Photoelectric effect

The photoelectric effect can be demonstrated by a simple experiment. Let us consider a metal plate made of zinc, which is illuminated by ultraviolet light. The illuminated surface emits electrons, and the plate becomes positively charged. (Fig.1.a) The emitted electrons called photoelectrons. Despite of these if red light is used for illumination, we cannot observe the photoelectric effect even if the intensity of the red light is much higher than the UV light applied in the previous experiment. (Fig.1.b)

(a) (b)

Fig. 1. Demonstration of the photoelectric effect.

The experimental results disagree with classical electromagnetism, which predicts that continuous light waves transfer energy to electrons, which would then be emitted when they accumulate enough energy. Because a low-frequency beam at a high intensity does not build up the energy required to produce photoelectrons, as would be the case if the energy of the light accumulated over time from a continuous wave, Albert Einstein proposed that a beam of light is not a wave propagating through space, but a swarm of discrete energy packets, known as photons.

The energy E_f of the photons is proportional to the frequency f of the electromagnetic radiation as it is expressed by the next equation:

$$E_f = hf = \frac{hc}{\lambda} \quad (1)$$

Where h is the Planck-constant. The value of this universal constant is:

$$h = 6{,}62 * 10^{-34} Js$$

In case the λ wavelength of the radiation is known instead of frequency, the photon energy can be expressed using the speed of light:

$$c = 3 * 10^8 \frac{m}{s}$$

In the photoemission process, when an electron within some material absorbs the energy of a photon and acquires more energy than its binding energy, it is likely to be ejected. If the photon energy is too low, the electron is unable to escape the material. Since an increase in the intensity of low-frequency light will only increase the number of low-energy photons, this change in intensity will not create any single photon with enough energy to dislodge an electron. Moreover, the energy of the emitted electrons will not depend on the intensity of the incoming light of a given frequency, but only on the energy of the individual photons.

The energy equation of the photoelectric effect is:

$$E_f = E_{kin} + W \qquad (2)$$

It expresses that the one first of energy of the photon is used to push the electron from the material to the free space (W) and the other part of the photon energy is converted to the kinetic energy of the free electron.

Photocell

The vacuum photocell is the simplest application of the photoelectric effect. It contains two electrodes in a glass tube. The surface of the cathode plate made of special materials designed for efficient electron emitter. The anode is a wire loop, which collects the electrons travels through the vacuum space between the two electrodes.

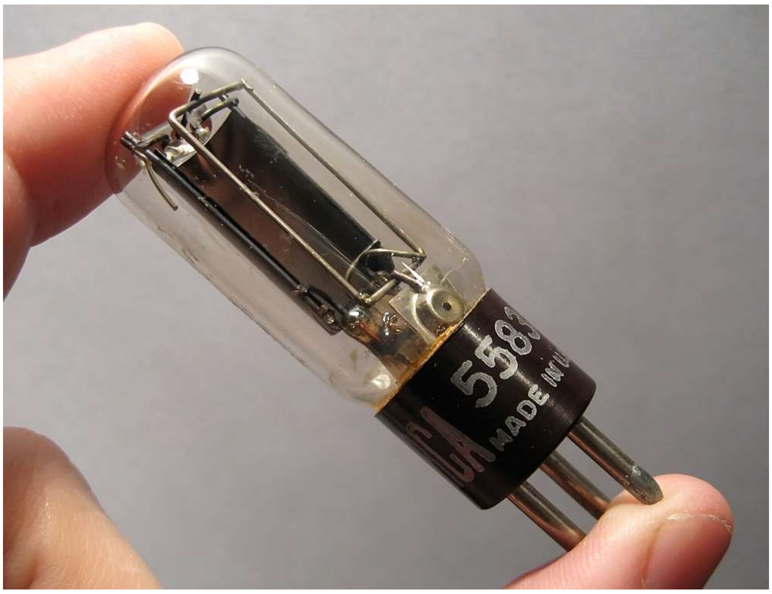
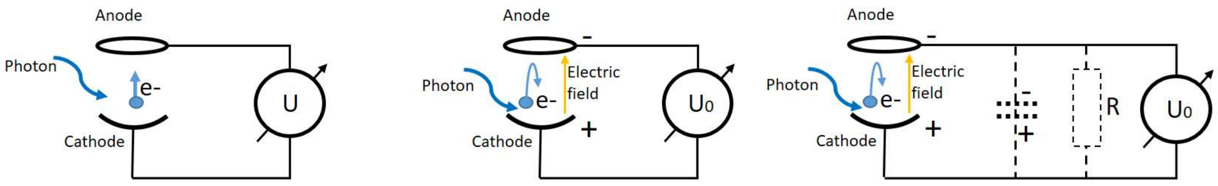


Fig.2. Classic vacuum photocell

In case the cathode is illuminated, the cathode becomes positively charged because of the leaving photoelectrons, and the anode becomes negatively charged. A voltmeter can be applied to measure the increasing voltage between the two electrode. (Fig.3.a) After some time the voltage is saturated. Charges of the electrodes produce an increasing electric field between the electrodes. The Coulomb force repulses the electrons and they cannot reach the anode. (Fig.3.b)



(a) (b) (c)

Fig.3. Simple method to test a vacuum photocell

The charge saturation is realized in case the equilibrium state, when the initial kinetic energy of a photoelectron is equal to the potential energy between the electrodes:

$$U_0 e = E_{kin} \qquad (3)$$

Let us substitute it to the eq. (2):

$$hf = U_0 e + W \qquad (4)$$

After some derivation we can show that the voltage U_0 of the illuminated photocell is proportional to the frequency of the illuminating light.

$$U_0 = \frac{h}{e} f - \frac{W}{e} \qquad (5)$$

It means that the voltage U_0 is independent from the intensity of light, U_0 depends only on the 'colour' of the light.

Theoretically the measurement method proposed on Fig.3. could be applicable to determine the Planck-constant or the material specific W energy constant.

In practice the simple setup of Fig.3. is a quite inaccurate measurement method. We have not enough information about the capacitance of the electrode system. The internal resistance of the realistic voltmeter modifies the measured value. However the foton flux (power of the illumination) also has an effect on the measurement result.

Photocell measurement setup

A more precious setup is presented on Fig.4. An external power supply is connected to the photocell. The voltage U_f of the power supply can be tuned. Because of the photoelectric effect, some current flows through the illuminated cell. This current flows through the resistance R too, thus the current can be measured by measuring the voltage U_2 of the resistance.

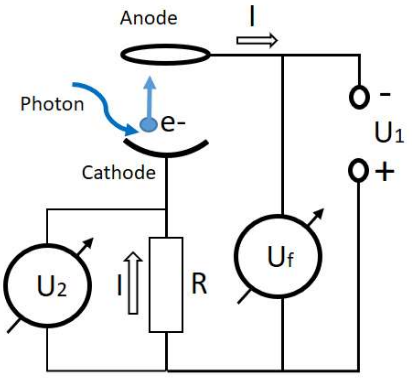


Fig.4. measurement setup

If the current of the illuminated photocell is measured as a function of the voltage U_f connected to the photocell electrodes, we get the caracteristic presented on the Fig.5. diagram.

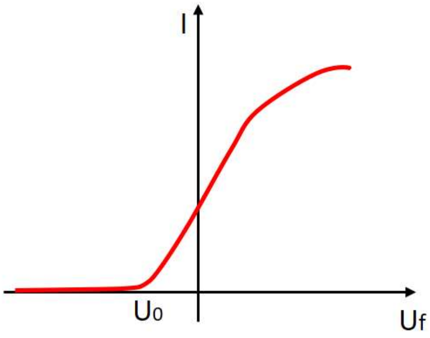


Fig.5. Typical voltage-current characteristic of a photocell

In case the anode has a significant negative potential, the photocurrent is approximately zero, because the negatively charged anode repulses the photoelectrons. There is a critical U_0 voltage in the negative regime, where the photocurrent appears. In the regime beyond U_0 the initial kinetic energy of a photoelectron is enough to reach the anode. Based on these we can suppose that in the critical point of the I-U_f curve the equation (3) is valid. The slope of the curve beyond U_0 depends on the photon flux illuminated on the cathode. But the position of the U_0 knee depends only on the energy of the individual photons determined by the wavelength of the light.

Measurement tasks

1. Set and switch on the given LED light sources and measure the wavelength of each by the given spectrometer. Calculate the frequencies of the radiations.

2. Build up the setup of Fig.4. using the given elements.

3. Chose the UV light source and illuminate the photocell. Measure the photocurrent as a function of the U_f voltage. Plot the results on a diagram, and determine the voltage U_0.

4. Repeat the measurement using other wavelengths for illumination. Evaluate U_0 corresponding to each applied wavelengths.

5. Plot the U_0 as a function of the frequency of the corresponding illumination. Fit a line on the data points based on the theory of equation (3) Evaluate the slope of the diagram, and relate it to the theoretical h/e ratio.

After the measurements there will be a lab tour to show the current applications of photonics.