III.4. THE PHOTODIODE

1. Work purpose

The study of the photovoltaic effect. The direct conversion of light energy in electric energy.

2. Theoretical concepts.

The photovoltaic effect consists in the appearance of an electromotor bias in a p – n junction when light falls upon it. Thus the direct conversion of light energy into electric energy is realized.

In an intrinsic semiconductor, the electric conduction is realized under the influence of the external electric field by both the electrons from the conduction band (creating the electron current density $\vec{j}_n$) and the holes from the valence band (resulted from the electrons thermal excitation into the conduction band and which, from the conduction point of view, behave like elementary positive charges that create the hole current density $\vec{j}_p$). The current densities $\vec{j}_n$ and $\vec{j}_p$ are:

$$\vec{j}_n = n e \mu_n \vec{E}, \tag{1}$$

$$\vec{j}_p = p e \mu_p \vec{E}, \tag{2}$$

where n is the electron concentration, p is the hole concentration, $e \cong 1{,}6 \cdot 10^{-19}\ C$ it is the elementary electric charge, μ_n and μ_p are electron and respectively hole mobilities. In the intrinsic semiconductor,

$$n = p = n_i \tag{3}$$

and the total current density is:

$$\vec{j} = e\left(n\mu_n + p\mu_p\right)\vec{E} = en_i(\mu_n + \mu_p)\vec{E}. \tag{4}$$

In the extrinsic (doped) semiconductors, the conduction is realized mostly by the electrons in the semiconductors doped with donor impurities

– n-type semiconductors, and by the holes in the p-type semiconductors – doped with acceptor impurities. The current density is again

$$\vec{j} = e\left(n\mu_n + p\mu_p\right)\vec{E}, \qquad (5)$$

but $n \neq p$.

The p – n junction is a region that separates, in the same monocrystal, two regions of different conduction types: p and n. In each of these regions, the movement of free carriers has an random character, the electrons diffusing towards p region and the holes towards the n region. When an electron meets a hole, the recombination phenomenon takes place, determining a decrease in the electron concentration in the n zone and of holes in the p zone. As a consequence, the n region becomes electropositive and the p region electronegative. In the junction appears a built-in electric field, directed from the n region towards the p region, which limits the charge carrier diffusion.

The diffusion of the carriers trough the p – n junction can be stimulated by illuminating it. Because of the photons, supplementary electrons are excited from the valence band into the conduction band, and new holes appear in the valence band. These non-equilibrium carriers will diffuse, increasing the built-in electric field. The appearance of this supplementary field, creating a bias, is called photovoltaic effect. The efficiency of the conversion between light and electric energy depends on the nature of the semiconductor material, on the spectral composition of light and on the characteristics of the used device, called a photodiode.

The main piece of a photodiode is a germanium foil of type n in which the p – n junction was realized. The following technology was used (see Fig. 1): On the foil was placed a small piece of indium (indium has a melting temperature lower than the germanium melting temperature). By heating, the indium piece melted and the indium atoms diffused in the germanium foil. The region, in which the indium atoms (acceptors) penetrated, becomes a p-type region. At the limit of this region, the p-n junction is formed. To the two regions, connection wires were attached and then all the parts were encapsulated in a glass tube. The glass tube is all blackened excepting the top end that has the shape of a lens, with the purpose to concentrate the light on the p-n junction.

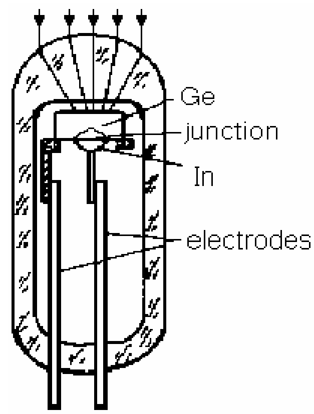

Figure 1.

The increase of the light flux determines the increase of the excess carrier concentrations (*n* and *p*), that will lead to the rise of the photovoltaic bias, together with the rise of the generated current. The current depends on the external circuit resistance: the higher the resistance, the lower the current. In this laboratory we use the method of varying the current with the illumination, at different values of the external resistance.

3. Experimental set-up.

The experimental set-up (version A) is presented in Figure 2. B is an optical bed on which the electric lamp L and the photodiode F can slide. The electric lamp is supplied with 220V a. c. The optical bed is divided into centimeters. The photodiode supplies a circuit formed by a microammeter (μA) in series with a resistance box (with plugs). Each resistance can be introduced in the circuit by extracting the respective plug.

An alternate set-up (version B) has fixed positions for the lamp and the photodiode, but the lamp is provided with a graduated stop, in order to vary the light flow. The working procedures and experimental data processing are presented for both versions.

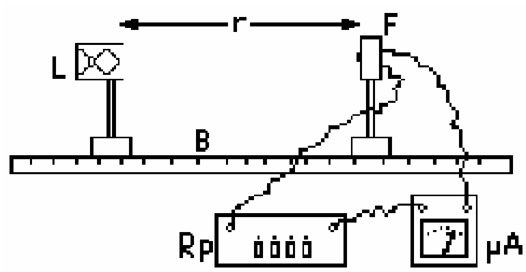

Figure 2.

4A. Working Procedure.

The electrical draft is checked. The lamp is plugged in and the opaque cover of the photodiode is removed. The lamp stands still during the whole experiment. For the null external resistance *R* (the box has all the plugs in), the photodiode is moved at the distance *r* values given in Table 1. For each *r*, the measured current is written in Table 1 (in μA).

Table 1.

r (cm)		8	10	12	15	20	30	50	80
r^2 (cm^2)									
$1/r^2$ (cm^{-2})									
R (Ω)	0								
	100								
	500								
	1000								
	5000								
U_{ph} (V)									
R_d (Ω)									

5A. Experimental data processing.

Eight graphs $1/I = f(R)$ are plotted on the same millimetric paper, for $r = const$, using the experimental data from Table 1. From Ohm's law,

$$\frac{1}{I} = \frac{R + R_d}{U_{ph}}, \tag{6}$$

that is the graph consists of straight lines, their slopes being $1/U_{ph}$ and their origin ordinates R_d/U_{ph}. As the light source is small compared with the distance r, we can consider that the illumination decreases proportional with $1/r^2$. The graphs $U_{ph} = U_{ph}\left(1/r^2\right)$ and $R_d = R_d\left(1/r^2\right)$ are then plotted.

4B. Working Procedure.

The light flow is modified by adjusting the stop in the positions 1, 2, …, 10. The illumination is considered to be proportional with the stop index. The measured data are written in Table 2.

Table 2

No.	E (a.u.*) / R (k Ω)	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}
1.	1.0										
2.	2.0										
...	...										
10.	10.0										
U_{ph}(V)											
R_d(Ω)											

* arbitrary unit.

5B. Experimental data processing.

The procedure is analogous to that of the previous method. The only difference is that one has to replace $1/r^2$ with E (E = 1, 2, ..., 10) in the last two graphs ($U_{ph} = U_{ph}(E)$, $R_d = R_d(E)$).

6. Questions.

1. What is the photovoltaic effect?
2. What is a p – n junction?
3. What is a photodiode?