

INFLUENCE OF ELECTRON AND PHONON HEATING ON THE CHARACTERISTICS OF SOLAR PHOTOCELLS

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Abstract. The paper investigates the effect of heating of electrons, holes and crystal lattices on the currents of p-n-junction heterostructures. The article analyzes the power of a solar photocell, the dependence of the change in the filling factor and the efficiency of a photocell at different temperatures, on the electrons of the leakage resistance and the base resistance. Theoretical calculations are compared with the current-voltage characteristics, power, filling factor, and efficiency of heterostructures obtained experimentally.

Key words: EMF – electromotive force, base resistance, leakage resistance, filling factor, hot electrons and holes, photoEMF – photoelectromotive force, thermoEMF – thermoelectromotive force, microwave ultrahigh-frequency waves, microwave measurement.

1. INTRODUCTION

In this work, we investigated the dependence of the power, filling factor, and efficiency on the temperature of hot electrons and holes, base resistance, and photocell leakage resistance.

Influence of temperature on the characteristics of the p-n junction.

Well researched. The sensitivity of the properties of the p-n transition to temperature changes is due to the peculiarities of the energy spectrum of the semiconductor, both transitions between the energy states of the valence-conduction band and the redistribution of electrons within each conduction band and valence band [1].

The probabilities of transitions of electrons between bands and within the band states strongly depend on the temperature of the crystal lattice and on the energy of free electrons. To explain the effect of temperature on the characteristics of p-n junctions and bipolar semiconductor devices on the characteristics of p-n junctions, it is assumed that the temperatures of electrons, holes, phonons are the same. This condition is not always met [2, 3].

When exposed to strong electric fields and strong electromagnetic waves, the average energy of electrons and holes increases greatly. The electron distribution function strongly deviates from the equilibrium Fermi-Dirac function. This leads to

the emergence of new physical phenomena due to the heating of electrons and holes in p-n junctions [4, 5].

It was found that with an increase in the temperature of electrons and holes, diffusion currents in inhomogeneous regions increase more strongly than field currents in the same regions of the sample. The excess of photon energy during the transfer of electrons from the valence band to the conduction band is transferred to the electron-hole gas. This leads to an increase in the temperature of charge carriers in the conduction and valence bands. An increase in the intensity of the electromagnetic field in the p-n junction always increases the recombination currents [6].

Thus, the heating of the crystal lattice and the electron gas has a different effect on the characteristics of the p-n junction. Heating of the crystal lattice of cases can be considered as a state slightly different from thermodynamic equilibrium and as a distribution function of electrons and phonons can be used in the first approximation of the Fermi-Dirac distribution function and the Planck distribution [7].

However, when the electron-hole gas is heated and the temperature of the hot carriers differs from the temperature of the crystal lattice, as the symmetric part of the function, the distribution of electrons and holes strongly differs from the equilibrium function and this leads to a significant change in the characteristics of the electron-hole gas and p-n transition. The possibility of heating electrons and holes independently, but separately, should be considered on the lattice temperature.

Changing the temperature of electrons and holes strongly affects the characteristics of semiconductor devices. However, this is not always taken into account when analyzing the results of measuring the experiments of many bipolar devices. The question of how important is the effect of heating electrons and holes on the characteristics of solar photocells requires additional research [8].

I-V characteristic of a photocell with hot current carriers. Let us consider a p-n junction with hot current carriers with an electron temperature T_e and a hole temperature T_h . The temperature of the crystal lattice T differs from the ambient temperature. When illuminated with light, photoelectrons and holes are generated. The system becomes highly disequilibrium. EMF of hot carriers and valve photovoltage are generated in the photocell. The resulting photocell current is determined by the resulting effect of heating the charge carriers and the gate photovoltage at the p-n junction [9].

2. RESULTS AND DISCUSSION

2.1. *I-V* CHARACTERISTIC OF P-N JUNCTION IN A STRONG MICROWAVE FIELD

The density of the total current flowing through the sample in the p-n junction is the sum of the current densities of electrons and holes.

For this condition to be met during thermodynamic equilibrium, the voltage must be zero ($U = 0$), when the microwave wave is incident on the diode. The values

of T , T_h , T_e , U differ from the temperature T_0 in thermodynamic equilibrium, the I - V characteristic of the diode has the following form [10, 16]

$$J = J_{se} \left(e^{\frac{e\varphi_0}{kT} \frac{e(\varphi_0 - U - U_1 + J(R_b - AU))}{kT_e}} - 1 \right) + \frac{U}{R_u} + J_{sh} \left(e^{\frac{e\varphi_0}{kT} \frac{e(\varphi_0 - U - U_1 + J(R_b - AU))}{kT_h}} - 1 \right) + \frac{U}{R_u} - J_f. \quad (1)$$

Here φ is the potential, J is the current strength, U is the voltage, R_b is the base resistance, R_u is the leakage resistance.

Let us consider the dependence of I - V characteristic, the power released in the external circuit of the filling factor and the efficiency on thermopower diodes for heated electrons and holes, at the p-n junction. The power released by the photocell in the external circuit [12].

$$P = JU \quad (2)$$

$$P = JU = \left[J_f + J_{se} \left(e^{\frac{e\varphi_0}{kT} \frac{e(\varphi_0 - U - U_1)}{kT_e}} - 1 \right) + J_{sh} \left(e^{\frac{e\varphi_0}{kT} \frac{e(\varphi_0 - U - U_1)}{kT_h}} - 1 \right) \right] U. \quad (3)$$

This expression at the temperature of electrons, holes and phonons is equal to $T = T_e = T_h$ as follows

$$P = \left[J_f - J_s \left(e^{\frac{eU}{kT}} - 1 \right) \right] U. \quad (4)$$

The maximum power released in the external circuit is found from the condition of the maximum power

$$\frac{\partial P}{\partial U} = I + U \frac{\partial I}{\partial U} = 0. \quad (5)$$

Using the expression (5), we obtain

$$Jf + J_{sh} \left(e^{\frac{e\varphi_0}{kT} \frac{e(\varphi_0 - U - U_1)}{kT_e}} - 1 \right) + J_{se} \left(e^{\frac{e\varphi_0}{kT} \frac{e(\varphi_0 - U - U_1)}{kT_h}} - 1 \right) + U \left(\frac{e}{kT_e} J_{se} e^{\frac{e\varphi_0}{kT} \frac{e(\varphi_0 - U - U_1)}{kT_e}} + \frac{e}{kT_h} J_{sh} e^{\frac{e\varphi_0}{kT} \frac{e(\varphi_0 - U - U_1)}{kT_h}} \right) = 0. \quad (6)$$

Equation (6) allows you to find the value of U_m , P_m and J_m can also be calculated from this expression.

For simplicity, let us assume that $T_e = T_h$

$$J_f + J_{sc} \left(e^{\frac{e\varphi_0 - e(\varphi_0 - U - U_1)}{kT_e}} - 1 \right) + \left(\frac{eU}{kT_e} \cdot J_{sh} \cdot e^{\frac{e\varphi_0 - e(\varphi_0 - U - U_1)}{kT_e}} \right) = 0. \quad (7)$$

From the transcendental equation (7), we see that J_m , U_m , filling factor, efficiency depend on the electron temperature. Heating of the crystal lattice always causes a sharp increase in the saturation current J_s . This, in turn, strongly affects the CVC of the photocell [2]

$$J = J_s \left(e^{\frac{e\varphi_0 - e(\varphi_0 - U - U_1)}{kT_e}} - 1 \right) - J_f. \quad (8)$$

To study the dependence of filling on the power of an electromagnetic wave, electron, crystal and lattice temperature, it is necessary to correctly select the characteristics of a photocell (p-n-junction).

– the fill factor

$$FF = \frac{J_m U_m}{J_{kz} U_{xx}}; \quad (9)$$

– the maximum power

$$P_m = J_m U_m; \quad (10)$$

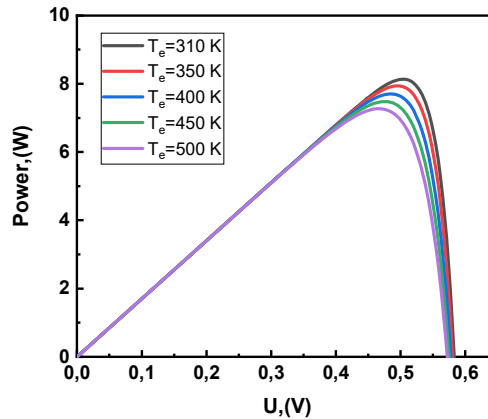


Fig. 1 – Change in power depending on the voltage under the action of hot electrons: $T = 300$ K; $J_f = 9 \cdot 10^{-2}$; $J_s = 10^{-9}$; $E_g = 1.1$ eV; $T_0 = 300$ K; $T_1 = 300$ K; $\varphi = 0.6$ V; $T_e = 310$ K; $T_{e1} = 500$ K.

– the efficiency

$$\eta = \frac{P_m}{P} = \frac{J_m U_m}{P}. \quad (11)$$

Consider the graphs of the photocell power as a function of the diode output voltage. Using formulas (8, 9, 10, 11), you can get the graphs of Figs. 1–7 [11–15].

At a constant temperature of the crystal lattice, with an increase in the temperature of the electron-hole gas, the power of the photocell decreases (Fig. 1). The power of the photocell depends both on the temperature of the lattice current and on the temperatures of electrons and holes. In a photocell, the carrier temperature is always greater than or equal to the lattice temperature. The maximum useful power obtained from the photocell from the temperature of the crystal lattice was investigated [20–24].

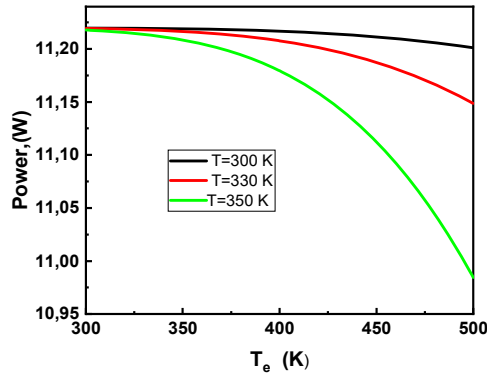


Fig. 2 – Dependences of the maximum power of the photocell on the electron temperature for various constant temperatures of the crystal lattice.

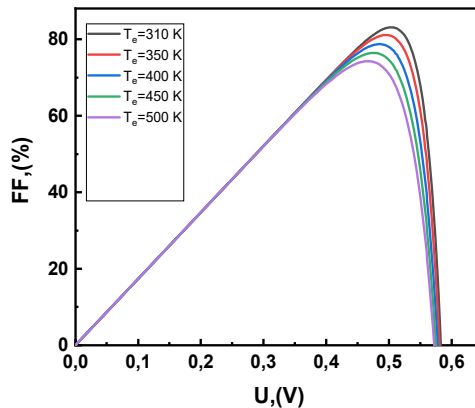


Fig. 3 – Dependence of the relative filling power of the photocell on the voltage at different values of the electron temperature.

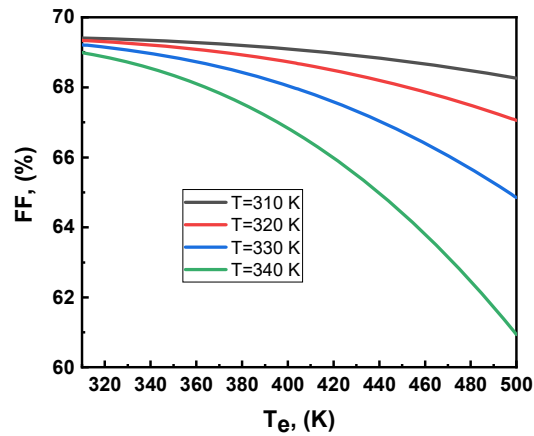


Fig. 4 – Dependence of the filling factor of the photocell on the electron temperature at different temperatures of the crystal temperature.

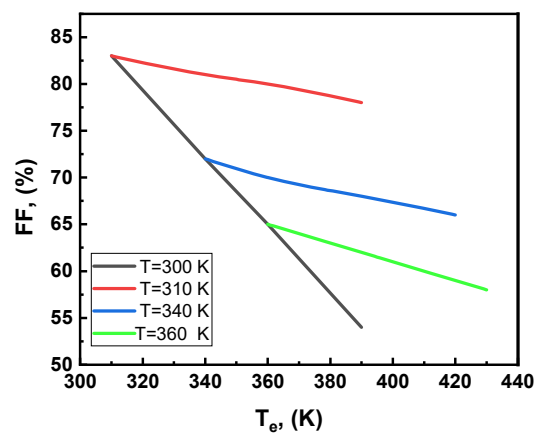


Fig. 5 – Dependences of the filling factor of the photocell on the lattice temperature T and the electron temperature.

The dependence of FF on the electron temperature starts from the initial temperature of the carriers equal to the lattice temperature. The lower the lattice temperature, the higher are the values of the filling factor lines on the electron temperature. Figure 6 shows the graphs of the temperature dependence of the filling factor on the electron temperature T_e [25–28].

Heating the grid reduces the filling factor of the photocell. Therefore, avoid heating the grate. The dependence of the efficiency on the temperature (Figs. 6–7) of the heated electron in different cases is as follows: $T_0 = 300$ K; $T = 310$ K; $T_e = 310 \dots 500$ K.

The graphs of power in three-dimensional space (dependence of power, voltage U , and on the electron temperature T_e) [29–31] may be observed in Fig. 7.

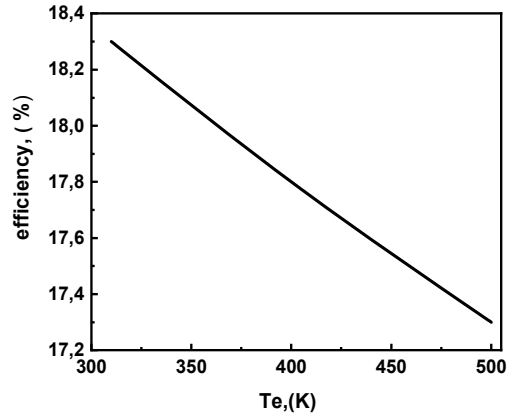


Fig. 6 – Dependence of the efficiency of the photocell on the electron temperature.

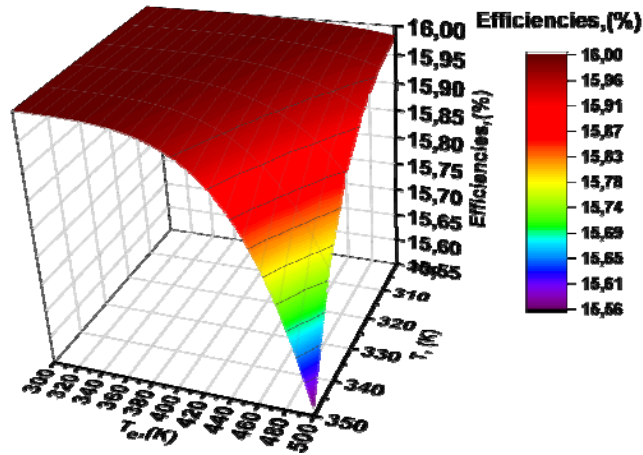


Fig. 7 – Dependence of the efficiency of the photocell on the lattice temperature T and the electron temperature Te .

The $I-V$ characteristic experiments. Let's carry out the calculation results according to the following formula

$$J = J_{s0} \left(\frac{T}{T_0} \right)^3 \cdot e^{\left(\frac{E_g e}{kT_0} \left(1 - \frac{T_0}{T} \right) \right)} \left(e^{\frac{e\phi_0 - e(\phi_0 - U - U_1 + J(R_b - AU))}{kT}} - 1 \right) + \frac{U}{R_u} - J_f, \quad (12)$$

with experimental data [17, 18, 19].

The experiment comparisons: black – $U = 1.75$ V; red – $U = 1$ V and theory, black – $J_f = 21$ mA/sm², $R_b = 0.01$, $R_u = 100\ 000$; red – $J_f = 1.38$ mA/sm², $R_b = 0.033$, $R_u = 100\ 010$.

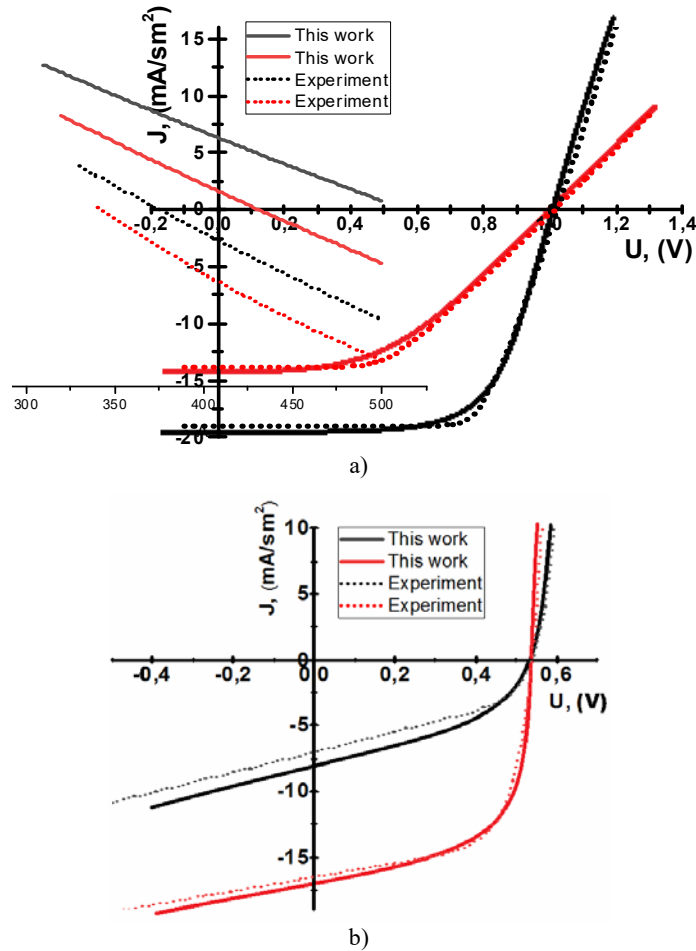


Fig. 8 – Change in the current-voltage characteristic under the action of heated electrons and photocurrent.

The experiment comparisons: red – $U = 1.5$ V; black – $U = 0.75$ V and theory red – $J_f = 16.5$ mA/sm², $R_b = 0.004$, $R_u = 0.19$, $T = 335$ K, $T_e = 520$ K; black – $J_f = 9.5$ mA/sm², $R_b = 0.005$, $R_u = 0.13$, $T = 312$ K, $T_e = 480$ K.

These graphs in Fig. 8 show that the fill factor and efficiency decrease with increasing temperature. Recombination currents increase when electrons and holes are heated [32–37]. The sign of the recombination current will be opposite to the sign of the photocurrent. Since the recombination currents are opposite to the generation current, the heating of electrons and holes decreases the resulting current. Heating reduces the efficiency of the solar cell. In addition, an increase in the base resistance reduces the efficiency of the photocell [38–42]. An increase in leakage resistance increases its efficiency.

3. CONCLUSIONS

The photocurrent and photovoltage generated in the diode move the I – V characteristic diode on the JU plane.

The photocell becomes an energy source as the I – V characteristic passes through quadrant II. When exposed to microwave radiation from a I – V characteristic diode with a p-n junction, it passes through quadrant II [1–3].

The I – V characteristic of the photocell can be adjusted by the light intensity or the intensity of the microwaves. If the recombination currents are greater than the generation currents, the current flowing through the diode will be positive, otherwise it will flow in the negative direction. If the magnitude of the EMF generated in the diode gives a constant current, the no-load voltage will cross the voltage axis at negative values of I – V characteristic [43–46].

Heated charge carriers increase the recombination currents. This causes the I – V characteristic p-n junction to move positively along the current axis and negatively along the voltage axis [47–49]. With an increase in the recombination current, the I – V characteristic of the diode crosses the voltage axis, at negative values. With an increase in the generation current of the I – V characteristic of the diode, the voltage axis at its positive values.

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