Photoelectric effect

Manual

1998 Marcus Dülk
rev. 2009 Michelle Gruner & Manuel Bischof
rev. 2023 Martina Kolbl, Mattia Morretti, Philipp Fabritius

ETH zürich

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Contents

1 Abstract

With the help of the photoelectric effect, the material specific work function of the illuminated potassium cathode of a photo cell and the ratio of the Planck constant h and elementary charge of the electron e can be determined. By using a modulated signal with a set optimal frequency, the photo current of the cathode can be measured for different optical light frequencies in the visible spectral range. The maximal stopping voltage, i.e. the maximal voltage where no more current can be measured, gets determined by varying the voltage difference between the anode and the cathode, called photo cell bias. By plotting these stopping voltages as a function of the frequencies, the ratio $\frac{h}{e}$ as well as the work function can be obtained.

2 Introduction

If a metallic surface is exposed to an electromagnetic wave with a given frequency, its energy gets absorbed by the electrons and they get expelled. This effect, called the photoelectric effect, is the subject of this experiment.

The photoelectric effect is one of the fundamental experiments which stressed the need for a new physical theory, the quantum physics, in the early 20th century. Many experimental observations could not be explained with the classical theories anymore, such as electrodynamics and the wavelike nature of the light. In 1888, Heinrich Hertz and his assistant Wilhelm Hallwachs discovered that electrons escape from metallic surfaces if they were irradiated by light with frequency above a certain threshold. In 1905, Albert Einstein explained these experiments by creating the light quantum hypothesis. Seventeen years later he was honoured by the Nobel Prize for his theory. It states that light can behave like a particle as well as a wave, known as wave-particle dualism, depending on the experiment. This paradox could not be explained until quantum mechanical theories were posted.

3 Theoretical background

In this chapter the physical background, which is relevant for the understanding of the photoelectric effect and the experimental setup, is summarized. It is assumed that some basic concepts of solid state physics are known (c.f. section B).

3.1 LEDs and their spectral width

LEDs, short for light emitting diodes, are omnipresent in our every day life. From the traffic lights you probably walked by today, to the display you're reading this manual on, nearly every electronic device has LEDs build in to it. One of the reasons why this way of using the recombination of electrons and holes in semiconductors gained a lot of popularity is the fact, that their spectral width is small enough to represent a single colour.

However a LED still has spectral width ranging from 20 nm to 50 nm, which is relatively big compared to the spectral width of a typical LASER covering only the range of a couple of nm. Without going into detail, this spectral width arises due to smeared out energy bands within semiconductors for the p-n junction, for further information we refer to the reference section of this manual or to any introductory solid state physics book. A qualitative comparison of the relation between relative intensity and wavelength for a LED and a LASER can be seen in fig.1.

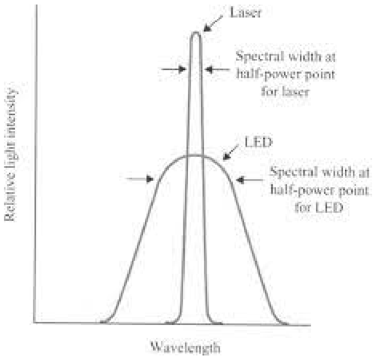

Figure 1: Qualitative sketch of the spectral widths of an arbitrary LED and LASER.

3.2 Diffraction grating

In order to determine the wavelength of the LEDs we can use a diffraction grating, which will decompose a non-monochromatic beam into it's constituents. The path difference between the beams emitted from each groove leads to the formation of a periodic pattern due to constructive interference happening at $\Delta s = n\lambda$, where n denotes the order of maxima/minima. Each maxima of intensity due to this is spaced by an angle α which we can measure to calculate the wavelength using $\sin\alpha = g\Delta s$, where g is the grating constant.

3.3 The photoelectric effect

Photons, which are energetic enough, can cause an emission of electrons out of a metallic lattice. Usually, the energy of the visible light is not sufficient to expel the electrons from the metal because they have to bring up a material specific work function W. Therefore, to observe the photoelectric effect, ultraviolet light is used. Alkali metals are an exception since the energy of visible light is sufficient to overcome the work function. If the metallic plate is negatively charged, electrons are released into the continuum. The difference between the photon's energy and the work function gives the kinetic energy of the free electrons, as given by Einstein's equation:

$$E_{kin} = \frac{1}{2}m_e v_e^2 = \hbar\omega - W \tag{1}$$

This kinetic energy can be measured by creating a reverse potential between the metal which emits the electrons, called cathode, and a positive electrode, the anode, which collects them, as seen in figure 2.

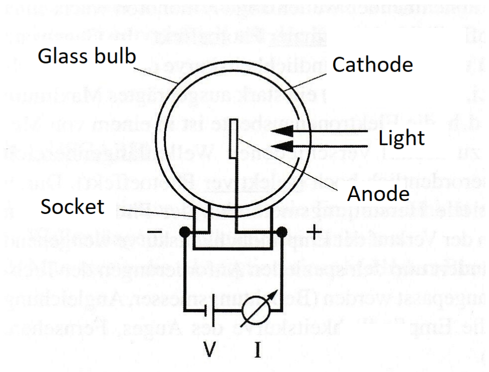

Figure 2: Photo cell with a surrounding cathode, where electrons get emitted, and an anode in the center where electrons get collected

For electrons expelled by photons of a specific optical frequency $\nu = \frac{\omega}{2\pi}$, the maximal kinetic energy can be determined by a maximum voltage $U_{max}(\nu)$, called stopping voltage, where the following relation is valid:

$$e \cdot U_{max}(\nu) = \frac{1}{2} m_e v_{max}^2 = h\nu - W \tag{2}$$

When a potential function $\phi = \frac{W}{e}$ is defined, equation 2 can be rewritten as:

$$U_{max}(\nu) = \frac{h}{e}\nu - \phi \tag{3}$$

By plotting the threshold stopping voltage $U_{max,stop}$ as a function of the frequency ν, a straight line with a slope $\frac{h}{e}$ results. The y-axis intercept represents the metal specific work function. This line was named after R.A. Millikan (1916) as the “Millikan’s curve”.

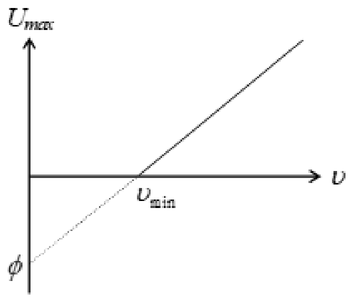

Figure 3: Millikan‘s curve a.k.a maximum stopping voltage U_{max} against frequency ν.

Photoelectrons can only be expelled if the minimum threshold frequency of the light is exceeded. The number of emitted electrons is linearly proportional to the intensity of the light. Their kinetic energy only depends on the frequency. The intensity determines the number of emitted electrons, but does not influence the kinetic energy. This behaviour contradicts classical electrodynamics where theoretically light of every frequency should expel photoelectrons because the energy of a wave is the product of the time and the intensity. The latter is proportional to the square of the waves amplitude. As a result, light of every frequency could free electrons if the metal plate were illuminated long enough. Quantum mechanical calculations show that energy can only be transferred in discrete quanta of $\hbar\omega$.

3.4 Work function and contact potential

The work function represents the energy that is needed to raise an electron from a solid state body to the so called vacuum level. This level is normally reached a few hundred Angström away from the surface. However, the vacuum level is a relative statement because surface effects play a significant role for the work function.

If an electron leaves the lattice, it has to transcend a field which gets created by the surface charges. Consequently, the minimum energy outside the lattice is not zero, as it would be for an infinite crystal, but equals a positive energy. Therefore, the effective work function is increased.

If the charges of two metals can be freely exchanged, it is said that they get in contact with each other. After some time, a thermodynamic equilibrium is reached. This is achieved via charge transfer such as electrons and holes. As a consequence, the potentials ϕ and ϕ' of the metallic surfaces get slightly altered, as seen in figure 5. However, the most important effect is that a contact voltage $e\Delta\phi$ is created at the surface of the metal due to the difference in work functions W and W':

$$e \cdot \Delta\phi = e(\phi - \phi') = W - W' = W_s - W_s' \tag{4}$$

As a result, the minimum energies of electrons differ outside of the lattice, i.e. the vacuum level of the metals is not at the same height. In other words, despite the fact that the voltage between the metals is zero, there is an electric field between the surfaces for the electrons in the “vacuum“.

To visualize this effect, assume a quantum well. As one can see in figure 5, two metals with different work functions stay in contact. Each metal represents a quantum well that the electrons need to overcome in order to leave the metallic material. The contact leads to a thermodynamic equilibrium. However, the upper edges of the quantum well have different heights. Therefore, it is possible that an electron can acquire the work function W' and leave the metal, but cannot enter the metal with the higher work function W. In this case, no current is measurable.

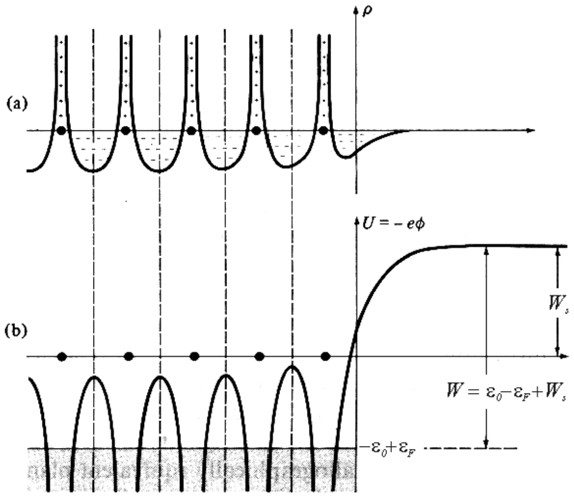

Figure 4: The shape of the electrical charge density ρ near the surface of the crystal (a). The charge density of the neighbouring cells gets deformed. Moreover, a negative charge density layer on the surface is built up (on the right-hand side of the y-axis). Electrons, which leave the lattice, have to transcend the field of this layer and do work W_s. The work function becomes $W = \epsilon_0 - \epsilon_F + W_S$ where ϵ_0 is a constant, which usually gets emitted, and F is the Fermi energy. The lowest energy level outside of the lattice is not zero but W_S, which depends on the orientation of the surface.

If one applies a voltage $e\Delta\phi$ between the metals, the upper edges of the quantum wells reach the same energy. Consequently, every electron that escapes from one metal can enter the other one and a current is measured.

3.5 Characteristic of a photo cell

The characteristic curve, shown in figure 6, describes the dependence of the photo current on the voltage difference between the electrodes, also known as current-voltage characteristic. It depends heavily on the geometry of the electrodes but extrinsic effects play an important role as well.

Assuming that the cathode and anode are made of the same material, two extreme examples of the current-voltage characteristic are illustrated in figure 6 for $T = 0\,\mathrm{K}$. Moreover, negative effects such as a reverse current are neglected.

In the upper chart, a point-shaped cathode emits photo electrons. For any exit angle, almost all the electrons emitted from the cathode reach the anode and therefore a photo current is detected. The current is already saturated for a zero photo cell bias, meaning voltage $U = 0\,\mathrm{V}$ between the anode and cathode. However, if there is a negative bias between the cathode and the anode, electrons, which occupied an energy level below the

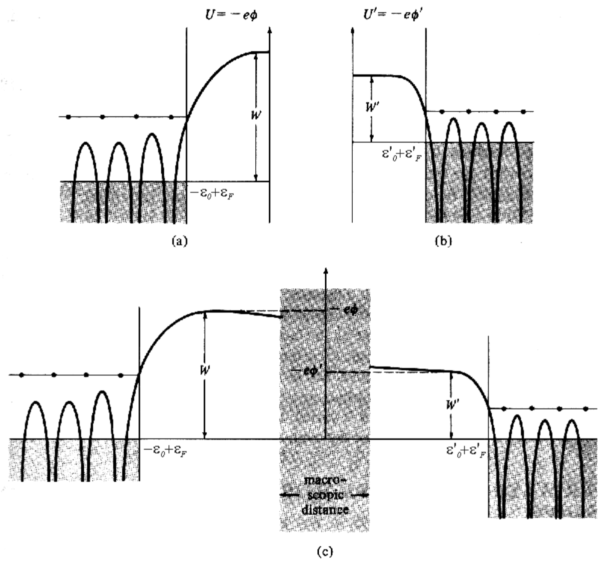

Figure 5: Work potential U for a metal with work function W and Fermi energy ϵ_F (a). Likewise for another metal with a lower work function (b). In figure (c) the metals stay in contact, the voltage is zero volts (Fermi levels equal). Due to the charge transfer, the surface charge slightly changed. As a result, electrons outside of the metals are affected by a potential gradient caused by the different work functions.

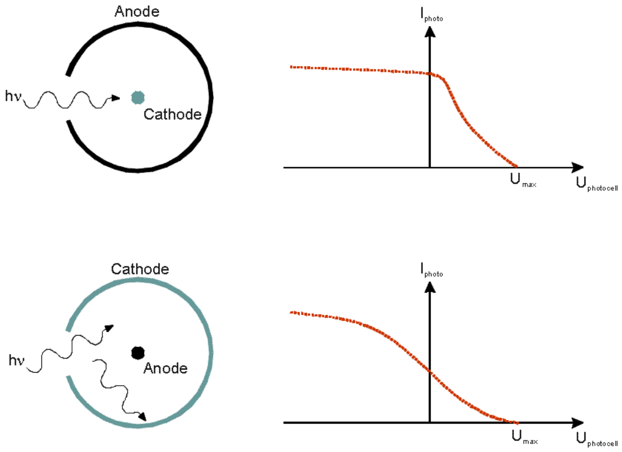

Figure 6: Schematic illustration of the characteristic line of photo cells with two different geometries for $T = 0\,\mathrm{K}$. For a positive voltage of the photo cell, the anode is negative compared to the cathode. This is the range of the stopping voltage. On the contrary, if the voltage of the photo cell is negative, the voltage is in the range of the suction power.

Fermi energy before the interaction with a photon, do not reach the anode anymore. Consequently, the photo current decreases.

In the lower part of figure 6, the anode is point-shaped in the centre of the cathode.

Electrons from the cathode barely reach the anode even if they have sufficient energy. Therefore, the current saturates only for high voltages.

3.5.1 Ideal Characteristic for Plane-Parallel Electrodes

By means of an ideal case of plan-parallel electrodes, it can be shown that for $T = 0\,\mathrm{K}$, the current-voltage characteristic is a parabola with a minimum at $U = U_{max}$, which is the maximum stopping voltage.

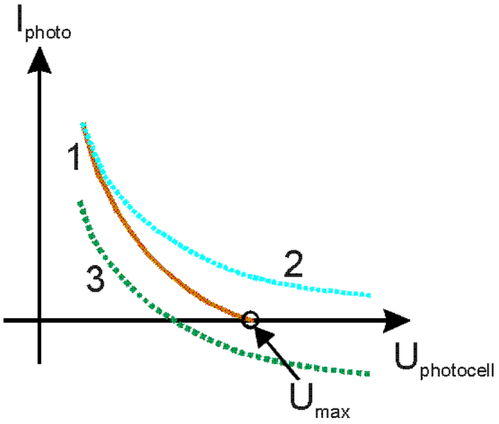

Figure 7: Schematic illustration of the theoretical characteristic of a photo cell with plane-parallel plates for $T = 0\,\mathrm{K}$ (1), for $T > 0\,\mathrm{K}$ (2) and if there is an additional reverse current (3).

In this experiment it is difficult to read the maximal stopping voltage directly from the current-voltage characteristic. This has to do with the following reasons: Firstly, the photo current asymptotically approaches zero for room temperature due to thermal excitation of electrons above the Fermi energy. Secondly, impurities on the electrodes can prevent the absorption or emission of electrons which affects the photo current. Especially for alkali metals, cathode material accumulates on the anode which leads to a measurable reverse current, i.e. a measured negative current, as seen in figure 7. It should also be mentioned that the current-voltage characteristic above is just a simple approximation.

3.6 Lock-in amplifier

Let's consider an experiment where we want to measure a relatively small signal covered by a relatively big noise. If one would use a typical amplifier the signal would be amplified, but so would be the noise.

By using a sinusoidal reference signal $R(t)$ and modulating the measured signal $S(t)$ sinusoidally with the same frequency and no phase shift, one can take advantage of the orthogonality of such functions with respect to the dot product $\langle f_1, f_2 \rangle = \int_\tau f_1(t) \cdot f_2(t) dt$, where $\tau \gg T$ for the period T of the two signals $S(t)$ and $R(t)$. We can extend this

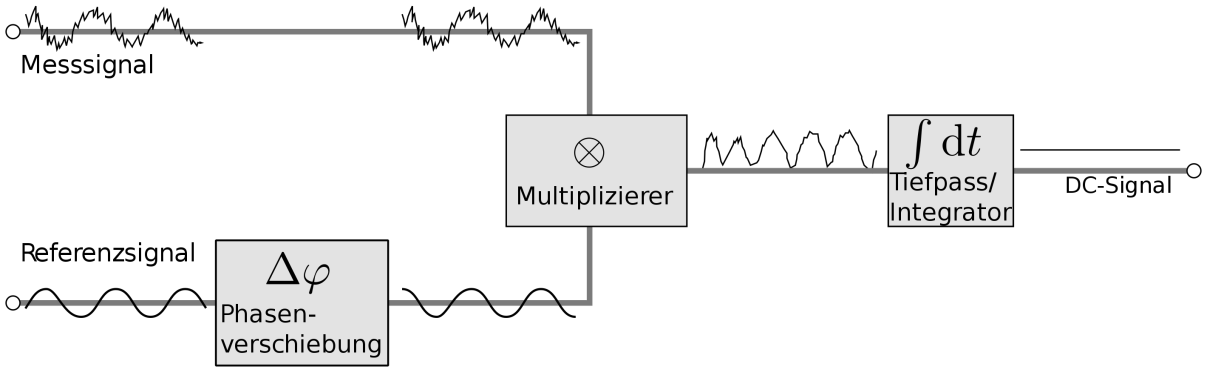

Figure 8: Principle of a simple lock in amplifier. Image taken from *Wikipedia - Lock-in amplifier*

discussion to a more general case, including a phase shift, by adding a factor of $\cos \Delta\varphi$, where $\Delta\varphi = \varphi_{ref} - \varphi_{sig}$. Thus we get that $U_{out} = (H_{lpf})^{\circ}(S(t)R(t) \circ \cos \Delta\varphi)$, H_{lpf} being the action of the low pass filter on the previous signal. Such filters, consisting of a resistor R and a capacitor with capacitance C, act as passive integrator with time-constant $\tau = RC$. The end result of this process will be a DC signal which can be again amplified, if necessary. A simple sketch of the principle can be seen in figure 8.

In this experiment the lock-in amplifier uses a square signal instead of sinusoidal one, since sinusoidal signals are hard to produces, especially for small frequencies. The output of the lock-in will still be the same. The signal is shown in figure 9a, the reference is a square wave with amplitude 1.

The product of reference signal and input signal is then shown in figure 9b. The final, averaged signal is shown in figure 9c, yielding a DC signal of 0.5.

4 Exercises

This chapter contains some questions in order to provide a better understanding of the experiment. It is advised to answer the questions prior to the start of the experimental work. Help can be found in the appendix.

4.1 Questions: Lock-in amplifier

1. The photo cell delivers a very low voltage. After an amplification stage the typical expected value is $U_0 = 250\,\mathrm{nV}$. However, the signal to noise ratio (SNR)[1] is $-50\,\mathrm{dB}$. Calculate the amplitude of the noise at the output of the photo cell.

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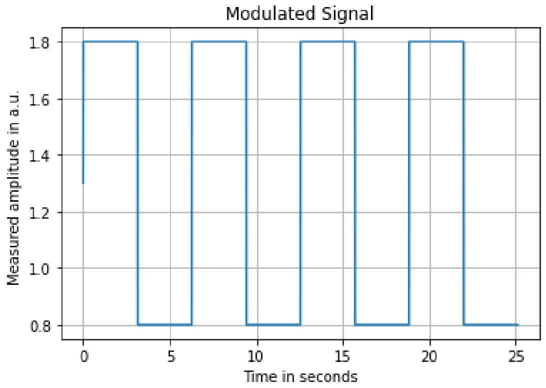
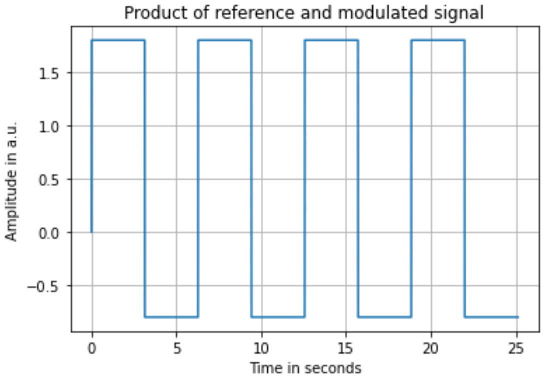
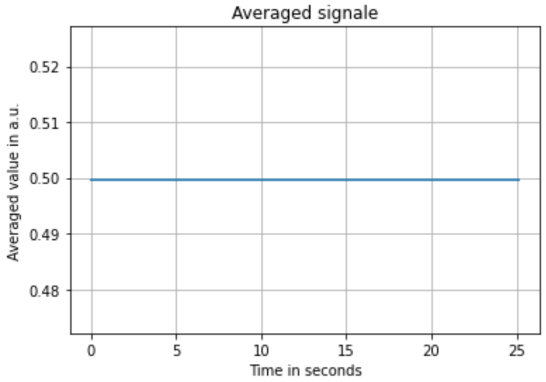
[1] The signal-to-noise ratio is defined by $\mathrm{SNR} = 10 \cdot \log\left(\frac{P_{signal}}{P_{noise}}\right)$. The unit is decibel (dB). For $0\,\mathrm{dB}$, the signal power is bigger than the noise power.



(a) Signal modulated with a square wave.



(b) Product of the reference signal with the modulated signal.



(c) Average value yielding the scaling factor.

2. In order to be able to measure a small output voltage, the signal gets modulated. The signal's amplitude is periodically modulated at a known frequency $f_{mod} = 150\,\mathrm{kHz}$. In the case of an analog lock-in amplifier the resulting modulated signal U_s has the form of a sinusoidal function:

$$U_s = U_0 \cdot \sin(2\pi f_{mod} \cdot t)$$

   where U_0 is the amplitude of the signal to be measured. Show that the product of U_s by a reference signal $U_{ref} = \sin(2\pi f_{ref} \cdot t + \phi)$ is equal to the sum of two sinusoidal functions oscillating at two different frequencies f_{low} and f_{high}.

3. Show that for $f_{mod} = f_{ref}$ the DC part is proportional to the amplitude of U_0. Is this the case for other frequencies as well?

4. What could happen if a periodic noise overlaps the modulated signal? Could you think of a periodic noise that could interfere with the signal that has to be measured?

5. Given an initial transimpedance gain of $1\,\mathrm{V/nA}$ inside the photocell what is the

overall gain of the system?

4.2 Questions: Photoelectric Effect

In this experiment, a potassium cathode and a platinum-rhodium alloy anode are used. In the literature we find a work function of 2.2 eV for potassium and 5.6 eV for platinum.

1. What maximal wavelength and threshold frequency does a photon need to free electrons from a platinum or potassium electrode?
2. Which influence does measuring at room temperature have on your results?
3. What are the energy ranges of the photons in your experiment, where red, yellow, green and blue LEDs are used?
4. Determine the expected threshold stopping voltage U_{max}.
5. Let us consider that the anode and cathode are made of the same material. Which are the advantages and disadvantages?
6. Take a closer look at the spectral response curve in the data sheet of the photocell. Upon looking at it, what are your expectations in terms of relative behaviour for the different LEDs?

5 Experimental setup

The experimental setup consists of an optical part and an electronic part. The optical part can be seen in figure 10.

It consists of lenses, gratings, LED lamps and apertures, which can be mounted and moved on an optical bench. At the middle of the bench is a prism, which deflects the light from the LED lamp. The bench segment between the light source and the prism can be rotated with respect to the other segment. The central apparatus is the photo cell, the output of which is a voltage signal. Photons with sufficient energy expel electrons from the potassium cathode. The difference between the energy of the photons and the work function gives the kinetic energy of the electrons which move towards the anode and make a contribution to the photo current. If one biases the anode negatively with respect to the cathode, the electrons have to overcome the counter electric field which leads to a decrease of the photo current. If one applies the stopping voltage, which is different for different wavelengths of the incident light, no more electrons will reach the anode leading to a decrease of the photo current. The photo cell is connected to a reverse voltage generator, which generates this photo cell bias. It can be varied from −3 V to 3 V with a built-in potentiometer. The stopping voltage is used to determine the work function of the cathode material.

The photo current emitted from the cathode lies in the range of nano- to picoampère and is overlaid by heavy noise due to scattered light which also expels electrons and produces a

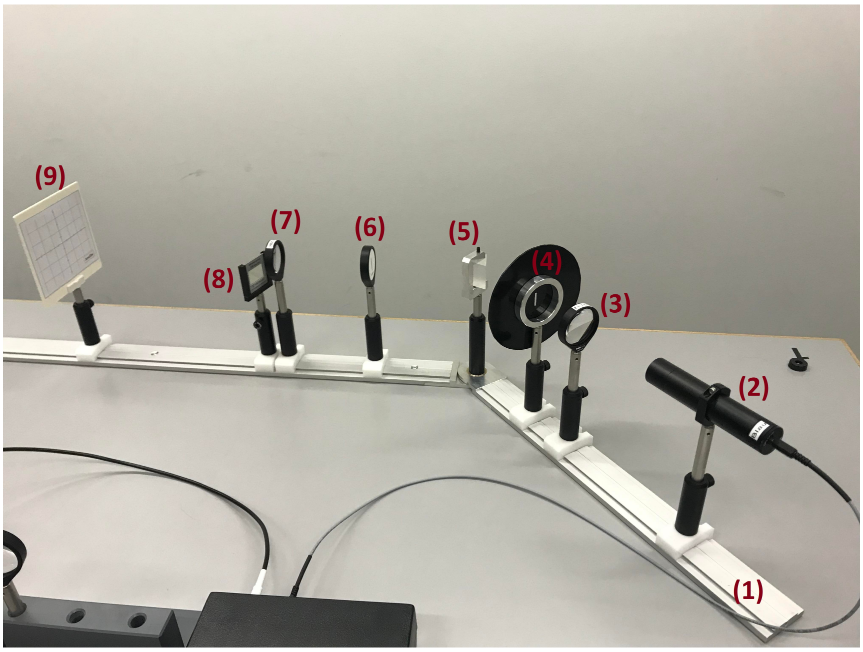


Figure 10: The optical setup of the experiment consisting of a bench (1), a LED lamp(2), two lenses (3) and (7), a prism (5), two apertures (4) and (6), a diffraction grating (8) and a white screen with a scaling grid (9).

photo current. Furthermore, existing electronical noise such as the internal photo cell noise will interfere with the measurement. To measure the actual voltage signal, the output of the photo cell gets modulated at a fixed frequency. In the experiment this can be done by connecting the LED to a signal generator, that generates a rectangular signal, which then switches the LED on and off periodically with the chosen frequency.

The output voltage at the photocell is connected to a controlled inverter. This one modulates the signal with the rectangular reference signal at a given frequency. The output signal from the controlled inverter then gets amplified by a factor of 20 in a non-inverting amplifier and passes through a low-pass filter before it is displayed on a multimeter. The low pass filter is used to filter out signals at high frequencies, so that only the chosen low frequencies of the actual signal have an influence on the displayed final voltage. The electronic setup is shown in figure 11.

Because a rectangular signal is used, the final output voltage displayed on the multimeter represents only half of the maximum output voltage. Therefore, considering the previous amplification of the signal by a factor of 20, the output voltage measured with the multimeter is 10 times bigger than the actual final output. This has to be considered in the analysis.

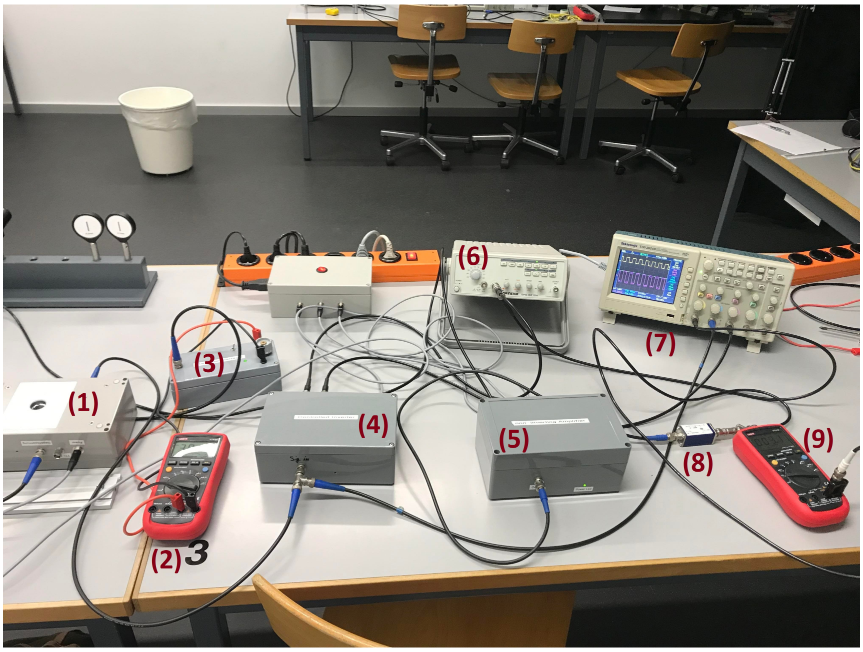


Figure 11: The electronic setup of the experiment, consisting of connecting cables, a photo cell (1), a multimeter to measure the bias (2), a potentiometer to vary the photo cell bias (3), a controlled inverter (4), a non-inverting amplifier (5), a signal generator (6), an oscilloscope (7), a low pass filter (8) and a multimeter to measure the output signal (9).

5.1 Photo Cell

The photo cell is an empty glass bulb whose inner wall is evaporated by potassium on one side. A ring-shaped platinum-rhodium alloy anode is positioned around an almost point-shaped potassium cathode rod. The incoming light illuminates the back wall of the photo cell where the potassium is evaporated. Providing that the aperture of the photo cell is small enough, the anode is not illuminated directly by the incoming light. Figure 2 shows a similar photo cell.

Potassium dust is deposited on the walls of the glass plunger as well as on the platinum electrode because potassium is neither chemically nor mechanically very stable. This has two important consequences:

1. There are photo electrons which are expelled from the potassium dust on the platinum wire and move towards the potassium electrode. Consequently, a measurable reverse current gets produced.
2. The photo electrons from the potassium cathode do not enter the platinum anode directly but the deposited potassium. Therefore, they do not have to overcome the additional potential due to the higher work function of platinum, but see a quasi-potassium electrode. Consequently, they do not have to do work to enter the anode. Hence, the photo electrode has not to be biased additionally to measure a photo

current.

Inside the photo cell is a high amplifying current-to-voltage converter, which has a one volt per nano ampere conversion, meaning if a one nano ampere photocurrent is detected, the output signal on the photo cell is a one volt voltage.

6 Experimental method

6.1 Adjustment of the optics

On one end of the bench, the light source (LED), a collimating lens with focal length 100 mm and then a 0.4 cm wide aperture have to be mounted. We use collimating lenses because the light beams from the LED are not collimated, which results in a lot of intensity and a less precise measurement.

On the other segment of the bench, another 0.4 mm aperture, a second lens of focal length 100 mm and a grating with 140 slits per millimeter are mounted after the prism. The lens should be positioned at a distance which corresponds approximately to its focal length from the second aperture.

At the far end of the bench, the photo cell is positioned. Since the main measurement tool is the a photo cell, which cannot be mounted on the optical bench at any chosen height, the first step is to adjust the height of all the optical parts on the bench to the height of the photo cell. Then the photo cell gets replaced by a white screen with a scaling grid, where the interference pattern of the light can be observed. Because even LED lights are not completely monochromatic, they have a spectrum of different wavelengths which can be seen when the light hits the second 0.4 mm aperture, where the image has to be sharp. To see a sharp image, the first lens and aperture have to be adjusted, where the lens has to be approximately a focal length from the LED.

Adjust the prism/the angle between the two segments of the bench, so that the light passes through the prism at the minimum deflection angle. This is the angle at which the light's direction of movement reverses when rotating the prism. By rotating the prism or the first bench segment slowly around its axis and following the refracted beam, which rotates in the same direction, the minimum deflection angle can be found at the position when the rotational direction of the beam is reversed.

6.2 Wavelength measurement

The firs step of the measurement is determining the wavelengths of the different LED lights that are used: blue, green, yellow and red. The positions of the second lens, the grating and the screen have to be adjusted so that the distance between the first and zeroth order of interference maxima can be read from the screen. Note the distance between the interference maxima and the distance between the grating and the screen.

The measured data has two different uncertainties. Firstly there is the uncertainty due to the measuring process, meaning the errors from measuring the distances. The calculation of this uncertainty is rather straight forward. In addition there is the uncertainty caused by the spectral width of the LED itself. The measured wavelength might only be the central one, but a wider spectrum hits the photocell in the upcoming experiments. Recall that the angle of refraction when passing through a prism depends on the wavelength. Using this information, the distance from the prism to the slit and the slit aperture itself one can calculate the effective angle corresponding to the range of wavelengths passing through the slit and therefore the linewidth. In order to determine the uncertainty of the measured wavelength the range of angles of refraction from the prism and the width of the selection slit has to be used.

6.3 Measuring the stopping voltage

In this part, the screen gets replaced by the photo cell and the grating is taken out. Make sure that the CMOS ouput of the waveform generator is connected to the LED driver and the lock-in amplifier. Before the actual measurement of the stopping voltage, for one LED, take some photo current measurements, i.e. the output voltage against the photo cell bias, for different modulation frequencies 10 Hz, 100 Hz and 1000 Hz, in order to see how different frequencies affect the output signal. For the actual measurement, the frequency of the modulation should be on the order of 100 Hz.

In order to analyse the importance of the lock-in amplifier, we first want to measure the stopping voltage without it for one LED of choice. Thus the photo cell output signal, measured with the oscilloscope, is noted while the photo cell bias is changed from -3 V to 3 V in steps of 0.1 V. Since the original signal would be very small, we still want to use a normal amplifier, the setup should look like 11 but without the signal generator (6), the low pass filter (8) and the lock-in amplifier (4). Furthermore the TTL option of the LED can be turned off. After completion of the first measurement, the full setup shown in figure 11 can be recreated and the measurement can be repeated with all LEDs while using the lock-in amplifier. What difference can you spot and does it correspond to what you expected? After the circuit in figure 11 is built, the photo cell output signal, measured with a multi-meter, is noted while the photo cell bias is changed from -3V to 3V in steps of $0.05 - 0.1$V. The same is repeated for all four different LEDs.

6.4 Relative intensity of the LEDs

Lastly we want to measure the relative intensity of the LEDs. For doing so, one can carry on using the previous setup 11. In addition the photocell bias is set to zero.

Having done so one can take note of the output voltages for the different LEDs. Using the spectral response curve of the photocell, giving the relative intensity as a function of the wavelength, and the relative output voltage (green has intensity 1) the relative intensity of the LEDs can be calculated.

What impact would a different relation have had on the results of previous experiments?

7 Data analysis

7.1 Stopping voltage and Millikan's curve

Determine for each color of the LED the maximal stopping voltage U_{max} and the corresponding uncertainty. The stopping voltages can be plotted against the measured frequency $\nu = \frac{c}{\lambda}$ to obtain the Millikan's curve. The slope of the linear fit should theoretically have the value of $\frac{h}{e}$. From the y-intercept of the curve, the work function W of the potassium cathode can be determined.

For the photo cell used in this experiment, the procedure explained below has shown to be successful in determining the stopping voltage. Having measured the output voltage V_{out}, the photocurrent I_{photo} can be calculated. As mentioned before the photocell converts a current of 1 nA into a voltage of 1 V. In addition one has to account for the amplification factor used and the average value of a square signal. The determined photocurrent I_{photo}, respectively the measured output voltage from which it is calculated, approaches asymptotically a given value in the region of the stopping voltage, as can be seen in figure 12.

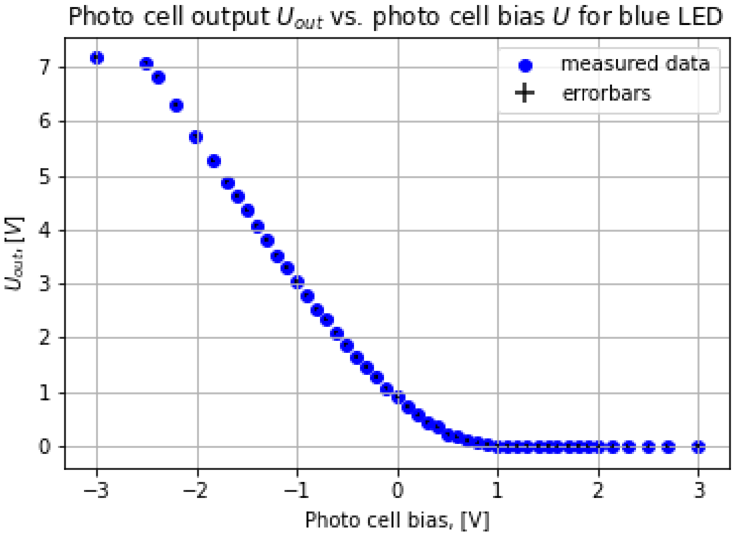


Figure 12: The output voltage of the photo cell U_{out} against the photo cell bias U for the blue LED at signal frequency 150 Hz, where the bias was measured from −3 V to 3 V. The error bars are too small to be seen.

This value is usually negative, because a reverse current is present due to material from the cathode accumulating on the anode. The reverse current $I_{reverse}$ has to be subtracted from all the measured values, so that the values asymptotically approach zero. From the corrected values the square root is taken, i.e. $\sqrt{I_{photo} - I_{reverse}}$, and the result is plotted over the photo cell bias voltage U, as can be seen in figure 13.

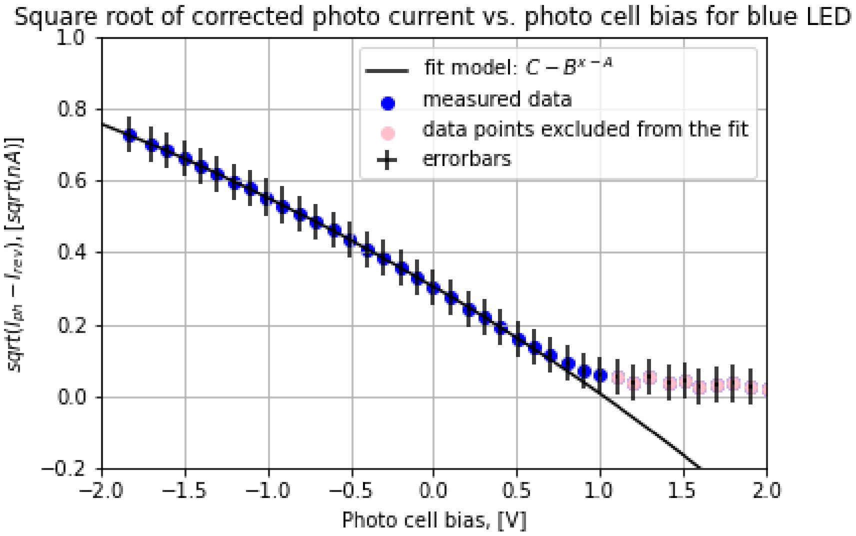


Figure 13: The root of the corrected photo current $\sqrt{I_{photo} - I_{rev}}$ against the photo cell bias with error bars for the blue LED at signal frequency 150 Hz. The data points were fitted with a function $f = C - B^{x-A}$.

As mentioned in section 3.5.1, the characteristic curve of a plane parallel photo cell is a parabola for $T = 0\,\mathrm{K}$. By plotting $\sqrt{I_{photo} - I_{reverse}}$ against the photo cell bias U, one should theoretically get a straight line. In the case of the plane parallel plates almost all the electrons, which are emitted from the cathode, reach the anode - independent of their solid angle - as long as the kinetic energy is sufficient.

However, the photo cell used in this experiment is rather point-shaped than plane parallel. The calculation of the exact shape of such a photo cell is possible, but fairly complicated. It is easier to evaluate the measuring values intuitively. By considering the plane parallel case, one can argue that every aberration from the straight line - up to a certain voltage - has to be given by the geometry of the photo cell. Therefore, one should try to fit the values $\sqrt{I_{photo} - I_{reverse}}$, non-linearly.

The power function $f = \sqrt{I_{photo} - I_{reverse}} = C - B^{(x-A)}$, where the independent variable x is the photo cell bias U and A, B, and C are parameters, yields pretty good results, as shown in figure 13 . This function can of course be expanded in a Taylor series, so that a polynomial fit of fourth or fifth degree can give similarly good results. Whichever procedure is chosen, an absolute error for the determination of the maximal stopping voltage should be specified as well as the obtained parameters of the fit.

In figure 13 an example for the evaluation of the measuring values of the blue LED is shown. One can clearly see that the calculated values $\sqrt{I_{photo} - I_{reverse}}$ lay on a common curve, whose shape is determined by the geometry of the photo cell, up to a stopping voltage, which is the x-axis intercept of the fit. The quality of the choice of the chosen power function can be investigated if one calculates the chi-square of the fit. The deviation from this curve for high stopping voltages can be attributed to effects such as the room temperature, impurities or the reverse current. The measured values that deviated too much should be ignored for the fitting of the experimental curve, as shown by the pink points in figure 13.

When all the stopping voltages for the different LEDs are determined, they can be plotted versus the respective frequencies. As shown in section 3.3, they should ideally stand on a straight line, the Millikan's curve. The slope of the Millikan's curve should have the value $\frac{h}{e}$, through the crossing with the y-axis gives the work function W can be calculated and the intersect with the x-axis gives the minimal frequency ν_{min}. Compare the theoretical values with the values gained from the experiment and discuss your results. What LEDs would you expect to trigger the photoelectric effect and what have you measured? Do you have ideas what could cause this discrepancy, elaborate.

A Appendix

A.1 Orthogonal distance regression

While evaluating the data of the Millikan's curve one might have noticed, that the values plotted have uncertainties in the x and y axis. Therefore our usual methods of calculating the uncertainties by the least squares method are not sufficient. One way of solving this issue is called orthogonal distance regression and can be implemented using the *scipy* function *scipy.ode*.

The key idea is to minimise the orthogonal distance to the data points instead of the vertical length to the fit. A simple sketch can be seen in figure14

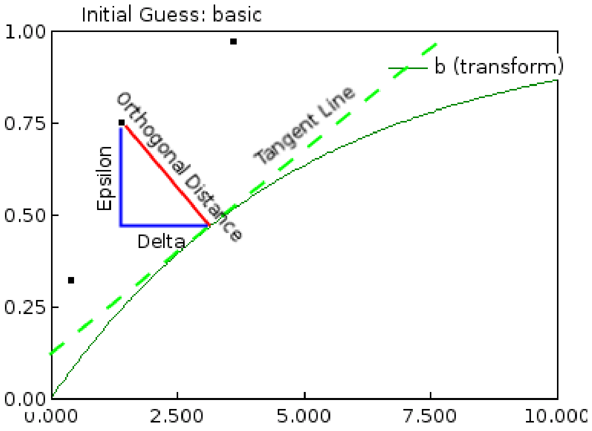


Figure 14: Qualitative figure showing the orthogonal distance.

A.2 Alignment procedure

Figures 15a-15d and 16a-16b give an overview over the optical alignment procedure.

A.3 Electronics overview

Figure 17a shows the electronic setup.

A.4 Datasheet photocell

Figure 18 and 19.

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- G.P. Harnwell, J.J. Livingood: “Experimental Atomic Physics“; McGraw-Hill, New York, 1st edition, 6th reprint, 1933.
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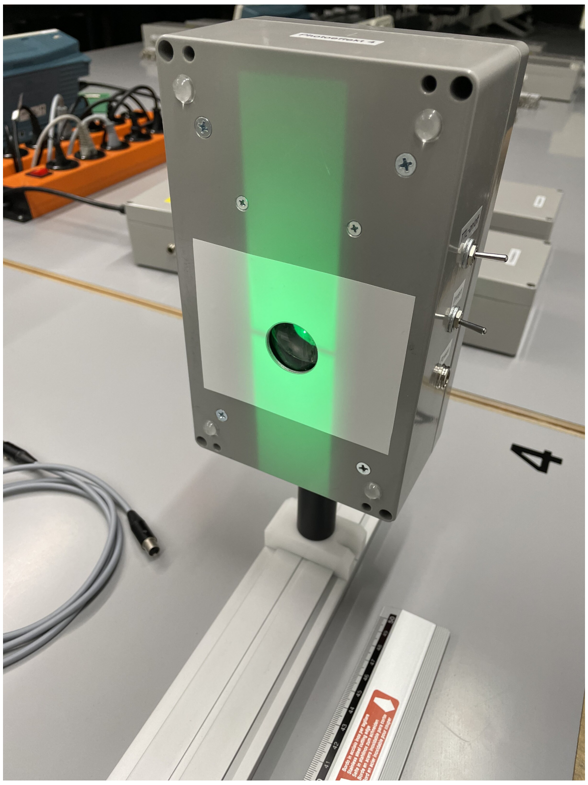
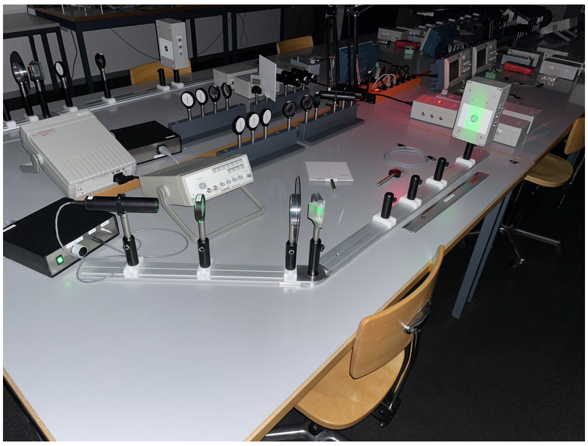
(a) Adjust the LED height to the photocell height.

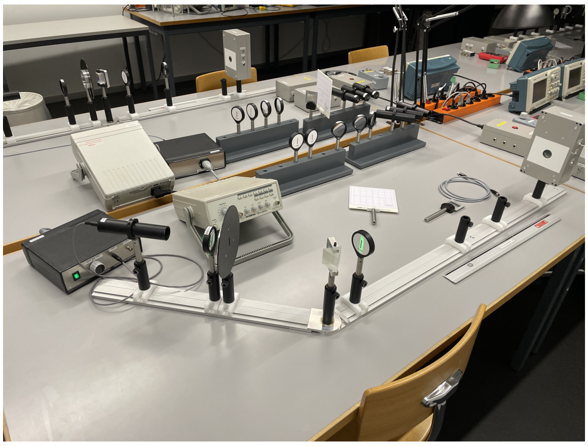
(b) Insert the first lens and collimate the LED in far field while keeping beam parallel to the table.



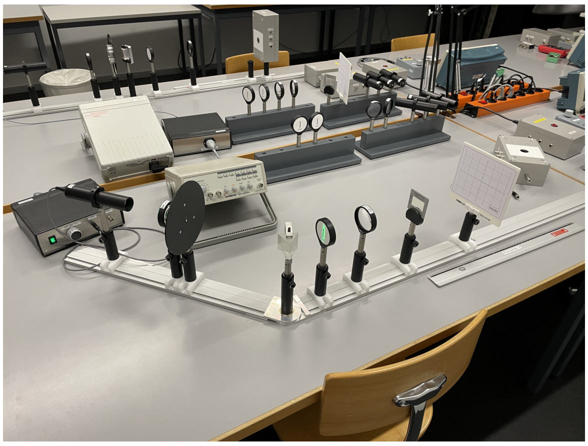
(c) Example for collimated LED, sharp shadow visible and aligned with photocell.



(d) Place the prism and align angle and height, s.t. light reaches photocell.



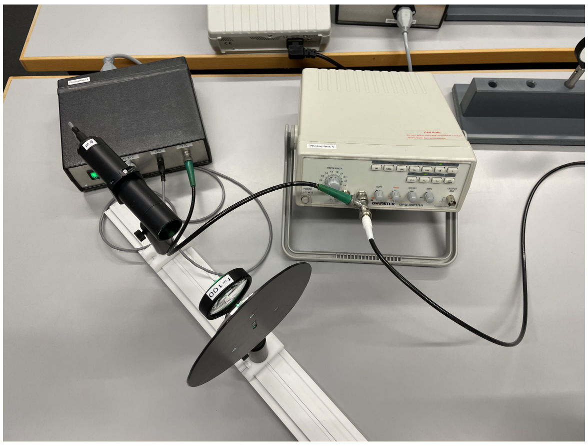
(a) Place the small slit and make sure the LED is collimated on it. The large slit is placed before the prism



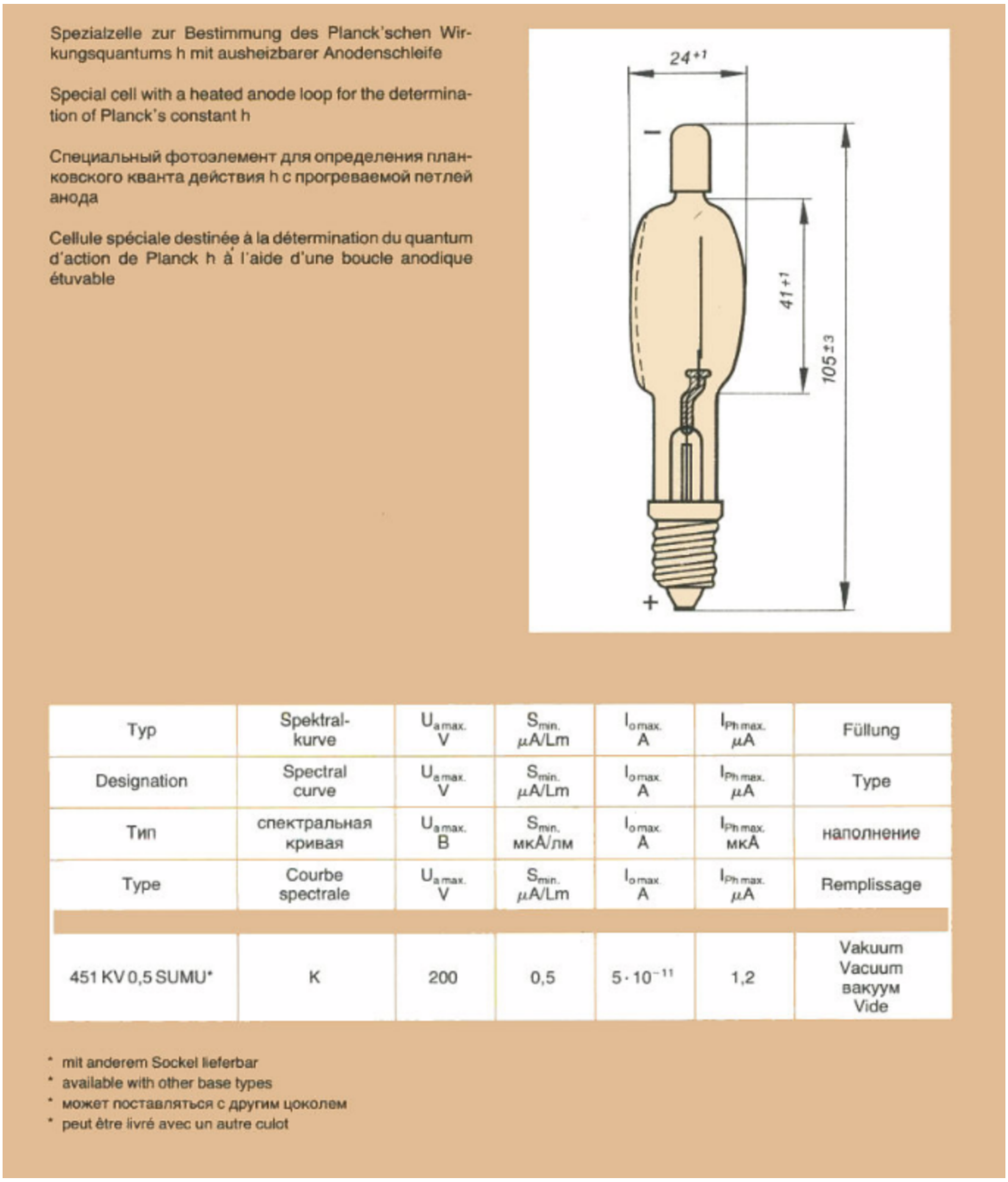
(b) Grating setup: Place the second lens and the grating followed by the screen.

(a) Photocell electronics: Reverse voltage, power supply and output needs to be connected. Voltmeter connects to reverse voltage source. Output of photocell goes to input of lock-in amplifier.

(b) Electronics overview: Power-supply, lock-in amplifier, normal amplifier, reverse voltage source, voltmeter, oscilloscope, low-pass filters.



(c) LED electronics: CMOS output of waveform generator connects to LED and lock-in amplifier. LED can be switched between always-on and external modulation mode.



Spezialzelle zur Bestimmung des Planck'schen Wirkungsquantums h mit ausheizbarer Anodenschleife

Special cell with a heated anode loop for the determination of Planck's constant h

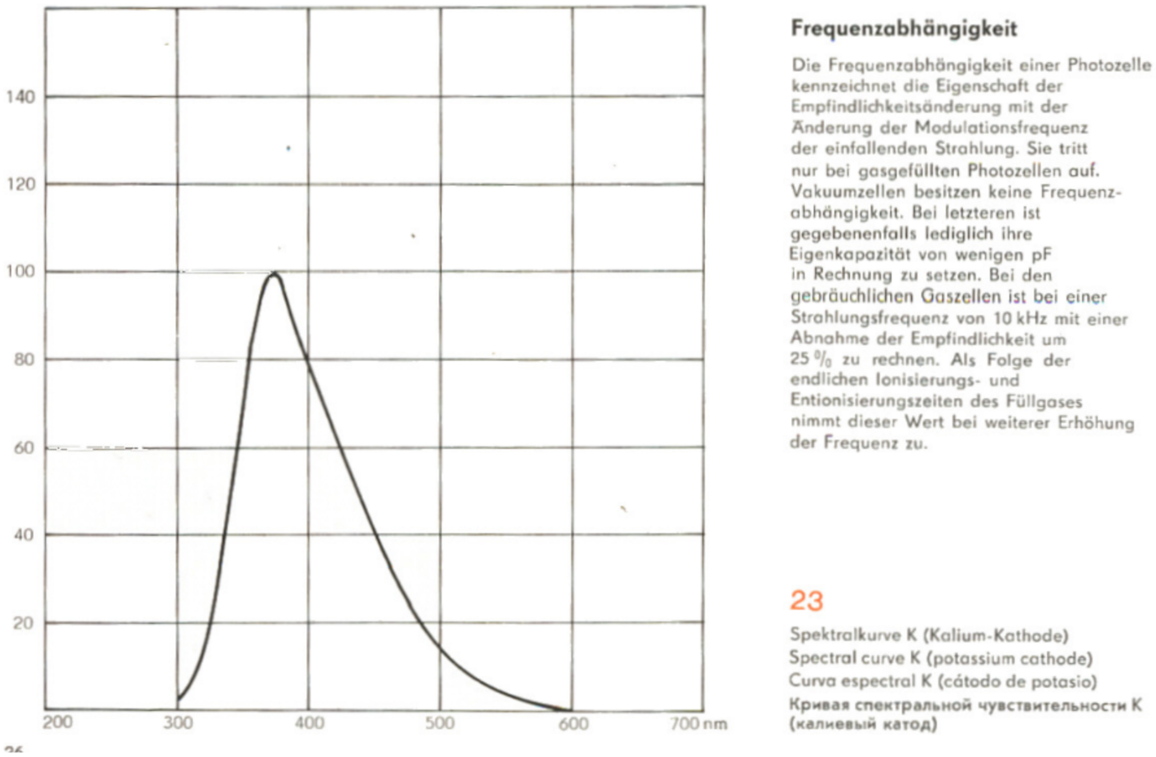
Специальный фотоэлемент для определения планковского кванта действия h с прогреваемой петлей анода

Cellule spéciale destinée à la détermination du quantum d'action de Planck h à l'aide d'une boucle anodique étuvable

Typ	Spektral-kurve	$U_{\mathrm{a\,max.}}$ V	$S_{\mathrm{min.}}$ μA/Lm	$I_{\mathrm{o\,max.}}$ A	$I_{\mathrm{Ph\,max.}}$ μA	Füllung
Designation	Spectral curve	$U_{\mathrm{a\,max.}}$ V	$S_{\mathrm{min.}}$ μA/Lm	$I_{\mathrm{o\,max.}}$ A	$I_{\mathrm{Ph\,max.}}$ μA	Type
Тип	спектральная кривая	$U_{\mathrm{a\,max.}}$ В	$S_{\mathrm{min.}}$ мкА/лм	$I_{\mathrm{o\,max.}}$ А	$I_{\mathrm{Ph\,max.}}$ мкА	наполнение
Type	Courbe spectrale	$U_{\mathrm{a\,max.}}$ V	$S_{\mathrm{min.}}$ μA/Lm	$I_{\mathrm{o\,max.}}$ A	$I_{\mathrm{Ph\,max.}}$ μA	Remplissage
451 KV 0,5 SUMU*	K	200	0,5	$5 \cdot 10^{-11}$	1,2	Vakuum Vacuum вакуум Vide

* mit anderem Sockel lieferbar
* available with other base types
* может поставляться с другим цоколем
* peut être livré avec un autre culot

Figure 18: Datasheet of 451 KV SUMU



Frequenzabhängigkeit

Die Frequenzabhängigkeit einer Photozelle kennzeichnet die Eigenschaft der Empfindlichkeitsänderung mit der Änderung der Modulationsfrequenz der einfallenden Strahlung. Sie tritt nur bei gasgefüllten Photozellen auf. Vakuumzellen besitzen keine Frequenzabhängigkeit. Bei letzteren ist gegebenenfalls lediglich ihre Eigenkapazität von wenigen pF in Rechnung zu setzen. Bei den gebräuchlichen Gaszellen ist bei einer Strahlungsfrequenz von 10 kHz mit einer Abnahme der Empfindlichkeit um 25 % zu rechnen. Als Folge der endlichen Ionisierungs- und Entionisierungszeiten des Füllgases nimmt dieser Wert bei weiterer Erhöhung der Frequenz zu.

23

Spektralkurve K (Kalium-Kathode)
Spectral curve K (potassium cathode)
Curva espectral K (cátodo de potasio)
Кривая спектральной чувствительности К (калиевый катод)

Figure 19: Spectral curve of 451 KV SUMU. Shown is the relative signal strength as a function of wavelength.