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RESEARCH PAPER

Effect of Variation of Non-ideal Ratio on Electrical Properties of P-N-Junction in Strong Microwave Field, Theoretical Study

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Abstract: *Under the influence of a strong electromagnetic field, Eddy currents are generated in the p-n junction, which affects the generated currents in the sample. When exposed to a strong electromagnetic field, the sensitivity of the p-n junction I-V curve non-ideality coefficient change increases. In this case, a recombination process occurs in the p-n junction under the influence of a strong electromagnetic field, and it strongly affects the coefficient of non-ideality. The current coming out of the diode in the alternating field is only determined by the convection current, and the average value of the displacement current is always zero, which has no effect on the average current coming out of the diode, this causes the currents generated in different diodes in the electromagnetic field. Taking this into account, in this study, when electrons and holes in the p-n junction are heated under the influence of strong and weak very high frequency (VHF) fields, and the height of the potential barrier is disturbed, the increase in the value of the coefficient of non-ideality of the p-n junction I-V curve leads to an increase in the differential resistance, as well as the diffusion capacity and it is shown that it occurs due to the decrease of differential conductivity.*

Keywords: *p-n junction, Strong microwave field, Differential resistance, Diffusion capacitance, Differential conductance, Non-ideality coefficient.*

1. INTRODUCTION

The basis of semiconductor devices is the p-n-junction, and the in-depth study of its theory plays a decisive role in the development of the physics of semiconductor devices. So far, many studies have been conducted to study the p-n-junction characteristics [1-14]. Experimental results show that the study of the capacitance-voltage characteristics of semiconductors in the production of photoelectric devices increases their efficiency [6]. Using the parameters R~ 10^2~ 10^4 Ohm, C= 10^2 pF, ν= 10^{10} Hz of typical samples in the experiments of A.I. Veynger [6, 7]. It was shown [9] that the shear current in operation is from a thousand to several hundred thousand times greater than the convection current and based on this experimental fact, it was assumed that the capacitance of the diode - C completely shunts its differential resistance - R. Indeed, at frequencies of ν= 10^{10} Hz, it can be considered that alternating current flows through the capacitor. In other words, the capacitance current of the diode is many times greater than the convection current in the p-n-junction.

In this case, the active conductance of the p-n-junction is strongly shunted by the capacitance of the diode, and it can be seen that the sample almost completely loses its rectification properties. The generation of lumped currents in p-n-junction under the influence of a strong electromagnetic field and its effect on the generated currents in the sample was considered in detail in Ref [13]. When exposed to light and a strong electromagnetic field at the same time, the sensitivity of the p-n-junction I-V characteristics to the change of the coefficient of non-ideality increases. In this case, the occurrence of recombination and generation processes in the p-n-junction under the influence of a strong electromagnetic field and light and their strong influence on the coefficient of non-ideality was determined [11]. The current coming out of the diode in the variable field is only determined by the convection current, and the average value of the displacement current is always zero, which does not affect the average current coming out of the diode, and the occurrence of currents generated in different diodes in this electromagnetic field is shown [9]. It was shown in Ref [10] that the p-n-junction current at low frequencies is determined only by the active resistance of the electron-hole junction and the resistance of p and n-junction of the semiconductor, and at high frequencies the

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inertia of the p-n-junction is determined by its capacitance. External influences on p-n-junction I-V characteristics were studied theoretically in Ref. [12]. External effects are of great importance in obtaining non-ideal p-n-junction diodes and increasing their performance [15-19]. In experiments, the following expression is used for the I-V characteristic of p-n junction diodes [20].

$$I = I_s\left[\exp\left(\frac{eU}{mkT}\right) - 1\right]$$

Here, m is the coefficient of non-ideality.

In works [21-28], it was considered that the non-ideality coefficient occurs due to the heating of the charge carriers of diodes as a result of external influences. In diodes, as a result of external influences, the non-ideality coefficient occurs in the contacts due to the higher temperature of electrons and holes compared to phonons. However, the various external effects on p-n-junction differential resistance, diffusion capacitance, and differential conductance have not been theoretically sufficiently studied in the works cited in the existing literature. Therefore, in this work, the main goal is to theoretically study various external effects, especially the effect of the change of the non-ideality coefficient of the p-n-junction I-V characteristics located in the strong microwave field on the differential resistance, diffusion capacity, and differential conductivity.

2. EXPERIMENTAL PROCEDURES

In this work, mathematical expressions of the electro-physical properties of the p-n junction: differential resistance, diffusion capacity, and differential conductivity were derived due to the change of the non-ideality coefficient of the p-n junction under the influence of a strong ultra-high frequency field. Using these expressions, the change in the electro-physical properties of the p-n junction is modeled using the Maple program. In this case, expressions of strong ultra-high-frequency field, weak ultra-high-frequency field, and p-n-junction I-V characteristics in an ideal state were used. Using these expressions, it was determined that the electro-physical properties of the p-n junction change as a result of external influences.

3. RESULTS AND DISCUSSION

3.1. Effect of Variation of the non-Ideality Coefficient on the Differential Resistance of the p-n Junction I-V Characteristics Located in the Strong Microwave Field Area

From the expression of dependence of p-n-junction current, p-n-junction I-V characteristics on the non-ideality coefficient when electrons and holes in p-n-junction are heated and the potential barrier height $T_e \neq T_h > T, U_B \neq 0$ is disturbed under the influence of the strong microwave field [11]:

$$\bar{j} = \frac{eD_e n_p}{L_e}\left(\frac{T_e}{T}\right)^{\frac{1}{2}}\exp\left(\frac{e\varphi_0}{mkT} - \frac{e(\varphi_0 - U)}{mkT_e}\right)\left\{\int_0^{2\pi}\exp\left(-\frac{eU_B\cos(\omega t)}{mkT_e}\right)\frac{d(\omega t)}{2\pi} - 1\right\} + \frac{eD_h p_n}{L_h}\left\{\left(\frac{T_h}{T}\right)^{\frac{1}{2}}\exp\left(\frac{e\varphi_0}{mkT} - \frac{e(\varphi_0 - U)}{mkT_h}\right)\int_0^{2\pi}\exp\left(-\frac{eU_B\cos(\omega t)}{mkT_h}\right)\frac{d(\omega t)}{2\pi} - 1\right\} \quad (1)$$

(1) To simplify expression, we introduce the following notation

$$e^{-\frac{eU_1}{mkT}} = \frac{1}{2\pi}\int_0^{2\pi}\left(\exp\left(-\frac{eU_B\cos(\omega t)}{mkT_e}\right)\right)d(\omega t),$$

$$e^{-\frac{eU_1}{mkT}} = \frac{1}{2\pi}\int_0^{2\pi}\left(\exp\left(-\frac{eU_B\cos(\omega t)}{mkT_h}\right)\right)d(\omega t)$$

by specifying

$$I = \frac{eD_e n_p}{L_e}\left(\left(\frac{T_e}{T}\right)^{\frac{1}{2}} e^{\left(\frac{e\varphi_0}{mkT} - \frac{e(\varphi_0 - U - U_1)}{ekT_e}\right)} - 1\right) + \frac{eD_h p_n}{L_h}\left(\left(\frac{T_h}{T}\right)^{\frac{1}{2}} e^{\left(\frac{e\varphi_0}{mkT} - \frac{e(\varphi_0 - U - U_2)}{mkT_h}\right)} - 1\right) \quad (2)$$

(2) we derive the expression

Using the p-n-junction differential resistance equation and equation (2), we get the following expression [1]

$$R = \left(\frac{dI}{dU}\right)^{-1} = \left(\left(\frac{eD_e n_p}{L_e}\left(\left(\frac{T_e}{T}\right)^{\frac{1}{2}} e^{\left(\frac{e\varphi_0}{mkT} - \frac{e(\varphi_0 - U - U_1)}{mkT_e}\right)} - 1\right) + \frac{eD_h p_n}{L_h}\left(\left(\frac{T_h}{T}\right)^{\frac{1}{2}} e^{\left(\frac{e\varphi_0}{mkT} - \frac{e(\varphi_0 - U - U_2)}{mkT_h}\right)} - 1\right)\right)\frac{1}{dU}\right)^{-1} \quad (3)$$

(3) By differentiating the expression concerning U, we get the expression of the dependence of the differential resistance on the non-ideality coefficient of the p-n-junction I-V characteristics:

$$R = \left[\frac{kL_e\sqrt{TT_e}}{e^2 D_e n_p} e^{\frac{e(\varphi_0 - U_1 + U)}{mkT_e} - \frac{e\varphi_0}{mkT}}\right] + \left[\frac{kL_h\sqrt{TT_h}}{e^2 D_h p_n} e^{\frac{e(\varphi_0 - U_2 - U)}{mkT_h} - \frac{e\varphi_0}{mkT}}\right] \quad (4)$$

Using the expression (4), it is possible to obtain a graph of the dependence of the differential resistance on the applied voltage (Fig. 1).

It can be seen that when the electrons and holes in the p-n-junction are heated and the potential

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barrier height is disturbed under the influence of the strong microwave field, the differential resistance increases with the increase in the value of the coefficient of non-ideality of the p-n-junction I-V characteristics.

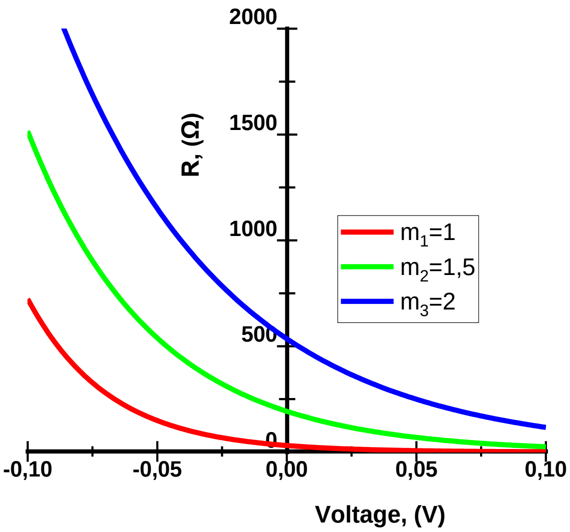

Fig. 1. The dependence of the differential resistance of a p-n-junction located in a microwave field on voltage, with a non-ideality coefficient m_1= 1, m_2= 1.5, m_3= 2

The current passing through $T_e = T_h = T, U_B \neq 0$ the p-n junction in the weak strong microwave field arises only from the perturbation of the potential barrier height and is determined by the following expression [11].

$$\bar{I} = I_s\left[\exp\left(\frac{eU}{mkT}\right)\int_0^{2\pi}\left(\exp\left(-\frac{eU_B\cos(\omega t)}{mkT}\right)\right)\frac{d(\omega t)}{2\pi} - 1\right] \quad (5)$$

Using the p-n-junction differential resistance equation and equation (5), we get the following expression [1]:

$$R = \left(\frac{dI}{dU}\right)^{-1} = \frac{mkT}{eI_s}e^{\frac{e(U+U_1-\varphi)}{mkT}} \quad (6)$$

(6) The expression is the expression of the dependence of the differential resistance on the coefficient of non-ideality of the p-n-junction I-V characteristics. Using this expression, it is possible to obtain a graph of the dependence of the determined differential resistance on the applied voltage (Fig. 2).

It can be seen that the electrons and holes in the p-n junction do not heat up under the influence of a weak strong microwave field, only the differential resistance increases with the increase in the value of the coefficient of non-ideality of the p-n junction I-V characteristics due to the perturbation of the potential barrier height.

If the dark current, electrons, and holes are not heated and if the disturbance of the potential barrier height is not taken into account, the current passing through $T_e = T_h = T, U_B = 0$ the p-n-junction is determined by the following expression [11]:

$$I = I_s\left[\exp\left(\frac{eU}{mkT}\right) - 1\right] \quad (7)$$

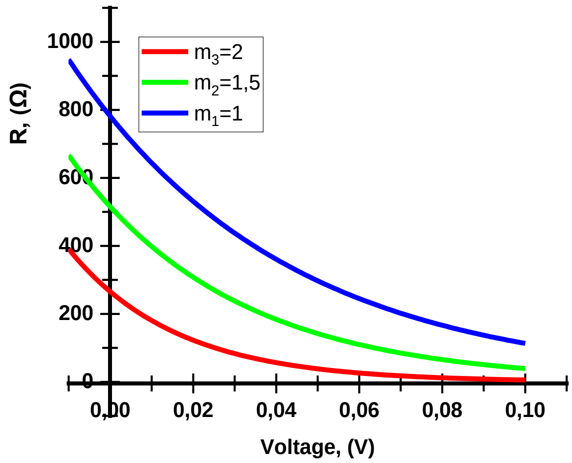

Fig. 2. The dependence of the differential resistance of a p-n-junction located in a weak microwave field on voltage, with a non-ideality coefficient m_1= 1, m_2= 1.5, m_3= 2

Using the expression (7), it will be possible to find the equation of the dependence of the differential resistance on the coefficient of non-ideality of the p-n-junction I-V characteristics:

$$R = \frac{mkT}{eI_s}e^{-\frac{eU}{mkT}} \quad (8)$$

Using this expression, a graph of the dependence of the differential resistance on the applied voltage can be obtained (Fig. 3).

It can be seen that if the dark current, electrons, and holes are not heated and if the potential barrier height disturbance is not taken into account, the differential resistance increases with the increase in the value of the non-ideality coefficient of the p-n junction I-V characteristics.

3.2. The Influence of the Change in the non-Ideality Coefficient of the p-n Junction I-V Characteristics Located in the Strong Microwave Field Area on the Diffusion Capacity

Imbalance in p- and n-junction creates a diffusion capacity of non-main charge carriers. The magnitude of the diffusion capacity of the p-n junction is proportional to the residence time of non-main charge carriers [1].

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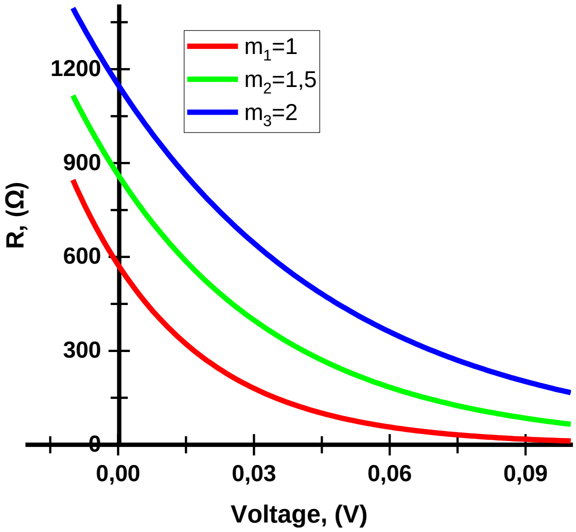

Fig. 3. The dependence of the differential resistance of the p-n-junction at the coefficient of non-ideality m_1= 1, m_2= 1.5, m_3= 2 for the case when the electrons and holes of the dark current are not heated and without taking into account the perturbation of the height of the potential barrier

$$C = R^{-1}\frac{\tau}{2} \tag{9}$$

τ- electron-hole residence time. (9) by putting the expression (4) of the dependence of the differential resistance on the coefficient of non-ideality of the p-n-junction I-V characteristics to the expression, we derive the expression of the dependence of the diffusion capacitance on the coefficient of non-ideality of the p-n-junction I-V characteristics:

$$C = \left(\left(\frac{kL_e\sqrt{TT_e}}{e^2D_en_p}e^{\frac{e(\varphi_0-U_1+U)}{mkT_e}-\frac{e\varphi_0}{mkT}}\right) + \left(\frac{kL_h\sqrt{TT_h}}{e^2D_hp_n}e^{\frac{e(\varphi_0-U_2-U)}{mkT_h}-\frac{e\varphi_0}{mkT}}\right)\right)^{-1}\frac{\tau}{2} \tag{10}$$

(10) In the expression, the residence times of electron-holes are assumed to be equal, and the voltage dependence graph of the diffusion capacity is as follows (Fig. 4).

It can be seen that when the electrons and holes in the p-n-junction are heated and the potential barrier height is disturbed under the influence of the strong microwave field, the diffusion capacity decreases with the increase in the value of the coefficient of non-ideality of the p-n-junction I-V characteristics.

Using expressions (9) and (6), we get the expression of the dependence of the diffusion capacitance on the coefficient of non-ideality of the p-n-junction I-V characteristics:

$$C = \frac{eI_s\tau}{2mkT}e^{\frac{e(U+U_1-\varphi)}{mkT}} \tag{11}$$

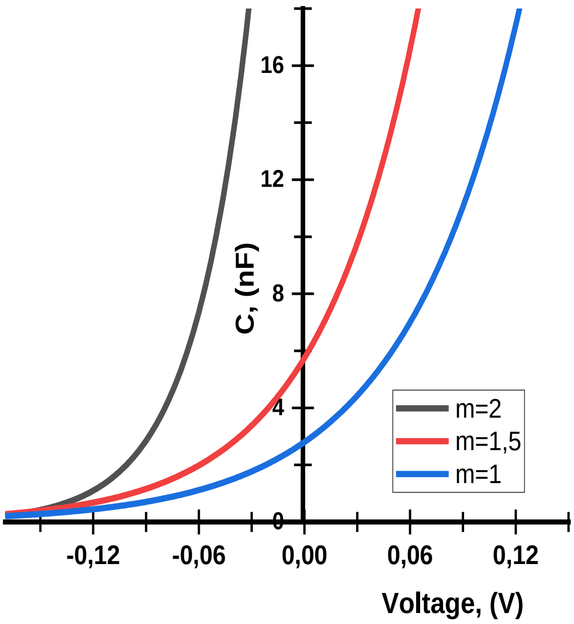

Fig. 4. The dependence of the diffusion capacitance of a p-n-junction located in a microwave field on voltage, with a non-ideality coefficient m_1= 1, m_2= 1.5, m_3= 2

In the expression, the heating of electrons and holes in the p-n junction was not taken into account, the height of the potential barrier was perturbed, and the residence times of electrons and holes were assumed to be equal. Using this expression, it is possible to obtain a graph of diffusion capacity versus voltage (Fig. 5).

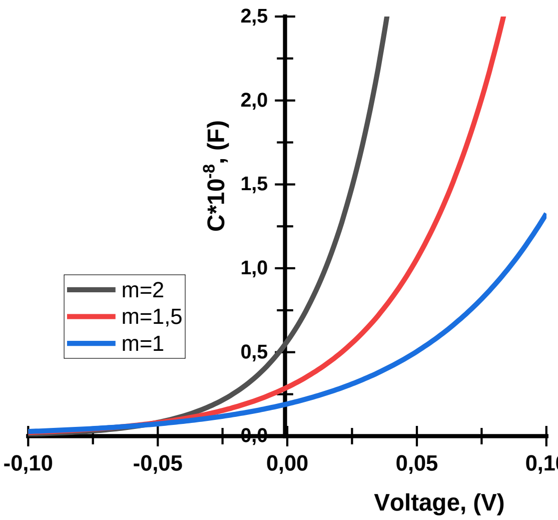

Fig. 5. Figure 5. The dependence of the diffusion capacitance of a p-n-junction located in a weak microwave field on voltage, with a non-ideality coefficient m_1= 1, m_2= 1.5, m_3= 2

It can be seen that the electrons and holes in the

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p-n-junction are not heated under the influence of a weak electric field, but the diffusion capacity decreases with the increase in the value of the coefficient of non-ideality of the p-n-junction I-V characteristics when the height of the potential barrier is disturbed.
Using expressions (9) and (8), we derive the expression for the dependence of the diffusion capacity on the non-ideality coefficient of the p-n junction I-V characteristics when the heating of electrons and holes in the p-n junction is not taken into account:

$$C = \frac{\tau e I_s}{2mkT} e^{-\frac{eU}{mkT}} \tag{12}$$

In the expression, the heating of electrons and holes in the p-n-junction was not taken into account, the height of the potential barrier was not disturbed, and the residence times of electrons and holes were assumed to be equal. Using this expression, it is possible to obtain a graph of the dependence of the diffusion capacitance on the voltage when taking into account the change in the non-ideality coefficient of the p-n-junction I-V characteristics (Fig. 6).

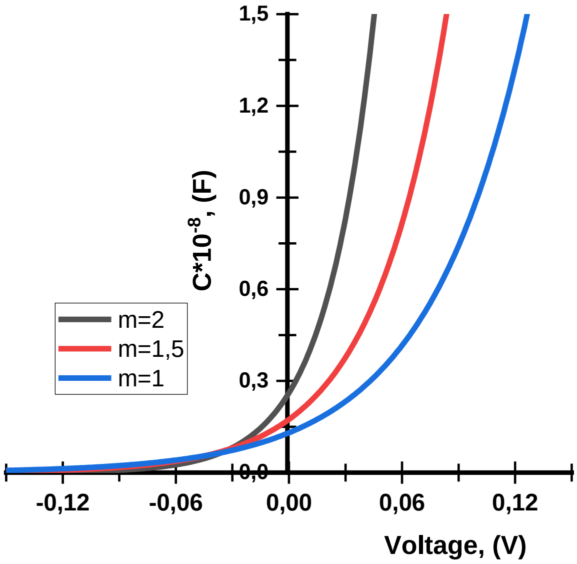

Fig. 6. Dependence of the diffusion capacitance of the p-n-junction at the non-ideality coefficient m_1= 1, m_2= 1.5, m_3= 2 for the case when the electrons and holes of the dark current are not heated and without taking into account the perturbation of the potential barrier height

It can be seen from Fig. 6 that the diffusion capacity decreases with the increase in the value of the non-ideality coefficient of the p-n-junction I-V characteristics when the electrons and holes are not heated and the potential barrier height disturbance is not taken into account.

3.3. Effect of Variation of the non-Ideality Coefficient of the p-n-Junction I-V Characteristics Located in the Strong Microwave Field Area on the Differential Conductance

When the electrons and holes in the p-n-junction are heated and the potential barrier height is disturbed under the influence of the strong microwave field, from the expression (4) of the p-n-junction differential resistance, we get the following expression for the p-n-junction differential conductance:

$$G = \frac{1}{\left(\frac{kL_e\sqrt{TT_e}}{e^2 D_e n_p} e^{\frac{e(\varphi_0 - U_1 + U)}{mkT_e} - \frac{e\varphi_0}{mkT}}\right) + \left(\frac{kL_h\sqrt{TT_h}}{e^2 D_h p_n} e^{\frac{e(\varphi_0 - U_2 + U)}{mkT_h} - \frac{e\varphi_0}{mkT}}\right)} \tag{13}$$

Using this expression, it is possible to obtain a graph of the dependence of the differential conductivity on the applied voltage (Fig. 7).

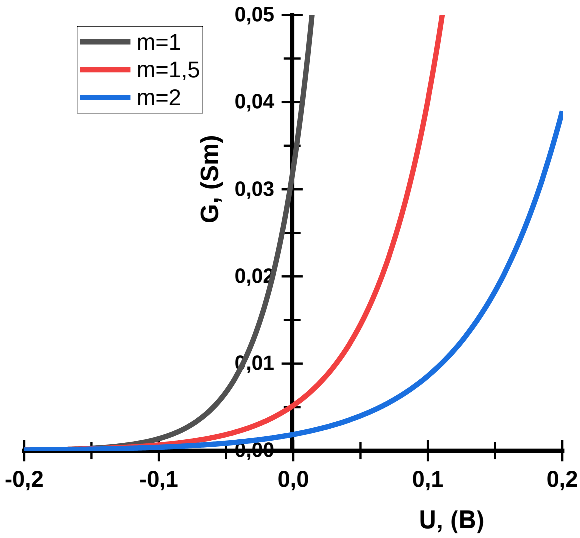

Fig. 7. The dependence of the differential conductivity of a p-n-junction located in a microwave field on voltage, with a non-ideality coefficient m_1= 1, m_2= 1.5, m_3= 2

It can be seen from Fig. 7 that when the electrons and holes in the p-n-junction are heated and the potential barrier height is disturbed under the influence of a strong electromagnetic field, the differential conductivity decreases with the increase in the value of the non-ideality coefficient of the p-n-junction I-V characteristics. Using the expression (6) of the differential resistance of the p-n-junction, we get the following expression for the differential conductance when the current passing through the p-n-junction in a

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weak strong microwave field arises only from the perturbation of the potential barrier height.

$$G=\frac{eI_s}{mkTe^{-\frac{e(U+U_1-\varphi)}{mkT}}} \qquad (14)$$

Using this formula, it is possible to obtain a graph of the dependence of the determined differential conductivity on the applied voltage (Fig. 8).

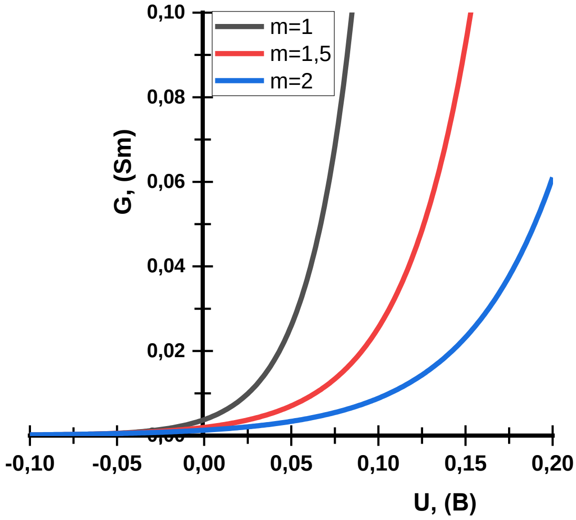

Fig. 8. The dependence of the differential conductivity of a p-n-junction located in a weak microwave field on voltage, with a non-ideality coefficient m_1= 1, m_2= 1.5, m_3= 2

It can be seen that the electrons and holes in the p-n junction do not heat up under the influence of a weak a strong microwave field, but the differential conductivity decreases with the increase in the value of the non-ideality coefficient of the p-n-junction I-V characteristics due to the perturbation of the potential barrier height.

Using the expression (8) for the differential resistance of the p-n-junction when the dark current, electrons, and holes are not heated and the potential barrier height perturbation is not taken into account, we get the following expression for the differential conductance.

$$G=\frac{eI_s}{mkTe^{-\frac{eU}{mkT}}} \qquad (15)$$

Using this expression, it is possible to obtain a graph of the dependence of the differential conductance on the applied voltage (Fig. 9).

It can be seen that if the dark current, electrons, and holes are not heated and if the potential barrier height perturbation is not taken into account, the differential conductance decreases with the increase in the value of the non-ideality coefficient of the p-n-junction I-V characteristics.

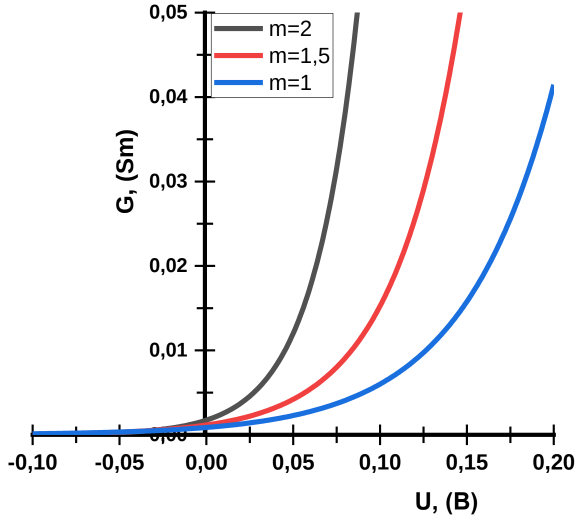

Fig. 9. Dependence of the differential conductivity of the p-n-junction at the non-ideality coefficient m_1= 1, m_2= 1.5, m_3= 2 for the case when the electrons and holes of the dark current are not heated and without taking into account the perturbation of the potential barrier height

4. CONCLUSIONS

When the electrons and holes in the p-n junction are heated and the potential barrier height is disturbed under the influence of strong and weak VHF fields, it was found that the increase in the value of the coefficient of non-ideality of the p-n junction I-V curve was caused by an increase in the differential resistance, as well as a decrease in the diffusion capacity and differential conductivity. This, in turn, provides an opportunity to determine the characteristics of p-n-junction diodes by the value of the coefficient of non-ideality.

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