Algorithm for determining photoresist characteristics

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Abstract. **This paper presents data from a photoresist stady. Computational models have been developed to determine basic physical characteristics. A software algorithm for their derivation has been developed. Models for the calculation of basic characteristics such as integral sensitivity, efficiency, photoresist activation energy are presented. A number of statistical and mathematical analyses are presented.**

Keywords: photoresistor,photocurrent, the intrinsic photoeffect.

I. INTRODUCTION

Photoresistors are elements sensitive to light and are used in the automation of machines and processes in various industries, they are also part of optocouplers that provide galvanic separation of electrical circuits.
The study of their characteristics is important from the point of view of the expected results when including them in controllers for managing various technological processes,[1],[2],[3],[4],[5],[6].
The research presented in this article is applicable and suitable for teaching students from various specialties such as electronics, automation and others,[1],[2].
A methodology for calculating the main characteristics of photoresistors and their experimental investigation is presented.

The purpose of this paper is to study the basic characteristics and derive models for their calculation.

The created computational methodology and experimental scheme is intended to support the students' training.

The purpose of the presented model with a photoresistor is to use it to construct programmable controllers for measuring illumination in workshops and laboratories. Also to develop 3D models similar to those mentioned in literature sources [7],[8],[9],[10],[11] ,[12],[13],[14],[15].

II. MATERIALS AND METHODS

In order to experimentally examine the characteristics, it is necessary to use a specialized model, through which the scheme presented in Fig. 1 is realized.

The model itself is a cylinder made of impermeable material. At the two ends of the cylinder, respectively, the light source, representing a lamp with an incandescent filament, is located, and at the other end, a photoresistor and a lux meter are located, with the help of which the illuminance -L,lux is read.

The length of the cylinder, respectively the distance between the light source and the photosensitive element is r = 21 cm. In the middle, at equal distances, a filter is placed to achieve a uniform distribution of light along the section of the cylinder.

The light energy emitted is of a wavelength determined by a spectrometer, in the white light spectrum λ=600nm[3]. The photoresist used has an area of S=0.005m². The experiment was carried out with illuminance varying from 0 lx to 2990 lx. The measured dark resistance is R 360kΩ. An autotransformer is used to vary the supply voltage of the light source from 0 to 230V. This makes it possible to adjust the luminous flux energy - Q[W/m2] and the intensity -J[cd] incident on the surface of the photocell.
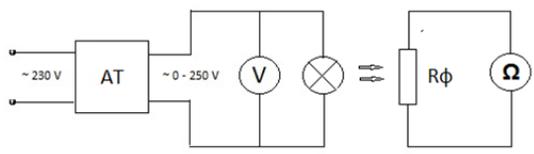
Fig.1 Schematic diagram of photo resistor

The light source has a fixed frequency in the visible light spectrum.Wien's law (1) states that.

$$T = \frac{2,9.10^{-3}}{\lambda} = \frac{0,002898}{600.10^{-9}} = 4816K \qquad (1)$$

To calculate the frequency f[Hz], we use :

$$f = \frac{c}{\lambda} = \frac{3.10^8 \, m/s}{600.10^{-9} \, m} = 5.10^{14} \, Hz \qquad (2)$$

The main characteristic of the photoresist is its efficiency , which depends on the absorbed luminous flux - Φ,[lm/m²] per 1 second [1],[2],[4]. This allows us to analyze the experimental data obtained in Fig. 2 where the resistance R,[Ω], depends on the illuminance - L [lux] ,area-S,[m²] of the photoresistor and illumination time -t,sec.

$$\Phi = LSt, W/m^2 \qquad (3)$$

The resistance drops exponentially from 360kΩ to 1.85kΩ at light intensities-J,cd from 1cd to 83.8cd in Fig.2. After measuring the illuminance L,lux, we use relation (8) to calculate the intensity J,cd of the incident light. With the help of an ammeter, we also measured the magnitude of the current flowing through the photoresistor.
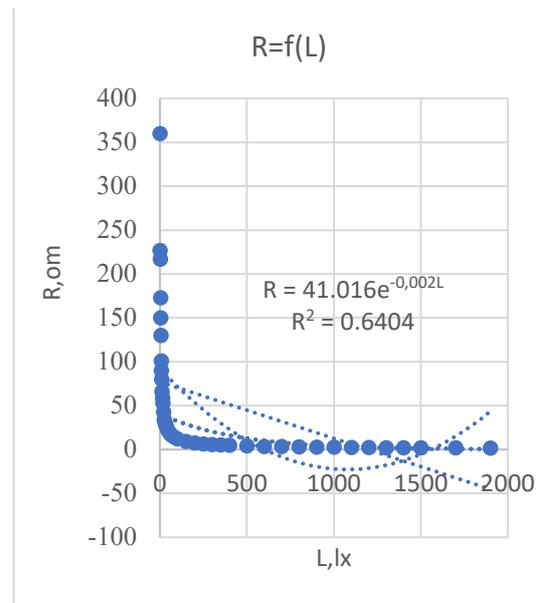
Fig.2 Photoefficiency

To observe an internal photoeffect, it is necessary to determine the separation work - A (4) and the number of photons - n (5), where[5]:

$$h = (6,62517 \pm 0,00023).10^{-34} \, J.s$$

$$\frac{h\nu}{e^-} = A \qquad (4)$$

$$n = \frac{\Phi}{h\nu} \qquad (5)$$

For the separation work which is 2 eV, we could write :

$$A = \frac{\Phi, W/m^2}{n_{ph} e^-} \qquad (6)$$

Here it is good to indicate the dependence of the measured current on the intensity .From Fig.3 it can be seen that, the maximum measured current is 2.63mA.

I[mA]=f(J[cd])

I[mA] = 0,0341J[cd] + 0,2346
R^2 = 0,9317
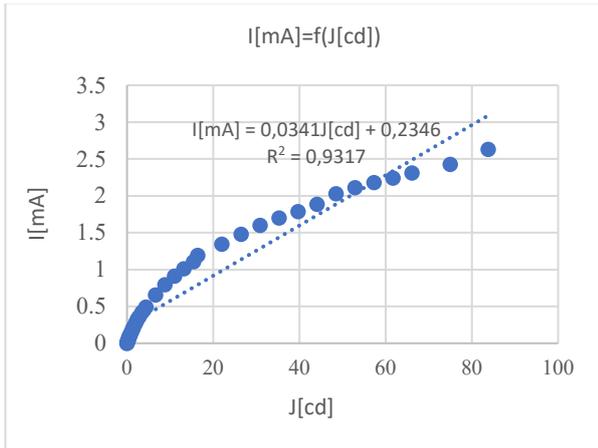
Fig.3 Dependence of the current flowing through the photoresistor on the intensity J[candela]

In the case of photocells, the main characteristic is the integral sensitivity-k, which calculates are the current flowing through the photoresistor - I,[mA] from the photometric characteristics intensity and incident energy flux-Φ per unit area (3) per unit time - t .

$$I = k\Phi \qquad (7)$$

Using Lmbert's law (8) where and the results obtained for the intensity of light J,cd in Fig. 3, the integral sensitivity-k (10) is 1.3 mA/lm at 217 kΩ.

$$L = \frac{J,cd}{r^2}\cos\theta \qquad (8)$$

$$\Phi = \frac{JS}{r^2} \qquad (9)$$

$$k = \frac{r^2 I}{JS}, \frac{mA}{lm} \qquad (10)$$

After certain substitutions :

$$k = \frac{I}{Ane^-} \qquad (11)$$

An Integrated Development *Environment* (IDE), visual studio 2023, was used to develop a programming model for calculating the sensitivity coefficient-κ.

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using System.Windows.Forms;
namespace GeorgiDobrev23
{
public partial class Form1: Form
{
public Form1()
{
InitializeComponent();
}
private void btn_CalculateJ_Click(object sender,
EventArgs e)
{
double Er2, cos_alpha, r2I, JS;
Er2          =          Convert.ToDouble(tbE.Text)*
Math.Pow(Convert.ToDouble(tbr.Text),2);
cos_alpha = Math.Cos( (Convert.ToDouble(tbAlpha.Text)
* (Math.PI)) / 180);
J.Text = Convert.ToString( Er2 / cos_alpha);
r2I   =   Math.Pow(Convert.ToDouble(tbr.Text),  2)  *
Convert.ToDouble(tbI.Text);
JS          =          Convert.ToDouble(J.Text)          *
Convert.ToDouble(tbS.Text);
k.Text = Convert.ToString(r2I/JS);
}
}
}
```

R=f(k)

R= $0.683e^{3,2946k}$
R^2 = 0.927
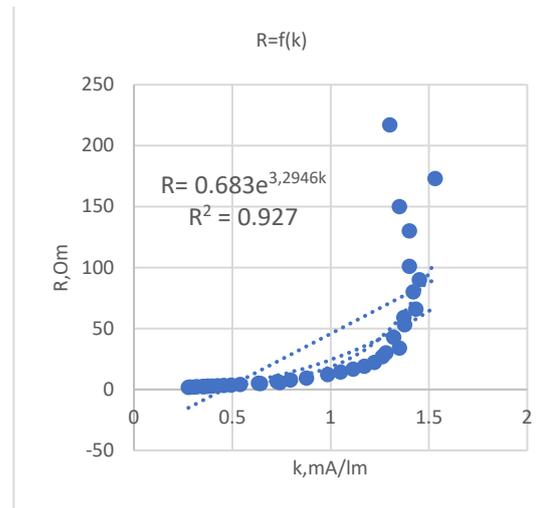
Fig.4 Integral sensitivity coefficient for photoresist.

The photoresist operates at a temperature of $298K^0$, this gives us the opportunity to calculate the width of the forbidden zone ΔW, we use the classical relation (11) and the results in Fig. 4.

$$R_{max} = R_{min}e^{\frac{U}{k_B T}} \qquad (12)$$

where:

$$\kappa_B = \frac{1,38.10^{-23} J/K}{1,6.10^{-19} C} = 8,625.10^{-5} eV/K$$

For the energy of the molecules we obtain:

$$\kappa_B.T = 8,625.10^{-5} eV/K \times 298 = 0,0257eV \quad (13)$$

$$\ln\left(\frac{360k\Omega}{1,47k\Omega}\right) = \frac{U}{0,0257} \quad (14)$$

Therefore, we look for an existing relationship between the measured resistance-R and the voltage-U in Fig.5.[6]
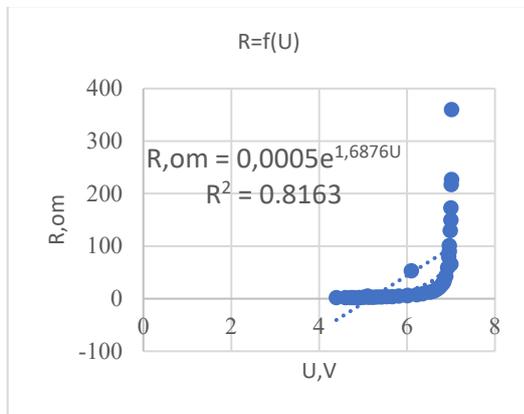
Fig.5 Characteristic of resistance variation R(U) for photoresistance

For the width of the forbidden zone ΔW we use a Fermi-Dirac distribution (13) which gives us a reason to write.

$$U = \frac{\Delta W}{2} \quad (15)$$

The calculated value is: $\Delta W = 0,63eV$

The electrical power generated is 0.012W.

III. RESULTS AND DISCUSSION

We investigate the existence of a correlation relationship between photocell resistance and illuminance [lux] and number of photons [peta photons] and current through the photocell [mA] using SPSS 25.0 with correlation and regression analysis.

Statistical methods are applied to establish dependencies describing these relationships between these quantities. With the help of statistical methods, conclusions can be drawn about the nature and strength of the investigated relationships under certain conditions .

Regression and correlation analysis are commonly used in research to obtain analytical relationships that describe the relationships between quantities[8]. They are methods for analysing statistical relationships and dependencies.Correlation analysis measures the strength of the relationship under investigation between a dependent variable Y and one or more independent variables X. Regression analysis can be used to determine the type of function that shows the dependence of the random variable Y on the independent variable X[9].The result of its application is a regression equation that describes the relationship between the dependent variable Y and the independent variable X[10]..

We evaluated the adequacy of the models in the dependencies at the significance level of the F criterion. These models are considered sufficient if the significance is less than 0.05 . If the models meet this criterion, we also decipher the statistically significant values of the regression coefficients. The univariate regression models examine the correlation between two phenomena (factors) Y and X. Typically, Y is the response variable (outcome) and X is the predictor variable. The universal form of the univariate regression model is given by the equation

$$Y_i = f(X_i, e_i) \quad (16)$$

where:
Y_i - is the response or outcome variable,
X_i - is the predictor variable or factor,
e_i - is the stochastic component in the model.

Study of the dependence of photocell resistance R [kΩ] as a function of illuminance [lux],(1),(2).

For the quantities photocell resistance R [kΩ] and illuminance [lx] we obtained the following results:

TABLE 1 ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	92,451	1	92,451	8373,895	,000
Residual	,408	37	,011		
Total	92,860	38			

The independent variable is L[lx].

TABLE 2 COEFFICIENTS

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
ln(L[lx])	-,704	,008	-,998	-91,509	,000
(Constant)	346,009	13,408		25,807	,000

The dependent variable is ln(R[kΩ]).

TABLE 3 MODEL SUMMARY

R	R Square	Adjusted R Square	Std. Error of the Estimate
,998	,996	,995	,105

The independent variable is L[lx].

Table 3 Model Summary gives the value of the correlation coefficient (R) of 0.998, indicating a strong correlation between the predictor variable X (illuminance [lx]) and the response variable Y (photocell resistance R [kΩ]).[11] The coefficient of determination (R-squared) quantifies the degree of influence of the predictor X on the result Y. It is 0.996 (99.6%), which means that 99.6% of

the variations in the photocell resistance R [kΩ] can be attributed to the different values of illuminance [lx]. The uncertainty factor is calculated using the formula 100% - R square (100% - 99.6% = 0.4%). This value measures the influence of factors other than X on the result Y. A value of 0.4% means that 0.4% of the variation in photocell resistance R [kΩ] is influenced by factors other than illuminance [lx]. The parameters of this model are statistically significant as the significance values are less than 0.05, confirming the adequacy of the model to study the relationship between the variables[12]. Column B of the Coefficients table contains the values of the non-standardised regression coefficients for the attribute factor. The value of these coefficients indicates the degree of change in photocell resistance R [kΩ] for a unit increase in luminance factor [lux]. Only those regression coefficients are interpreted whose significance level (significant.) in the coefficients table is lower than the selected level of agreement sig (<0.05).

The function that describes the relationship between the predictor variables and the response variable has the general form:

$$Y = b_0(x_1{}^{\wedge}b_1)\varepsilon_i, \qquad (17)$$

where:
Y - is the response variable;

b_0 - a constant that has no clear scientific interpretation;
b_1 - is a coefficient that provides information about the correlation relationship sought for factor X_1;

ε_i - random error;

The dependence is non-linear but can be linearised by logarithmisation.

This makes it easier to interpret the regression coefficients.

The dependence has the form:

Photocell resistance R [kΩ] = 346.009* Illuminance [lx]^(-0.704)*εI
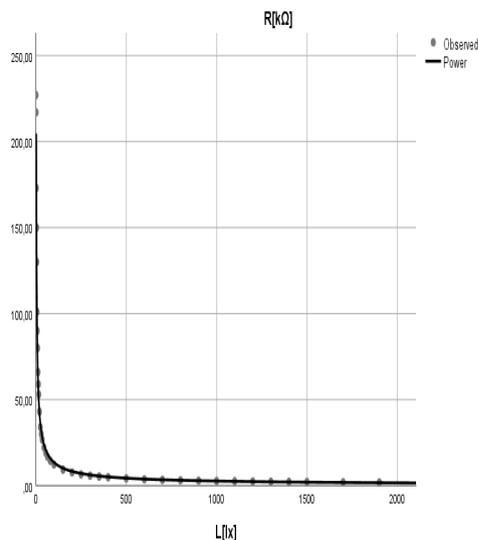
Fig. 6 Photocell efficiency obtained with SPSS.

Study of the relationship between the number of photons [peta photons] and the current passing through the photocell [mA]. The results obtained were recorded for the photon flux [peta photons] and the current through the photocell [mA]:

TABLE4 DESCRIPTIVE STATISTICS

	Mean	Std. Deviation	N
I[mA]	,8865897436	,8666568773	39
Nf[peta phot]	6463,267	8407,9205	39

TABLE 5 CORRELATIONS

		I[mA]	Nf[peta phot]
Pearson Correlation	I[mA]	1,000	,966
	Nf[peta phot]	,966	1,000
Sig. (1-tailed)	I[mA]	.	,000
	Nf[peta phot]	,000	.
N	I[mA]	39	39
	Nf[peta phot]	39	39

TABLE 6 MODEL SUMAARY

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	,966ᵃ	,932	,930	,2285422783	,932	509,443	1	37	,000

a. Predictors: (Constant), Nf[peta phot]

The Model Summary table, the correlation coefficient R is recorded as 0.966. This means that there is a robust correlation between the predictor variable X (number of photons [peta photons]) and the response variable Y (current through the photocell [mA]). The coefficient of determination (R-squared), which measures the strength of the influence of the predictor X on the response Y, is 0.932 (93.2%). This means that 93.2% of the variation in the current passing through the photocell [mA] can be attributed to the different values of the photon quantity factor [peta phot]. The uncertainty factor is calculated using the formula 100% - R square (100% - 93.2% = 6.8%). This value quantifies the influence of factors other than X on the result Y. A value of 6.8% means that 6.8% of the variation in the current passing through the photocell [mA] is influenced by factors other than the number of photons [peta photons].

TABLE 7 ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	26,609	1	26,609	509,443	,000ᵇ
	Residual	1,933	37	,052		
	Total	28,542	38			

a. Dependent Variable: I[mA]

b. Predictors: (Constant), Nf[peta phot]

The parameters of the model are statistically significant as the p-values are less than 0.05, indicating that the model is suitable for studying the relationship between the variables.

TABLE 9 COEFFICIENTS

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
Nf[peta phot]	9,953E-5	,000	,966	22,571	,000
(Constant)	,243	,046		5,246	,000

Column B of the coefficients table contains the non-standardised regression coefficients for the characteristic factor. This figure shows the change in photocell current [mA] when the factor, number of photons [peta photons], is increased by one. Only those regression coefficients with a significance level (p-value) in the coefficients table below the selected confidence level (<0.05) are interpreted.

The function that describes the relationship between the predictor variables and the response variable is usually expressed as:

$$Y = b_0 + b_1x_1 + \varepsilon_i, \qquad (18)$$

where:
Y - is the response variable;

b_0 - is a constant that has no clear scientific interpretation;
b_1 – is a coefficient that carries information about the correlation sought for a factor X_1;

ε_i - is a stochastic error;

The relation has the form

Current through the photocell [mA]= 0.243 + 9.953E-5* Number of photons [peta photons] + εi

Evaluation of the regression coefficients:

b_0 = 0.243- has no simple scientific interpretation, but includes unaccounted for influences of existing factors, measurement inaccuracies, biases due to the use of inappropriate models.

b_1 = 9.953E-5 gives an indication of the desired correlation relationship between factor X_1 and outcome Y. This value is non-zero, implying a correlation between the factor (independent variable) X_1, which in this case is the number of photons [peta phot], and the outcome (dependent variable) Y (current through the photocell [mA]). The value of the regression coefficient also indicates the change in the theoretical value of the result variable when the factor variable is increased by one unit. In conclusion, we can say that there is a robust correlation between the number of photons [peta phot] and the current through the photocell [mA]. If we increase the number of photons [peta photons] by 1, the theoretical value of the current through the photocell [mA] increases by 9.953E-5". This dependence is shown graphically in Figure 7.
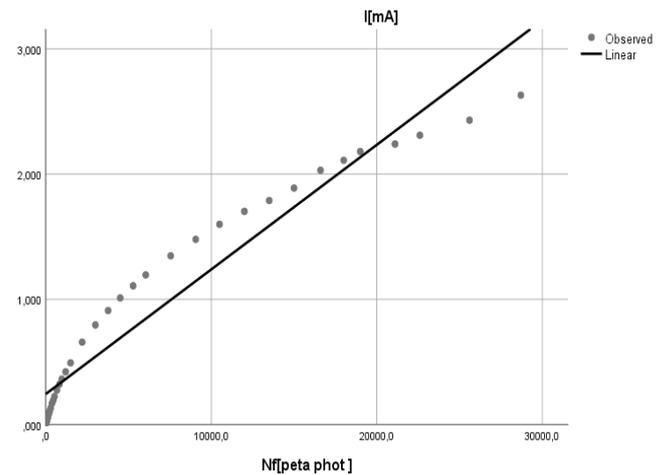
Fig.7 Photocurrent efficiency (number of quanta of current generated)

The results of the correlation and regression analysis show that

1.There is a strong positive relationship between the photocell resistance R [kΩ] and the illuminance [lx]. This is shown by the value of the correlation coefficient R, which is close to 1 (R= 0.998).

2. The value of the coefficient of determination R^2=0.996 indicates that 99.6% of the variation in the dependent variable Y is due to the influence of the independent factor variable X, and the remaining 0.4% to 100% is due to the influence of random factors not included in the model.

3. The regression equation relating photocell resistance to illuminance is as follows

Photocell resistance R [kΩ] = 346.009* Illuminance $[lx]^{\wedge}(-0.704)*\varepsilon_i$.

4. There is a robust correlation between the number of photons [peta phot] and the current flowing through the photocell [mA]. The correlation coefficient is R= 0.966.

5. The coefficient of determination R^2=0.932 indicates that 93.2% of the variation in the current through the photocell [mA] is due to the influence of the number of photons [peta phot] and the remaining 6.8% to 100% is influenced by other factors.

6. The regression equation, which gives the relationship between the current through the photocell and the number of photons, has the following form

Current through the photocell [mA]= 0.243 + 9.953E-5* Number of photons [peta phot] + εi.

In (14,15,16,17) the authors devoted considerable space to a detailed description of the theory and mathematical apparatus of regression and correlation analysis. In the present paper, the emphasis is not so much on the theoretical foundations of the analyses described, but on the practical application of these statistical methods to solve a specific problem.

IV. CONCLUSIONS

The models and statistical analysis presented address the intrinsic photoeffect phenomenon. This provides an opportunity for a number of assignments and laboratory exercises in the classroom.The presented methodology considers an algorithm for calculating basic characteristics for all photocells. The presented mathematical algorithm could be considered in 3D simulations .Also for designing electronic circuits for controlling various processes in mechanical engineering.

V. ACKNOWLEDGEMENTS

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