Investigating the Efficiency of a Photo Diode - Capacitor System

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Abstract. A laboratory experiment is presented that examines a scheme of charging a capacitor by means of a photodiode illuminated by an LED lamp at an angle of 0^0. A number of functional analyzes were made between illuminance, luminous flux, generated voltage, relaxation time, light and electrical energy. The efficiency under different lighting conditions was analyzed and the efficiency of the system was determined. A mathematical algorithm for calculating the physical characteristics used has been compiled. The laboratory experiment was developed in order to be used in a physics laboratory practicum in the sections optics and electricity. The considered analytical methodology can be used to analyze photovoltaic systems and improve their efficiency.

INTRODUCTION

Micro-electrical engineering uses a number of non-linear resistive semiconductor elements such as photodiodes, phototransistors, denistors, photomultipliers, containing n number of dynodes which are used to generate supply voltage after light irradiation in the visible or ultraviolet spectrum. In order to investigate photo-electromotive voltage and improve the efficiency of photovoltaic systems, it is necessary to investigate a number of physical characteristics. The generated photo-electromotive voltage is a characteristic dependent on the illumination - E [lux], the area -S[mm^2], the distance -r[mm] and the intensity – I [cd] of the light as well as the number of n-p pairs in Si elements. This determines the relaxation time-τ for charging a storage battery. The purpose of the present work is to investigate the charging efficiency of a capacitor with a capacity of 1000μF by illuminating a non-linear resistive element photodiode-SFH 206K - OSRAM. The main dependence is related to the illuminance –E [lux] at a different distance r [mm] from the illuminated surface-S, which is represented by Lambert's law. The photoelectromotive voltage can be represented by the relation (1):

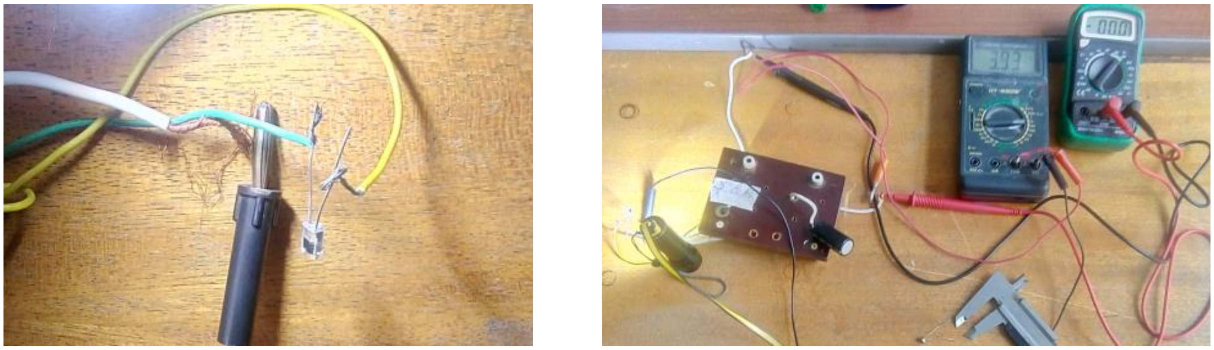
$$E\left[lux\right] = \frac{J\left[cd\right]}{r^2\left[m\right]}\cos(0) = k.U\left[V\right], \tag{1}$$

where: r [mm] - distance to the light source, k - coefficient of proportionality; light intensity - J [cd]. The photoeffect in semiconductor Si elements depends on the light energy and the generated n-p pairs.

EXPERIMENTAL PART

An experimental setup including a photodiode is -SFH 206K - OSRAM and a capacitor with a capacity of 1000μF which is shown in Fig. 1.The circuit includes a multi meter that measures voltage and, accordingly, a multi-meter that measures electric current until the capacitor is charged. Area of the illuminated surface of the photodiode is S [mm] - 5mm. The first experiment includes: The photodiode is illuminated by means of LED lighting indicated in Fig. 1, by changing the distance r and measuring the illuminance-E [lux] with the help of a virtual laboratory

EMANT 300.Measurements of E [lix] and the generated voltage -U [V] and calculations according to dependence (1) of the generated voltage – U [V], the distance -r[mm] and the light intensity J [cd] were made.



(a) (b)

FIGURE 1. Schematic of a photo diode (a) and photo diode-capacitor (b)

The illumination of the surface of the photodiode is at an angle of 00. After using dependence (1). The obtained results are shown in Table 1.

TABLE 1. Dependence of illumination and voltage for photodiode -SFH 206K

U [mV]	r [mm]	E [lux]	J [cd]	f [Hz]
395	100	4400	44	$2{,}1.10^{15}$
364	200	1100	44	$9{,}67.10^{14}$
354	300	488	44	$6{,}27.10^{14}$
347	400	275	44	$4{,}6.10^{14}$

The resulting dependence between illuminance and photo-electromotive voltage is indicated in Fig. 2. Figure 2 clearly shows that the dependence with the greatest approximation is a logarithmic regression with a regression coefficient of 1. The coefficient of proportionality in linear regression is k = 0.0197.

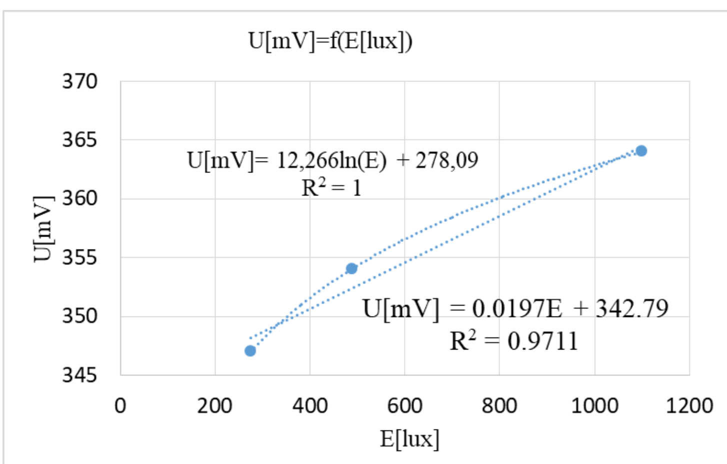


FIGURE 2. Logarithmic and linear regression of illuminance and photo-electromotive voltage

The second experiment includes a capacitor with 1000μF, the charging time of the capacitor was studied for a time of 60 seconds at a measured illuminance of 256 lux. Table 2 shows the main physical characteristics.

TABLE 2. Characteristics of the photodiode system - SFH 206K capacitor 1000μF.

t [sec]	U [V]	R [kΩ]	I [μA]	Q [C]	t [sec]
10	0,063	0,830	75,9	$0{,}62.10^{-4}$C	0,83
20	0,098	1,63	60,1	$0{,}97.10^{-4}$ C	1,63
30	0,137	2,43	56,3	$1{,}36.10^{-4}$ C	2,43
40	0,187	3,25	57,5	$1{,}86.10^{-4}$ C	3,25
50	0,238	4	59,5	$2{,}38.10^{-4}$ C	4
60	0,254	4,84	52,4	$2{,}53.10^{-4}$ C	4,84

The determination of physical characteristics such as: relaxation time - τ , number of accumulated charges - Q , and flowing photo-current - I dependence on light energy - ESt were calculated by means of algorithm from (2) to (14).Let us use basic dependencies in electrical engineering from which we could derive the relaxation time -τ [1,2,5]:

$$C_i = \frac{Q}{UI} = \frac{t}{U} \tag{2}$$

$$R = \frac{U}{I} \tag{3}$$

After the analysis of (2) and (3), the relaxation time- τ is obtained (4):

$$C = \frac{Q}{U} = \frac{I.t}{U} = \frac{t}{\frac{U}{I}} = \frac{t}{R} \Rightarrow \tau = f(t) = CR \tag{4}$$

The time for accumulation of charges on the capacitor plates is measured according to an exponential law according to [1].We could calculate the capacitor capacitance and relaxation time using the following algorithm:Let's write down the exponential dependence (5), (6) for a unit of time t and illumination-E of the photodiode with J=44cd, for the relaxation time we get:

$$C_{MAX}U = C_i U_i e^{-t/CR} \tag{5}$$

$$C_{MAX}U = C_i e^{-t/\tau} \rightarrow \ln\left(\frac{C_{MAX}}{C_i}\right) = -\frac{t}{\tau} \rightarrow \ln\left(\frac{C_i}{C_{MAX}}\right) = \frac{t}{\tau} \Rightarrow \tau = \frac{t}{\ln\left(\frac{C_i}{C_{MAX}}\right)} \tag{6}$$

After substituting (2) into (5) , we get (7) for the relaxation time.

$$C_{MAX}C_{MAX}U = te^{-t/\tau} \rightarrow \ln\left(\frac{t}{C_{MAX}U}\right) = \frac{t}{\tau} \Rightarrow \tau = \frac{t}{\ln\left(\frac{t}{C_{MAX}U}\right)} \tag{7}$$

From the data obtained in table 2, let's consider the following example where: t=60sec, U=0,254V, C_{MAX}=1000μF. After the calculations for 60 sec. the relaxation time from (7) is τ = 4.85s. To determine the resistance we use (2), (4) and (7):Therefore, the resistance will be:

$$C_{MAX}U = C_i e^{-t/\tau} \rightarrow \ln\left(\frac{C_{MAX}}{C_i}\right) = -\frac{t}{\tau} \rightarrow \ln\left(\frac{C_i}{C_{MAX}}\right) = \frac{t}{\tau} \Rightarrow \tau = \frac{t}{\ln\left(\frac{C_i}{C_{MAX}}\right)} \tag{8}$$

$$R = \frac{\tau}{C} = \frac{4{,}85}{1000\mu F} = 4{,}8k\Omega \tag{9}$$

The magnitude of the flowed current is:

$$I = \frac{U}{R} = \frac{0,254V}{4850} = 52\mu A \tag{10}$$

The accumulated charge on the plates of the capacitor, we could derive it by means of:

$$R = \frac{\tau}{C}, I = \frac{U}{R}, C = \frac{Q}{U} \tag{11}$$

After substitution:

$$\frac{U}{I} = \frac{\tau}{C} \Rightarrow Q = CU = \tau.I \tag{12}$$

Therefore

$$Q = I.\tau = 52\mu A.4,85 = 2,5.10^{-4}C \tag{13}$$

Dependence (13) can also be determined by means of the basic dependence for capacitor capacity:

$$C_{MAX}U = Q \Rightarrow 1000\mu F.0,254 = 2,54.10^{-4}C \tag{14}$$

In time 60 sec. the number - n of charges accumulated on the plates is:

$$n = \frac{Q}{e^{-}} = \frac{2,54.10^{-4}C}{1,6.10^{-19}} = 1,58.10^{15} \tag{15}$$

Therefore, the energy of the capacitor will be [2]:

$$E_c = \frac{Q}{2C} = \frac{2,54.10^{-4}}{2.1000.10^{-6}} = 0,128eV \tag{16}$$

The main task for any system is to determine its effectiveness. After lighting the photodiode according to dependence (1). The received light energy is defined by means of dependence (17), which represents a dependence of the electrical energy and the light energy flow.

$$h.f = E.S.U.e^{-}t[eV.\sec] \tag{17}$$

where: $Q_E = \Phi.t = E.S.t$ is the light energy, I=e/t (A) is electric current [3,4].

To determine the efficiency and effectiveness of the photo diode-capacitor system, we use dependence (18).

$$efficiency = \frac{electric\ energy}{Light\ \ energy} \times 100 \tag{18}$$

The light energy will be determined by the number of generated e^{-}, respectively n_n-carriers in a time of 60 seconds.

$$h.f = n_n e^{-}U.t[eV].6,24.10^{18} = Q_E[J] \tag{19}$$

After substitution:

$$h.f = 1,58.10^{15}.1,6.10^{-19}.0,254.60.100 = 0,38eV \tag{20}$$

To determine the frequency we use dependence (17):

$$h.f = ESe^{-}.U.t \Rightarrow f = \frac{ESe^{-}U.t}{h}[Hz]$$

$$f = \frac{0,05.256.1,6.10^{-19}.0,254}{6,62.10^{-34}} = 7,85.10^{14}Hz \tag{21}$$

After substituting (10) and (17) in (18) for the efficiency of the system, we obtained:

$$efficiency = \frac{0,128}{0,38}.100 = 33\% \tag{22}$$

After substituting E and integrating over an interval of 0 to 400 mm for the frequency we can write:
Where : t = 1sec, the distance changes from r1=0 , rn = 400mm.

$$hf = \int_0^{r_n} \frac{J}{r^2} Se^{-}Udr = JSe^{-}U\int_0^{r_n} r^{-2}dr = -Se^{-}U\left(\frac{r^{-2+1}}{-2+1}\right)_0^{r_n} = JSe^{-}U\frac{1}{r_n} \tag{23}$$

$$hf = \int_0^{r_n} ES.e^{-}Udr = \frac{J}{r^2} Se^{-}U.r = \frac{J}{r_n} S.e^{-}U \quad (24)$$

For the frequency of the incident light wave, we get:

$$f = \frac{J.Se^{-}U}{h.r_n}, [Hz] \quad (25)$$

where: J[cd]- the intensity of the light wave, h - Planck's constant: $h = 6,62517 \pm 0,00023.10^{-34} J.\sec.$

The conclusions that can be drawn from the conducted experiments is that the light energy is a function of the light energy flow and the electrical energy. The presented algorithm can be used to study the efficiency of different photoelectric drive systems. It follows from (7) that the relaxation time is a logarithmically dependent quantity, therefore the efficiency of the system changes according to an exponential law. By using the law of conservation of mass, it is possible to calculate the resulting p-n pairs in a time of 60 seconds [2,3]. After replacing (7) in (11) for the photodiode-capacitor system, the dependence is fulfilled:

$$h.f = E.S.Ue^{-}t.\ln\left(\frac{t}{C_{MAX}U}\right)^{-1} \quad (26)$$

Let us divide on 1/ t and substitution with the electric current we get:

$$\frac{h.f}{t} = ESUI \ln\left(\frac{t}{C_{MAX}U}\right)^{-1} \quad (27)$$

Dependence (27) shows that the light energy flow ESt determines the magnitude of the generated photocurrent I for the semiconductor crystals and the accumulation of charges Q on the plates of a capacitor for a unit of time t.The dependence of photo current I on relaxation time-τ according to Table 2 is shown in Fig. 3.

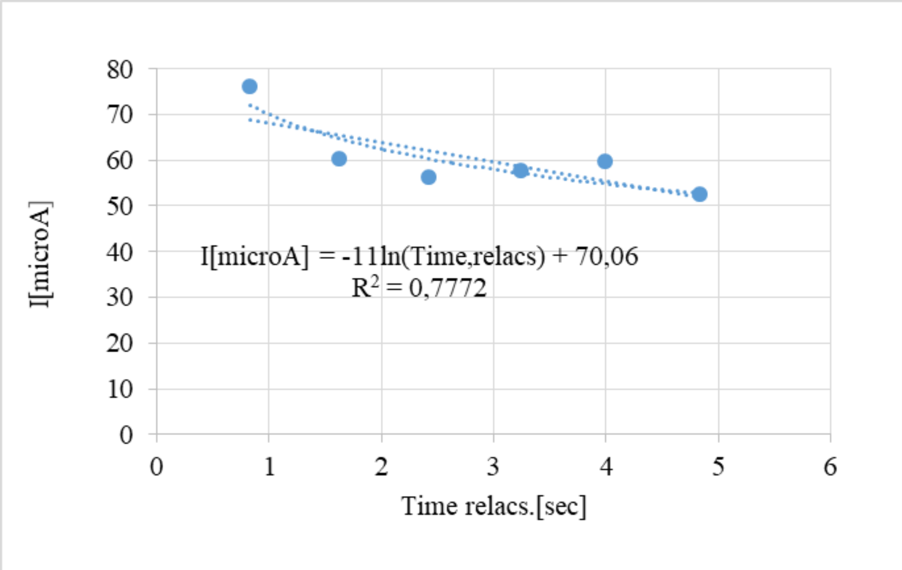


FIGURE 3. Dependence between electric current and relaxation time

CONCLUSION

The presented laboratory study can conveniently be used to compose a number of experimental and computational tasks for STEM projects. The mathematical model is suitable for constructive solutions by using photoelectric systems that include dinistors, Schott diodes, photodiode batteries, as well as improving their efficiency. The described and derived algorithm raises questions for the compilation of a number of software solutions for deriving the main measured quantities, determining the number of photons and number of n-p pairs.

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