\right)$	-1.55 mV/K	-1.7 mV/K	-1.8 mV/K	-2.0 mV/K

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

B.1 (1.5 pt.)

Graph $I_{\mathrm{LED}}(U_{\mathrm{LED}})$ 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

T_{J} are the most important parameters to be calculated in this section.
T_{J} have to be calculated by matching the U_{LED} values of B section with calibration curves in A section at certain current values. This can be done by selecting the nearest points of A.3 and calculating (interpolating) the T_{J} using the calculated $\left(\frac{\Delta U(I,T)}{\Delta T}\right)$ coefficients. Graphical interpolation is also possible, but is not as accurate as the first one.

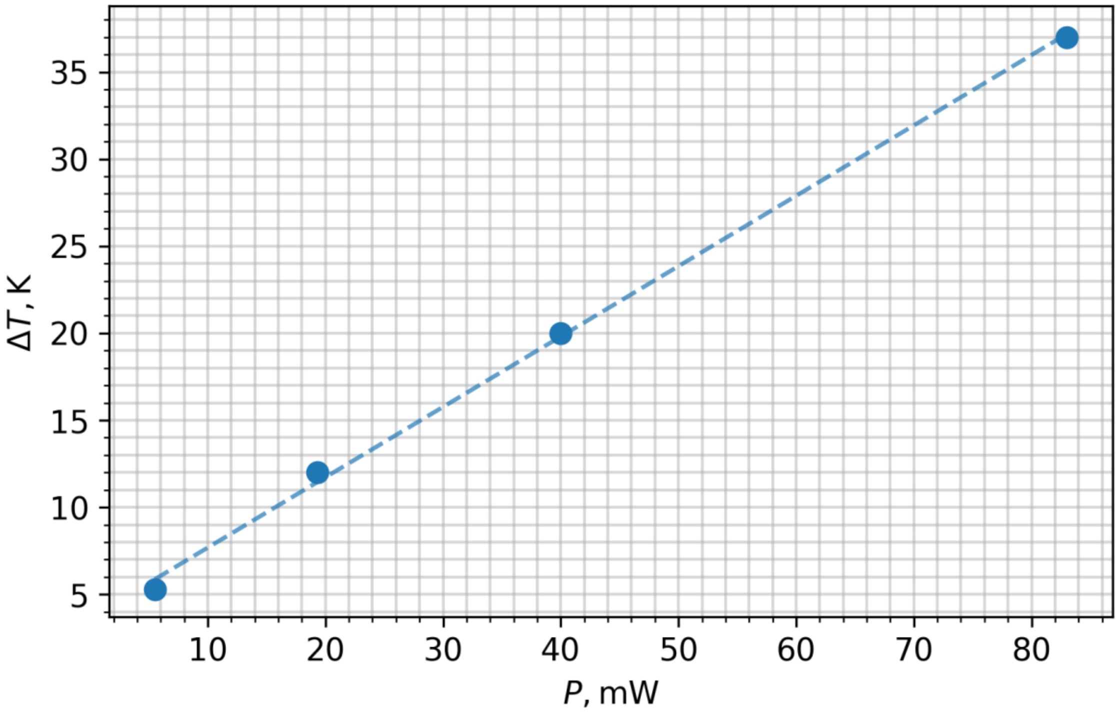
B.2 (0.5 pt.)

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
$\frac{\mathrm{d}I}{\mathrm{d}U}$	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 $\Delta T = T_{\mathrm{J}} - T_{\mathrm{PCB}}$ from the data of B.1.
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 $\frac{\mathrm{d}}{\mathrm{d}P}\big(\Delta T(P)\big) \cong 400\ \mathrm{K/W}$.



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)

Method 1:

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

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

To be accurate, we have to understand, that $\frac{\mathrm{d}I(20\ \mathrm{mA}, U)}{\mathrm{d}U}$ from B.1 involves the temperature increase of the PCB with rising current, but there is no technical capabilities to perform the measurements at constant PCB temperature. Furthermore, since the current is decreasing significantly, application of the derivatives at 20 mA is not very accurate.

Method 2:

The required values can be calculated by interpolating/extrapolating A.3 data with T_{J} calculated using ΔT values from B.3. Accuracy in this way suffers a bit due to the dependence of electrical power P on temperature.

$I_{LED}(U_{20\mathrm{mA}}, 0°\mathrm{C}) \cong 10\text{–}15\ \mathrm{mA}$, $\quad I_{LED}(U_{20\mathrm{mA}}, 40°\mathrm{C}) \cong 22\ \mathrm{mA}$.