



Óbuda University
Kandó Kálmán Electrical Engineering Faculty
Institute of Microelectronics and Technology

Sensor laboratory,
Micro- and nanotechnology
Laboratory measurement guide

Issue date: 2023.3.14.

I. Study of photodetectors

1 Measurement goal

- Study the spectral characteristic of a filament lamp.
- Study the spectral response of three different types of optic sensors.
- Measure the output characteristic of the phototransistor.
- The parameters to be measured are:
- The irradiance–wavelength characteristic of a filament lamp.
- The relative spectral sensitivity (wavelength dependence of the photo response) of the different photo detectors (a photoresistor, a photodiode, and a phototransistor).
- The output characteristic of the phototransistor at a given wavelength of the irradiating light.
- In the course of the exercise the spectral responses of different detectors will be compared.

2 Theoretical background

2.1 The light source (the filament lamp)

The filament lamp (incandescent lamp) is emitting a continuous spectrum (white¹ light) which is produced by a heated filament made of tungsten (also known as wolfram). The intensity of the emitted light is different according to the wavelength, with the strongest emission in the near-infrared.

2.2 Interaction of light and matter

Part of the light reaching the material boundary (surface) will be reflected, part will be absorbed and part will be transmitted and also refracted (its direction changing). In our measurement, the sensors work by absorbing light. This type of spectrometer was also originally used to examine liquid solutions, getting information about their transmittance spectra.

The propagation speed for electromagnetic waves depends on the material. Changes in this speed at boundary of different materials will cause refraction. The refraction index is given by Snellius-Descartes' Law:

$$n_{21} = \frac{\sin \alpha}{\sin \beta} = \frac{c_1}{c_2}$$

Where α is the angle of the incident light,

c_1 is the speed of the light in material 1,

β is the angle of the refracted light,

c_2 is the speed of the light in material 2.

¹ It's not as white as sunlight, its color temperature is much lower (ie. its light is more red) but our eyes adapt to it and see it as white. See also "white balance" setting for electronic cameras.

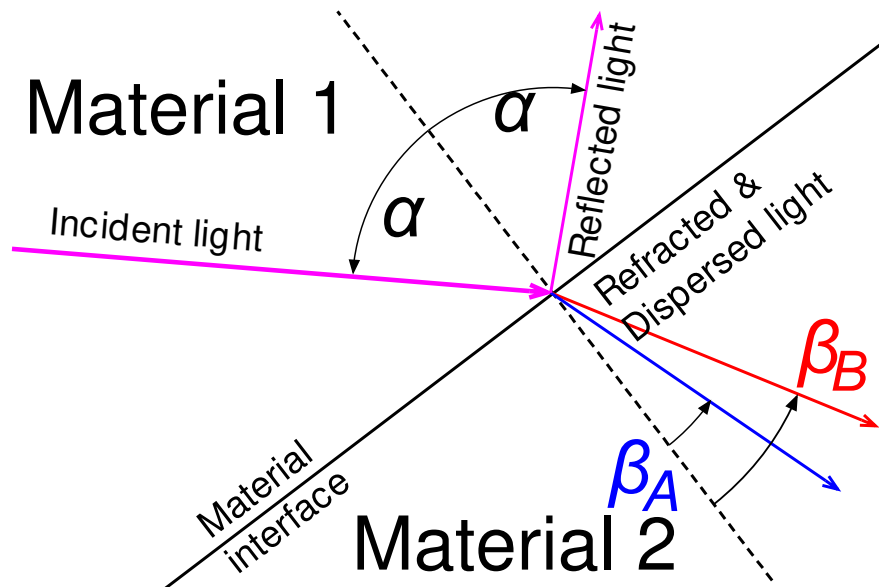


Figure 1: The refraction and dispersion of the light

Light's velocity in matter is wavelength dependent, thus the different components of the incident light will be refracted into different directions, as shown in Figure 1. This phenomenon is called dispersion. The light's dispersion can be used to separate the different wavelength components of the incidence light using prisms or gratings. In our measurement, the emitted light of filament lamp is separated to its spectral components by applying a turnable optical prism and an optical shield with a slot.



Figure 2: Prism and slot operation

The intensity of the outgoing narrow-bandwidth light is adjusted changing the size of the optical slot.

2.3 The transfer function of the optical system

The prism and the shield with the optical slot act as a band pass filter. The characteristic transfer function is shown in Figure 3.

The characteristic values shown in Figure 3 are:

- λ_{FWHM} : Full Width at Half Maximum (bandwidth of the filter)
- λ_0 : center wavelength (where light intensity is maximal)
- λ_l and λ_u : lower and upper limit wavelengths (3dB points)
- A_{λ_0} : maximum intensity value at λ_0

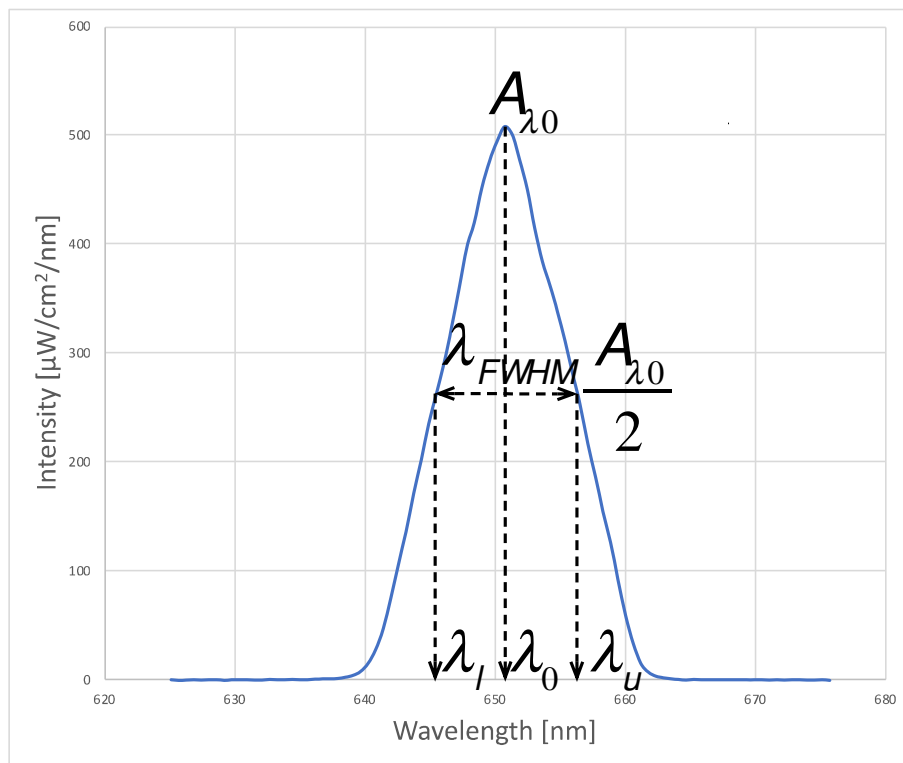


Figure 3: The transfer function of the optical system (example)

2.4 The operating principle of the photodetectors

The photons of the absorbed light transfer their energy to the material. If the photon energy is equal or somewhat greater than the forbidden gap (energy level between conductance and valence bands), then an electron in the valence band can "jump up" to the conduction band. The electron leaves behind a "hole" that acts like a positive charge carrier.

The generated electron-hole pair increase the conductivity of the material, ie. decrease the resistance. This is the principle behind the photoresistors (ie. their resistance decreases in light).

In semiconductors with a PN junction, the junction has an internal electric field. The electron and hole pair generated by the photon will be moved in opposite directions by this electric field, thus generating voltage and current. This is the basis of operation of the photodiode and phototransistor. The photodiode is also used as a solar cell (photovoltaic cell).

3 Measurement setup

The measurement device consists of a refurbished "Spektromom 203" equipment, which contains the lamp, turnable prism and slot (the big grey box on the photo). The wavelength and slot size can be adjusted by the white knobs. An electronic "AvaSpec-ULS2084" type spectrophotometer is built into the right side of the Spektromom device. The Avaspec is used to measure the light spectral intensity, using a PC to display the results.



Figure 4: The Spektromom 203 spectrophotometer (the insert shows the outputs of the sensors)

3.1 The Spektromom 203 spectrophotometer

The external power supply unit of the Spektromom 203 (see Figure 5) drives the selected light source and the PC as well.



Figure 5: The power supply unit of the Spektromom 203

Turning on the power supply unit will turn on the PC as well. When finishing the measurement, please make sure to exit Windows properly before shutting off the power supply!

The Spektromom has two light sources, a filament lamp (for approx. 400nm to 1100nm) and a deuterium lamp (for approx. 200nm to 400nm). The switch on the left bottom of the power supply can be used to turn on one of these. In this measurement we are only going to use the filament (incandescent) lamp.

The front panel of the Spektromom 203 (Figure 6) contains the following:

- WAVELENGTH selector, located to the left from the Reset button,
- The control of optical slot size (SLIT²), located to the right from the Reset button
- The electrical outputs of the sensors – located to the right from the slit knob
- The sensor selector, located above the electrical outputs. (Push/pull to use.)

Turning the wavelength selector knob, the prism's angle to the incident light will be changed letting the desired wavelength through the slot.

Turning the slit knob, the width of the slot is controlled, setting the desired intensity of the incident light.



Figure 6: The front panel of the Spektromom 203.

² slot and slit have similar meanings

The sensor (also called a DUT, "device under test") selector is a push-pull rod with markings (1..4) on it showing which sensor is in the measurement position. Pulling the rod into the marked positions, the rotating sample holder (Figure 7) will turn 90° putting the chosen sensor into the measuring position. In Figure 7 an LED is inserted into the position 1 and in this way facing to the optical input of the AvaSpec-ULS2084 spectrophotometer. In the course of the given laboratory task the position 1 will be empty, allowing the light from the prism to get to the optical fibre input (at left) of the AvaSpec.

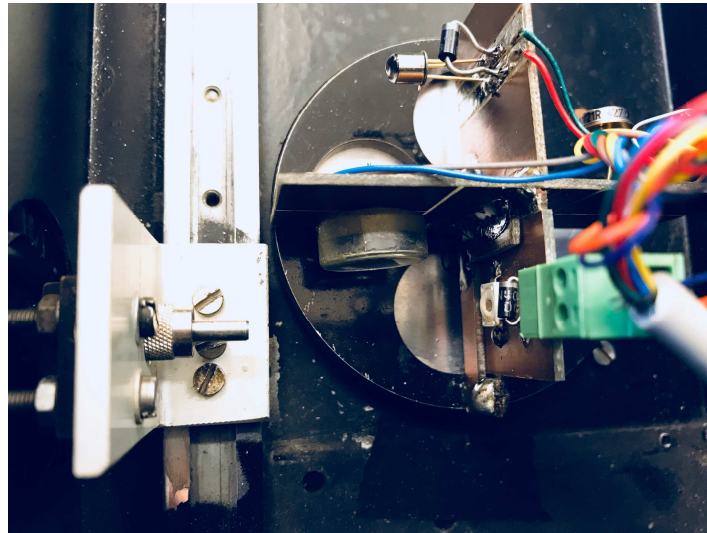


Figure 7: The turnable sample holder

3.2 The operation of AvaSpec-ULS2084 spectrophotometer

The spectral distribution of the given light sources can be measured applying the AvaSpec-ULS2084 spectrophotometer.

The control program of the AvaSpec-ULS2084 spectrophotometer is the "AvaSoft 7.5 for USB" program that runs on the PC. It can be started by double-clicking on its icon.

The spectral distribution of the irradiated power in $\mu\text{W}/\text{cm}^2/\text{nm}$ units is obtainable using the "I" (Irradiance) mode in calibrated status. Applying the "S" (Scope) regime the y-axis will show only the counts (C) of the detector. This is an uncalibrated regime, it won't be applied during the measurement.

The measurement starts with clicking the Start button (upper left). Starting the measurement in "I" (Irradiance) mode, the background values have to be measured and saved by clicking the black-squared button (when the lamp is still off and the sensor enclosure is closed).

Below the Start button there are the Integration time and the Average switch. Increasing the integration-time the unit become more sensitive. It is not necessary to modify during the measurement, only if too small values are detected. The Average function is used to filter the

noise. Changing the averaging value and restarting the measurement its effect can be seen. The “S” “A” “T” “I” icons partly mentioned before, they are pushbuttons for the different modes of operation. Right to the “I” icon is the button (showing up-down arrow) for automatic scaling of the y-axis. It is advisable to use in the course of the measurement. To the right from it the fifth button is the Cursor switch. Applying the Cursor switch, a cursor line will appear which is moveable by the mouse. The position of the cursor the actual wavelength is displayed above the graph, while the actual amplitude is given below the graph.

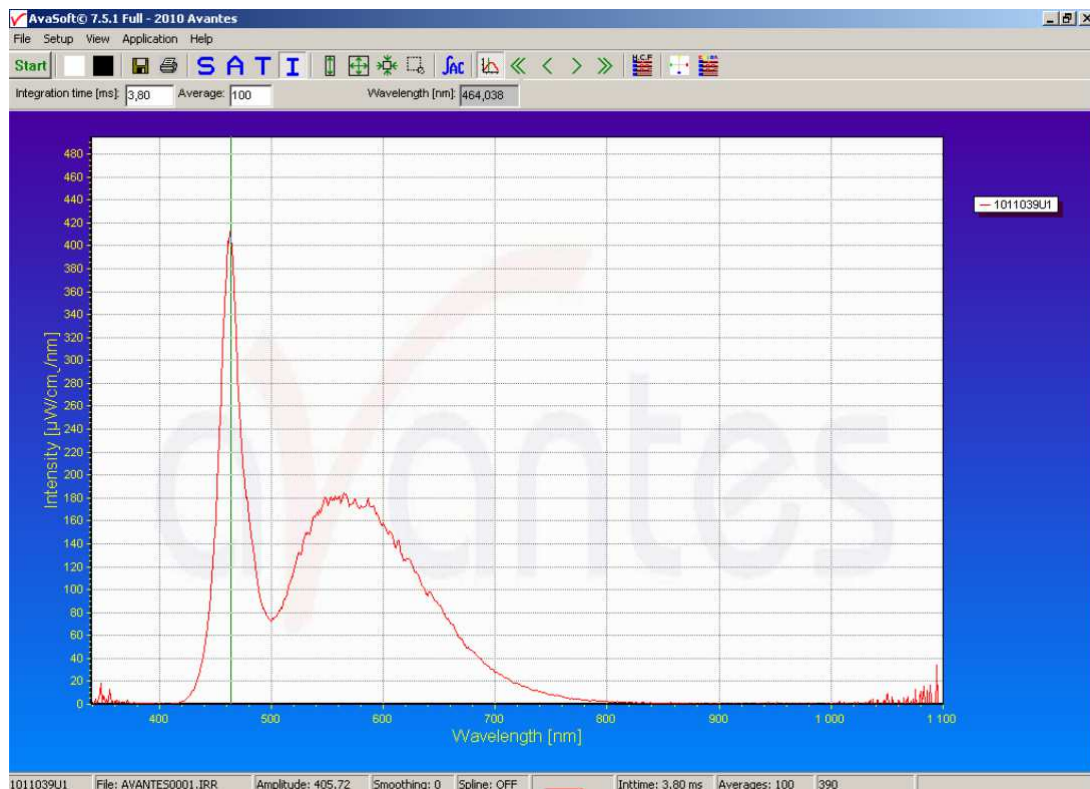


Figure 8: The spectra of a cold-white LED with the cursor line

The measured spectra can be saved onto the PC's desktop with the command sequence:

File->Save->Experiment

The saved filename will be *.IRR.

The saved data could be transcribed to Excel format applying the command sequence:

File->Convert graph->To Excel

The desired *.IRR file should be chosen. (If more than one file is chosen, the program will convert all to one Excel table.)

3.3 The measurement setup of sensors

3.3.1 Photoresistor

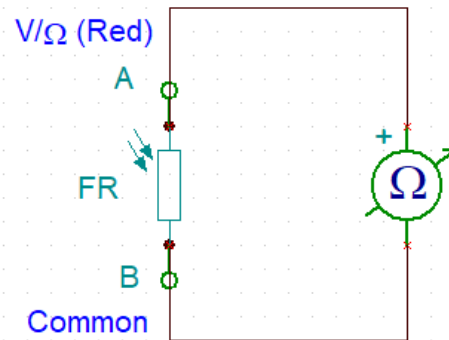


Figure 9: Test setup for photoresistor characterization

In the case of the photoresistor its resistance is to be measured (Figure 9). The easiest way is to use the multimeter in Ohmmeter mode. The resistance of the photoresistor is the highest in the dark (could be as large as megaohms) and will be much smaller when irradiated. When calculating the relative response of the resistor, its conductance should be applied!

The response time of the resistor is rather high, this is why it is applied in such situations where the fast response is not needed or even undesirable, for example as a nightfall switch.

3.3.2 Photodiode

The photodiode is applied in the solar cell (photovoltaic cell) mode since the planned measurement does not require high accuracy. The solar cell mode means the 4th quadrant in the V-I plot (Figure 10), by applying a properly chosen (small) load the photodiode works as a current generator, its current is proportional to the incident light power. Since the input resistance of a current meter is small (max 1k Ω), it can be used to measure the light induced current of the diode.

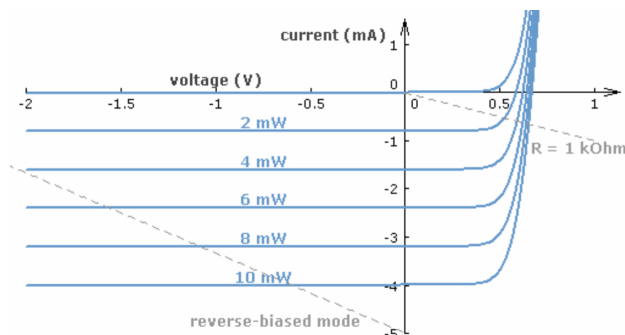


Figure 10: V-I plot of a photodiode

The Zener-diodes shown in Figure 11 are applied to safeguard the photodiode against overvoltage.

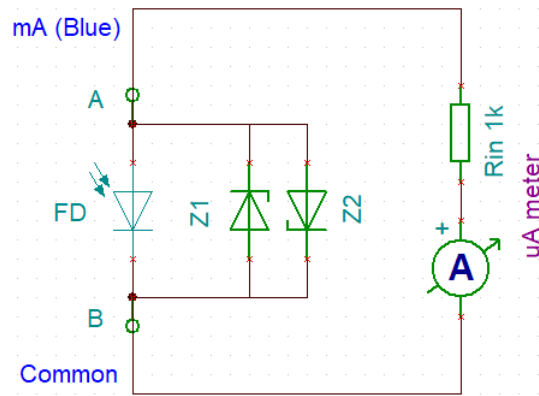


Figure 11: Test setup for photodiode characterization

3.3.3 Phototransistor

The light absorbed in the base of a phototransistor generates the base current. The collector current is controlled by this base current according to $I_C = \beta \cdot I_B$ when there is a proper power supply applied between collector and emitter. To measure the collector current of the phototransistor the milliamp meter has to be connected in between the power supply (+15V) and the collector point (Figure 12). To measure the output characteristic, adjust the power supply voltage (as it will be nearly equal to the collector-emitter voltage).

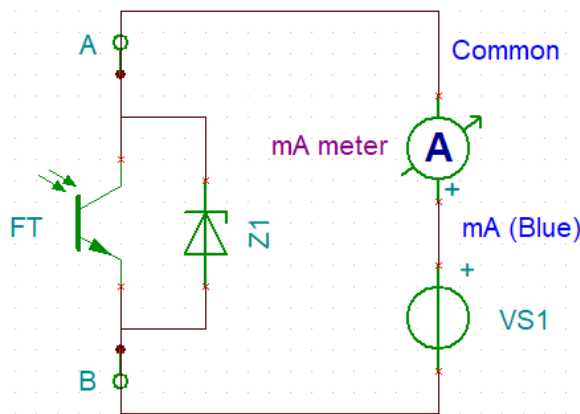


Figure 12: Test setup for phototransistor characterization

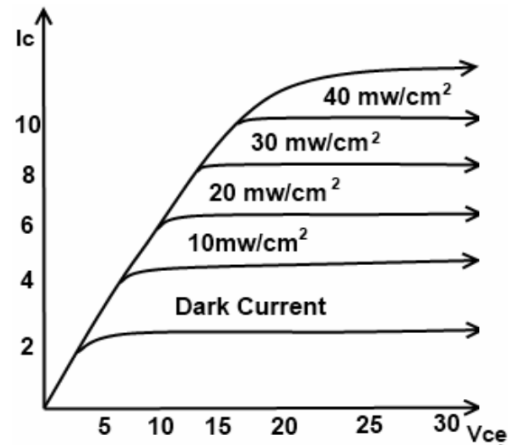


Figure 13: The $V_{CE} - I_C$ characteristic at a fixed wavelength (example)

4 Measurement tasks

4.1 Obtaining the spectral intensity of the filament lamp

Using the spectrophotometer AvaSpec-ULS2084 and the program "AvaSoft 7.5 for USB" the spectrum of the filament lamp should be measured and documented.

4.1.1 The turn-able sample holder has to be set into its "1" position. In this case the spectrophotometer can see directly the light coming from the prism through the slot.

4.1.2 In the Avasoft program choose the "I" (Irradiance) mode.

4.1.3 Save the "Dark Current" values.

4.1.4 The maximum light intensity has to be set not to overcome $1100 \mu W/cm^2/nm$ on the AvaSoft. To ensure this you must scan through the investigated wavelength region (450 - 1000 nm) and set the size of the optical slot.

4.1.5 Set the wavelength from 450 nm to 1000 nm in 50 nm steps. Measure and record the maximum intensity (A_{λ_0}), the lower (λ_l) and upper limit wavelengths (λ_u) at each measurement point (λ_0).

4.1.6 Create the $A_{\lambda_0} - \lambda_0$ and $\lambda_{FWHM} - \lambda_0$ graphs.

4.2 Obtaining the relative spectral sensitivity of the photodetectors

In this task a photoresistor (Tesla WK65037), a photodiode (BPW21) and a phototransistor (BPW43) will be characterized. Measure each sensor's electrical properties at each wavelength.

- 4.2.1 Set up the electrical measurements as described in Chapter 3.3 (ie. connect power supply and multimeters to the sensors).**
- 4.2.2 Measure the studied electrical parameter (resistance for photoresistor, current for photodiode and collector current for phototransistor) without the illumination.**
- 4.2.3 Set the sample holder into position "1". Turn on the lamp.**
- 4.2.4 Set the light source to produce a given intensity signal (light) at the desired wavelength, e.g. $900 \mu\text{W}/\text{cm}^2/\text{nm}$ at a chosen wavelength between 450 nm and 1000 nm.**
- 4.2.5 Record the applied light's parameters, (the maximum intensity (A_{λ_0}), the lower (λ_l) and upper limit wavelengths (λ_u) at each measurement point (λ_0)).**
- 4.2.6 Set the sample holder into the position "2" for photoresistor, into the position "3" for photodiode, or into the position "4" for phototransistor.**
- 4.2.7 Record the studied electrical parameter.**
- 4.2.8 Repeat steps from 4.2.3 to 4.2.8 to get the electrical parameter – wavelength function in the whole wavelength range. (450 nm – 1000 nm with 50nm steps.)**
- 4.2.9 Calculate and draw the relative change of measured parameter as a function of applied light wavelength, i.e., the relative spectral sensitivity curve of the detector. Because the lamp light's intensity is different at each wavelength, you will need to do correction calculations to get the sensor sensitivities. Find the wavelength where the light amplitude is maximal. This will be the reference. At all other wavelengths, calculate the ratio of the light amplitude to the reference. Use this ratio to normalize the sensors' output data, ie. to remove the effect of the non-uniform light spectrum and measure only the sensors' spectral response.**

4.3 Output characteristics of the phototransistor

Setting the illumination wavelength to 850nm, the V_{CE} - I_C illumination intensity chart has to be measured at least for three different intensity value.

4.3.1 Set up the electrical measurement as described in Chapter 3.3.

4.3.2 Set the sample holder into position “1”.

4.3.3 Set the light source to produce a given intensity signal (light) at the desired wavelength, e.g., $900 \mu\text{W}/\text{cm}^2/\text{nm}$ at 850 nm.

4.3.4 Record the applied light's parameters, (the maximum intensity ($A_{\lambda 0}$), the lower (λ_l) and upper limit wavelengths (λ_u) at each measurement points (λ_0)).

4.3.5 Set the sample holder into the position “4” for phototransistor.

4.3.6 Measure the I_C , setting the voltage of the power supply (V_{S1}) between +15 V and 0 V at 1V steps to get V_{CE} - I_C curve at the given illuminance value.

4.3.7 Perform the previous steps with another light intensity, e.g., $800 \mu\text{W}/\text{cm}^2/\text{nm}$ and later $700 \mu\text{W}/\text{cm}^2/\text{nm}$.

4.3.8 Draw the V_{CE} — I_C charts for each illumination (in same graph, with proper legend).

4.3.9 Calculate the output characteristic's dynamic resistance at $V_{CE} = 8 \text{ V}$ and at each of the different illuminance intensities!

5 Equipment to be used

1. Spektromom 203
2. AvaSpec-ULS2084 type spectrophotometer (built-in into the Spektromom's enclosure)
3. Triple power supply (Hameg HM8040), $\pm 15V$ and $+5V$
4. Digital multimeter (Hameg HM8012)

6 Review questions

5. What is the relative spectral sensitivity of the detector?
6. What processes are taking place during the light-surface interaction?
7. How is the desired wavelength of light separated?
8. What are the characteristic parameters of the transfer function?
9. Sketch the V-I luminance characteristics of a photodiode!
10. Sketch the V_{CE} - I_C characteristics of a phototransistor!
11. In what way is the collector current of a phototransistor controlled?
12. Which electrical parameter will change in the case of the different detectors?
13. How to calculate the relative spectral sensitivity value?
14. Sketch a simple light intensity measuring circuit applying a photodiode!
15. What circuit would be used as a nightfall switch applying a photoresistor?

7 Measurement protocol

To prepare the report Excel or Numbers is strongly recommended.

Each measuring group is asked to give in one report. The report should be submitted in PDF format and not more than 5 pages, at latest two weeks after the measurement performed.

The file name has to contain the surname of the authors and the short title of the exercise, e.g., "maxwell_newton_photodetector.pdf"

The report has to contain:

- The title of the measurement
- The names of the colleagues performing the task
- The date and location of the measurement
- A declaration stating that the task is performed by the enumerated colleagues
- The list of applied equipment with types and identification numbers
- The tabulated list of the measured values (if it is feasible), the calculated values, and the requested graphs
- Any theoretical based calculations or homework solutions
- Short discussion of the results for each measurement task, comparison of theoretical expectations, calculations and measurement results

PLEASE do not copy previous protocols. Identical protocols will be refused.