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CALCULATION OF THE TOTAL CURRENT GENERATED IN A TUNNEL DIODE UNDER THE ACTION OF MICROWAVE AND MAGNETIC FIELDS[†]

Gafur Gulyamov[a], Sharifa B. Utamuradova[b], Mukhamadjon G. Dadamirzaev[a], Nozimjon A. Turgunov[b], Munira K. Uktamova[b,§], Kakhramon M. Fayzullaev[b,*], Arofat I. Khudayberdiyeva[c], Alisher I. Tursunov[d]
[a]Namangan Engineering Construction Institute, Namangan, Uzbekistan
[b]Institute of Semiconductor Physics and Microelectronics at the National University of Uzbekistan, Tashkent, Uzbekistan
[c]Tashkent Institute of Chemical Technology, [d]Termiz State University, Termiz, Uzbekistan
**Corresponding Author e-mail: qahramonfayzullayev8@gmail.com, [§]e-mail: umk9391@gmail.com*
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In this paper, a formula was derived for calculating the total current generated in a tunnel diode under the action of a microwave field and a magnetic field. In addition, the dependence of the total current of the tunnel diode on the total power induced by the microwave field is theoretically presented and compared with experimental data. For the total current in the tunnel diode, without taking into account the excess current, volt-ampere characteristics was obtained for cases with and without the influence of a microwave field.
Keywords: *Chynowet model; Tsu-Esaki model; microwave field; magnetic field; barrier transparency coefficient; excess current*
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INTRODUCTION

At present, the study of semiconductor-based nanostructures is a very topical direction in both fundamental and applied aspects [1–5].

The tunneling effect was experimentally discovered by Yajima and Esaki in a highly doped germanium-based diode [6]. A model was proposed by Leo Esaki in 1958 to explain this effect. In 1960, Evan O [7] developed a comprehensive theory of experience. Shortly thereafter, Karlovsky [8] proposed a simpler version of Esaki's model. In the Karlovsky model, the Fermi levels were sufficiently small. I. Shalish [9] and Kane, who worked independently, proposed the same model of the tunnel effect mechanism without knowing each other. In 1969, Duke presented a more advanced version of tunnel models [10]. As research on the properties of semiconductor materials and devices based on them continues, various tunneling models for p-n junction diodes have been presented. Since the electrical properties of semiconductor materials mainly depend on the state of impurity atoms in their volume, when choosing an alloying element, one should pay attention to their physicochemical parameters [11–14]. At a conference in Berlin in 1989, Herks presented a new model that related the rate of Shockley-Reed-Hall (SRH) recombination and zone-tunneling in the opposite direction [10]. In his work, Herks calculated the contribution of the tunneling effect as the recombination rate of the flux density. In the same direction, in 1991, Claassen [10] presented his model for the case of direct tunneling. The tunneling probability can also be calculated using the Wenzel-Kramers formula, but it is more convenient to calculate the tunneling probability using the transfer matrix method. Currently, the calculation of the tunnel current for diodes with a p-n junction using the Tsu-Esaki model [15] gives good results. This model was developed taking into account the possibility of tunneling mentioned above. Today, scientists are proposing new models, as silicon-based diodes are used in many experimental works.

Tunnel diodes are widely used in the manufacture of various modern devices, such as nuclear weapons guiding installations, the creation of aerospace equipment, microwave ovens, etc. This indicates that the study of the properties of tunnel diodes and their wide application has great scientific and practical meaning. From the works presented above and from the available literature data, it can be seen that the effect of a magnetic field and an electromagnetic field with an ultrahigh frequency on a tunnel diode has not been studied enough. Based on this, the purpose of this work is to develop a new model for calculating the total current for a tunnel diode, taking into account the impact on the tunnel diode of a magnetic field and a microwave electromagnetic field [12–14].

A NEW MODEL FOR CALCULATING THE TOTAL CURRENT IN A TUNNEL DIODE

According to the Tsu-Esaki theory, the direct current flowing through a tunnel diode is determined by the product of the $N(E_X)$- distribution function and the $T_C(E_X)$**-** transfer coefficient [10, 15, 16]:

$$I_T = \frac{4\pi m_{ef} q}{\hbar^3} \int_{min}^{max} T_C(E_X) N(E_X) dE_X. \tag{1}$$

The values of tunnel currents passing from region p to region n and from region n to region p are determined by the following expressions [15]:

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$$I_{p\to n} = A\int_{\varepsilon_n}^{\varepsilon_p} f_p(\varepsilon)\,\rho_p(\varepsilon)P[1-f_n(\varepsilon)]\rho_n(\varepsilon)d\varepsilon. \tag{2}$$

$$I_{n\to p} = A\int_{\varepsilon_n}^{\varepsilon_p} P\,f_n(\varepsilon)\rho_n(\varepsilon)\big[1-f_p(\varepsilon)\big]\rho_p(\varepsilon)d\varepsilon. \tag{3}$$

The total tunnel current in the p-n junction is equal to the difference between expressions (2) and (3):

$$I = A\int_{\varepsilon_n}^{\varepsilon_p} \rho_p(\varepsilon)\rho_n(\varepsilon)P\big[f_n(\varepsilon)-f_p(\varepsilon)\big]d\varepsilon. \tag{4}$$

The $T_C(E_X)$**-**transfer coefficient and $N(E_X)$-distribution functions can be specified as follows [16]:

$$N(E_X) = \int_0^{\infty}\big[f_n(\varepsilon)-f_p(\varepsilon)\big]\,dE_P, \tag{5}$$

$$T_C(E_X) = \int P\rho_P(\varepsilon)\,\rho_n(\varepsilon)d\varepsilon. \tag{6}$$

where ε_n and ε_p - are the minimum energy that electrons can accept in the conduction band of an n-semiconductor and the maximum energy that electrons can accept in the valence band of a p-semiconductor.

If we take the lower part of the conduction band as the beginning of the energy axis, that is, if we take $\varepsilon_n = 0$ (Fig. 1), and, based on this figure, we have the following expression for the energy (ε_P):

$$\varepsilon_P = qV_K - E_g = \mu_n + \mu_P. \tag{7}$$

where $\mu_n$and μ_P are the chemical potentials (Fermi level) for the regions n and p, respectively.

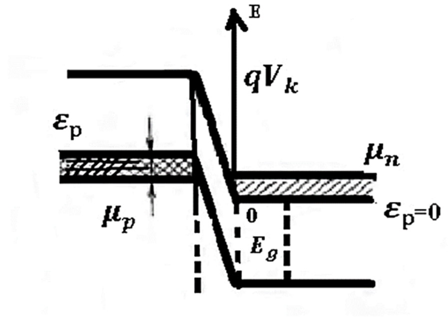

Figure 1. Scheme of forming the current-voltage characteristic of a tunnel diode

Also, when an external voltage is applied, we have:

$$\varepsilon_P = \mu_n + \mu_P - qV. \tag{8}$$

And the distribution function is determined by the expressions:

$$f_n(\varepsilon) = \frac{1}{exp\left(\frac{\varepsilon-\mu_n}{kT}\right)+1}, \tag{9}$$

$$f_P(\varepsilon) = \frac{1}{exp\left(\frac{\varepsilon+\mu_P-qV_K+E_g+qV}{kT}\right)+1}. \tag{10}$$

The density of states of electrons and holes is $\rho_n(\varepsilon) = C\sqrt{\varepsilon}$, $\rho_P(\varepsilon) = C'\sqrt{qV_K - E_g - qV - \varepsilon}$, where C and C' - are constant numbers. Taking into account the above, using expression (10), we obtain the following expression for the tunnel current [15]:

$$I_T = PTA\left(\int_0^{qV_K-E_g-qV}\left(\frac{1}{exp\left(\frac{\varepsilon-\mu_n}{kT}\right)+1} - \frac{1}{exp\left(\frac{\varepsilon+\mu_P-qV_K+E_g+qV}{kT}\right)+1}\right)\sqrt{\varepsilon\big(qV_K - E_g - qV - \varepsilon\big)}\right)d\varepsilon. \tag{11}$$

Using expressions (9) and (10), finding qV_k and substituting expression (11), we obtain the following expression for the tunnel current:

$$I_t = APT\int_0^{\mu_n+\mu_p-qV}\sqrt{\varepsilon\big(\mu_n+\mu_p-\varepsilon-qV\big)}\left(\frac{1}{exp\left(\frac{\varepsilon-\mu_n}{kT}\right)+1} - \frac{1}{exp\left(\frac{\varepsilon-\mu_n+qV}{kT}\right)+1}\right)d\varepsilon. \tag{12}$$

where: $A = C'C\frac{4\pi m_{eff}q}{\hbar^3}$. For the transparency coefficient, we use the following formula [10, 17]:

$$P = exp\left(-\frac{\alpha E_g^{\frac{3}{2}}}{F}\right). \tag{13}$$

where: E-field strength, $\alpha = \theta\frac{4\sqrt{2m_e}}{3q\hbar}$; θ≈1 (θ is a constant parameter of the Chynoweth model). In many models [10, 17, 18], the barrier transparency coefficient was not taken into account, since E=const. Taking the value for the drift velocity of an electron at a p-n junction:

$$\vartheta = \mu E_x. \tag{14}$$

(Where, m_{eff} is the mobility of the electron, E_x is the intensity of the microwave field), the expression of the power generated by the microwave field:

$$F = qE_x. \tag{15}$$

as well as the value for the total power induced by the microwave field:

$$P_1 = F\vartheta. \tag{16}$$

we have the following expression for the power under the action of a microwave field at a p-n tunnel junction:

$$\frac{P_1 - P_0}{N} = F\vartheta. \tag{17}$$

where N is the number of electrons, is the difference between the total powers of the microwave field applied to the diode and the sample. If we generalize the above expressions, then the expression for the power spent on an electron under the action of a microwave field in a p-n tunnel junction can be written as follows.

$$\frac{P_1 - P_0}{N} = q\mu E_x^2. \tag{18}$$

from this expression we have the following formula for the Ex-strength of the field under action:

$$E_x = \sqrt{\frac{P_1 - P_0}{Nq\mu}}. \tag{19}$$

And the expression for the transparency coefficient of the barrier under the action of the microwave field will have the form:

$$P = exp\left(-\frac{\alpha E_g^{\frac{3}{2}}}{E+E_x}\right) = exp\left(-\frac{\alpha E_g^{\frac{3}{2}}}{E+\sqrt{\frac{P_1 - P_0}{Nq\mu}}}\right). \tag{20}$$

The expression for the diffusion current for a heated electron is given by the following formula [19, 20]:

$$I_d = \left(I_0 \cdot \left(\frac{T}{T_0}\right)^3\right) \cdot exp\left(\frac{E_g \cdot q}{k \cdot T_0}\left(1 - \frac{T_0}{T}\right)\right) \cdot \left(e^{\frac{q\cdot\phi}{k\cdot T} - \frac{q\cdot(\phi - V)}{k\cdot T_e}} - 1\right). \tag{21}$$

It is known that the total current I generated in a tunnel diode is the sum of the tunnel current, I_{Ch}excess current, and I_d diffusion currents in the tunnel diode [20].

If the excess current in the tunnel diode is affected by the microwave field, then we have the following expression for volt-ampere characteristics:

$$I_{Ch} = DP = \int_{\mu_n+\mu_p}^{0}\left(\sqrt{\varepsilon(\mu_n + \mu_p - \varepsilon - qV)}\left(\frac{1}{exp\left(\frac{\varepsilon-\mu_n}{kT}\right)+1} - \frac{1}{exp\left(\frac{\varepsilon-\mu_n+qV}{kT}\right)+1}\right)\right)d\varepsilon \times exp\left(-\frac{\alpha E_g^{\frac{3}{2}}}{E+E_x}\right) \tag{22}$$

Here we have obtained the electric field strength as $E_X = \frac{V_K - V + V_m}{d}$, V - external voltage, V_k - contact potential difference, d - potential barrier width, V_m- voltage applied by the microwave field). Also, here we assumed that the density of states formed by impurities in the band gap in a p-n tunnel diode is constant. Now, summing all the current expressions, we obtain the following expression for the resulting total current for the tunnel diode:

$$I = TA\,exp\left(-\frac{\alpha E_g^{\frac{3}{2}}}{E+\sqrt{\frac{P_1-P_0}{Nq\mu}}}\right)\times$$

$$\times\int_0^{\mu_n+\mu_p-qV}\left(\sqrt{\varepsilon(\mu_n+\mu_p-\varepsilon-qV)}\left(\frac{1}{exp\left(\frac{\varepsilon-\mu_n}{kT}\right)+1}-\frac{1}{exp\left(\frac{\varepsilon-\mu_n+qV}{kT}\right)+1}\right)\right)d\varepsilon +$$

$$+I_0\left(\frac{T}{T_0}\right)^3 exp\left(\frac{E_g q}{kT_0}\left(1-\frac{T_0}{T}\right)\right)\left(exp\left(\frac{q\phi}{kT}-\frac{q(\phi-V)}{kT_e}\right)-1\right)$$

$$\int_{\mu_n+\mu_p}^{0}\left(\sqrt{\varepsilon(\mu_n+\mu_p-\varepsilon-qV)}\left(\frac{1}{\exp\left(\frac{\varepsilon-\mu_n}{kT}\right)+1}-\frac{1}{\exp\left(\frac{\varepsilon-\mu_n+qV}{kT}\right)+1}\right)\right)d\varepsilon\ exp\left(-\frac{\alpha E_g^{\frac{3}{2}}}{E+E_X}\right) \tag{23}$$

Let us compare the graph of the dependence of the total current of the tunnel diode on the total power of the acting microwave field, calculated using the above theoretical expression (Fig. 2), with the experimental graph (Fig. 3) shown in [21].

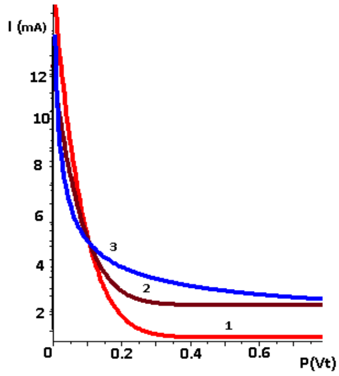

Figure 2. Graph of the dependence of the total current of the tunnel diode on the total power of the microwave field, calculated by expression (23).

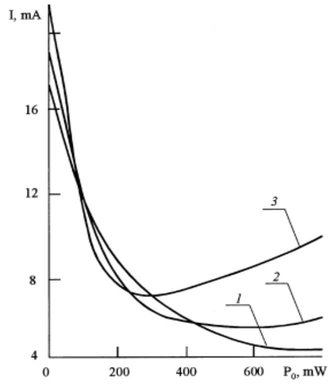

Figure. 3. Graph of the dependence of the total current of the tunnel diode on the total power of the microwave field [21] (experimental result).

It can be seen from these compared graphs that the theoretical and experimental results are qualitatively compatible. If we express the density of states of electrons in the conduction band of the n-region and in the valence band of the p-region given in expression (23) in terms of the Landau levels [22] under the action of a magnetic field, we obtain the following:

$$\rho_C(\varepsilon) = \frac{1}{4\pi^2}\left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}}\hbar\omega_H^C\sum_0^{N_C}\frac{1}{\sqrt{\varepsilon-\varepsilon_C-\left(n+\frac{1}{2}\right)\hbar\omega_H^{N_C}}}d\varepsilon;$$

$$\rho_V(\varepsilon) = \frac{1}{4\pi^2}\left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}}\hbar\omega_H^{N_V}\sum_0^{N_V}\frac{1}{\sqrt{\varepsilon-\varepsilon_V-\left(n+\frac{1}{2}\right)\hbar\omega_H^{N_V}}}d\varepsilon. \tag{24}$$

We can get the Hall voltage arising from the action of a magnetic field on the diffusion current in terms of the total current in the tunnel diode by adding it to the field voltage U_{xx}-microwave field. The Hall voltage is defined as [23]:

$$U_{XX} = \frac{IdB}{qn}. \tag{25}$$

Let us use the expression for the dependence of the Hall coefficient on the mobility of electrons and holes $R_{XX} = \frac{-A(nu_n^2-pu_P^2)}{q(nu_n+pu_P)^2}$. If we take the concentrations of electrons and holes equal, then for the Hall coefficient we get the following:

$$R_{XX} = \frac{-A(u_n-u_P)}{qn(u_n+u_P)}. \tag{26}$$

where, we use the expression $n=\int_0^\infty \rho(\varepsilon)f(\varepsilon)d\varepsilon$ for the electron concentration, for $\rho(\varepsilon)=\rho_c(\varepsilon)\,\rho_V(\varepsilon)$ equals and $f(\varepsilon)$we give the following:

$$\rho(\varepsilon)=\rho_C(\varepsilon)=\frac{1}{4\pi^2}\left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}}\hbar\omega_H^C\sum_0^{N_C}\frac{1}{\sqrt{\varepsilon-\varepsilon_C-\left(n+\frac{1}{2}\right)\hbar\omega_H^{N_C}}}d\varepsilon\times$$

$$\times\frac{1}{4\pi^2}\left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}}\hbar\omega_H^{N_V}\sum_0^{N_V}\frac{1}{\sqrt{\varepsilon-\varepsilon_V-\left(n+\frac{1}{2}\right)\hbar\omega_H^{N_V}}}d\varepsilon$$

$$f(\varepsilon)d\varepsilon=\left(\frac{1}{exp\left(\frac{\varepsilon-\mu_n}{kT}\right)+1}-\frac{1}{exp\left(\frac{\varepsilon-\mu_n+qV}{kT}\right)+1}\right)d\varepsilon \tag{27}$$

In this case, expression (23) for the tunneling current under the action of a microwave field and a magnetic field will have the following form:

$$I=I_t(E_X,B)+I_{Ch}(E_X,B)+I_d(E_X,B), \tag{28}$$

$$I_T(E_X,B)=AT\,exp\left(-\frac{\alpha E_g^{\frac{3}{2}}}{E+\sqrt{\frac{P_1-P_0}{Nq\mu}}}\right)\int_0^{\mu_n+\mu_p-qV}\frac{1}{4\pi^2}\left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}}\hbar\omega_H^{N_V}\sum_0^{N_C}\frac{1}{\sqrt{\varepsilon-\varepsilon_C-\left(n+\frac{1}{2}\right)\hbar\omega_H^{N_C}}}d\varepsilon\times$$

$$\times\frac{1}{4\pi^2}\left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}}\hbar\omega_H^{N_V}\sum_0^{N_V}\frac{1}{\sqrt{\varepsilon-\varepsilon_V-\left(n+\frac{1}{2}\right)\hbar\omega_H^{N_V}}}d\varepsilon\left(\frac{1}{exp\left(\frac{\varepsilon-\mu_n}{kT}\right)+1}-\frac{1}{exp\left(\frac{\varepsilon-\mu_n+qV}{kT}\right)+1}\right)d\varepsilon$$

$$I_X(E_X,B)=exp\left(-\frac{\alpha E_g^{\frac{3}{2}}}{E+\sqrt{\frac{P_1-P_0}{Nq\mu}}}\right)\int_0^{\mu_n+\mu_p}\left(\begin{array}{l}\frac{1}{4\pi^2}\left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}}\hbar\omega_H^{N_V}\sum_0^{N_C}\frac{1}{\sqrt{\varepsilon-\varepsilon_C-\left(n+\frac{1}{2}\right)\hbar\omega_H^{N_C}}}d\varepsilon\times\\ \times\frac{1}{4\pi^2}\left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}}\hbar\omega_H^{N_V}\sum_0^{N_V}\frac{1}{\sqrt{\varepsilon-\varepsilon_V-\left(n+\frac{1}{2}\right)\hbar\omega_H^{N_V}}}d\varepsilon\times\\ \times\left(\frac{1}{exp\left(\frac{\varepsilon-\mu_n}{kT}\right)+1}-\frac{1}{exp\left(\frac{\varepsilon-\mu_n+qV}{kT}\right)+1}\right)\end{array}\right)d\varepsilon$$

$$I_d(E_X,B)=I_0\left(\frac{T}{T_0}\right)^3 exp\left(\frac{E_gq}{kT_0}\left(1-\frac{T_0}{T}\right)\right)\left(exp\left(\frac{q\phi}{kT}-\frac{q(\phi-V+U_{XX})}{kT_e}\right)-1\right)$$

In a tunnel diode, the total current consists of the tunnel current according to the Tsu-Esaki model, as well as diffusion and excess currents. If we do not take into account the excess current here, then the total current consists of tunneling and diffusion currents. For this case, the volt-ampere characteristics graph was shown with and without the influence of the magnetic field and without the influence of the tunnel diode (Fig. 4 and 5).

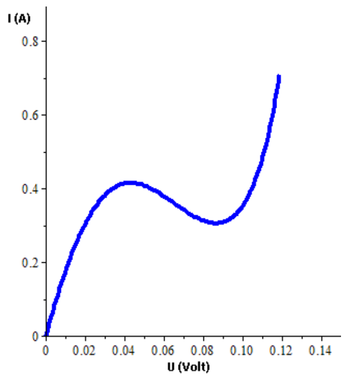

Figure 4. Volt-Ampere characteristics of total current without the influence of the microwave field and magnetic field and without taking into account excess current

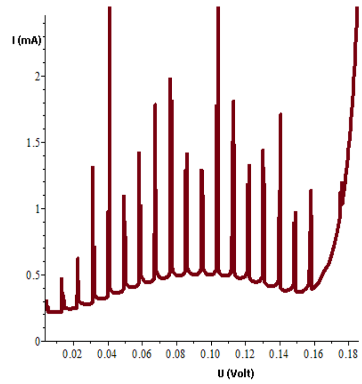

Figure. 5. Volt-Ampere characteristics of the total current taking into account the microwave field and magnetic field and without taking into account the excess current

A three-dimensional spatial view of the CVC of the above tunnel diode under the action of a magnetic field is presented in two forms - in fig. 6 on the change in the magnetic field induction, in fig. 7 - by temperature change.

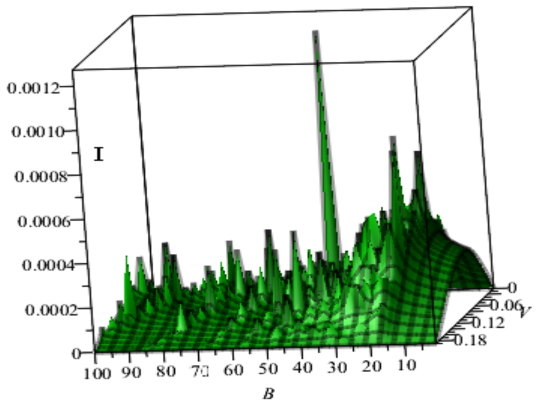

Figure 6. Three-dimensional view of the volt-ampere characteristics of a tunnel diode under the influence of various magnetic fields

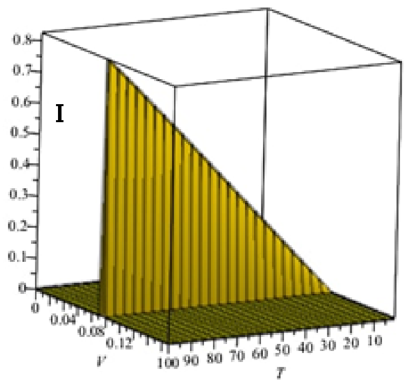

Figure 7. Three-dimensional spatial representation of the change in the volt-ampere characteristics at different temperatures for a tunnel diode under the influence of a magnetic field.

CONCLUSION

An expression volt-ampere characteristics for the excess current of a tunnel diode under the action of a microwave field is obtained, as well as a formula for calculating the total current generated in a tunnel diode under the action of a microwave field and a magnetic field. In addition, the dependence of the total current of the tunnel diode on the total power induced by the microwave field is theoretically presented and compared with experiments in the available literature. For the total current in the tunnel diode, without taking into account the excess current, the volt-ampere characteristics were obtained for the affected and unaffected states, respectively.

ORCID IDs

Gafur Gulyamov, https://orcid.org/0000-0001-9879-3165
Sharifa B. Utamuradova, https://orcid.org/0000-0002-1718-1122
Mukhamadjon G. Dadamirzaev, https://orcid.org/0000-0001-8258-4617
Nozimjon A. Turgunov, https://orcid.org/0000-0003-3481-5622
Kakhramon M. Fayzullaev, https://orcid.org/0000-0001-7362-1439

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РОЗРАХУНОК ПОВНОГО СТРУМУ, ЩО ГЕНЕРУЄТЬСЯ В ТУНЕЛЬНОМУ ДІОДІ ПІД ДІЄЮ МІКРОХВИЛЬОВОГО ТА МАГНІТНОГО ПОЛІВ

Гафур Гулямов[a], Шаріфа Б. Утамурадова[b], Мухамаджон Г. Дадамірзаев[a], Нозімджон А. Тургунов[b], Муніра К. Уктамова[b], Кахрамон М. Файзуллаев[b], Арофат І. Худайбердієва, Алішер І. Турсунов
[a]Наманганський інженерно-будівельний інститут, Наманган, Узбекистан
[b]Інститут фізики напівпровідників та мікроелектроніки Національного університету Узбекистану, Ташкент, Узбекистан,
[c]Ташкентський хіміко-технологічний інститут, [d]Термізький державний університетт, Терміз, Узбекистан

У цій роботі була виведена формула для розрахунку повного струму, який утворюється в тунельному діоді під дією мікрохвильового та магнітного полів. Крім того, теоретично подано та порівняно з експериментальними даними залежність повного струму тунельного діода від повної потужності, індукованої НВЧ полем. Для повного струму в тунельному діоді без урахування надлишкового струму отримано вольт-амперну характеристику для випадків з і без впливу НВЧ поля.

Ключові слова: *модель Чиновета; модель Цу-Есакі; мікрохвильове поле; магнітне поле; бар'єрний коефіцієнт прозорості; надлишковий струм*