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

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, voltmeter 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 proposing new models, as silicon-based diodes are used in many experimental works.
\[ I_{p-n} = A \int_{\varepsilon_n}^{\varepsilon_p} f_p(\varepsilon) \rho_p(\varepsilon) P[1 - f_n(\varepsilon)] \rho_n(\varepsilon) \, d\varepsilon. \] (2)

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

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

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

The \( T(E_\chi) \)-transfer coefficient and \( N(E_\chi) \)-distribution functions can be specified as follows [16]:

\[ N(E_\chi) = \int_0^\infty [f_n(\varepsilon) - f_p(\varepsilon)] \, dE_p, \] (5)

\[ T(E_\chi) = \int P \rho_p(\varepsilon) \rho_n(\varepsilon) \, d\varepsilon. \] (6)

where \( \varepsilon_n \) and \( \varepsilon_p \) 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 (\( \varepsilon_p \)):

\[ \varepsilon_p = qV_K - E_g = \mu_n + \mu_p. \] (7)

where \( \mu_n \) and \( \mu_p \) 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:

\[ \varepsilon_p = \mu_n + \mu_p - qV. \] (8)

And the distribution function is determined by the expressions:

\[ f_n(\varepsilon) = \frac{1}{\exp\left(\frac{\varepsilon - \mu_n}{kT}\right) + 1}. \] (9)

\[ f_p(\varepsilon) = \frac{1}{\exp\left(\frac{\varepsilon - \mu_p - qV_K + E_g + qV}{kT}\right) + 1}. \] (10)

The density of states of electrons and holes is \( \rho(\varepsilon) = C \sqrt{\varepsilon}, \rho_p(\varepsilon) = C' \sqrt{qV_K - E_g - qV - \varepsilon} \), 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]:

\[ I_I = PT A \int_0^{qV_K - E_g - qV} \left( \frac{1}{\exp\left(\frac{\varepsilon - \mu_n}{kT}\right) + 1} - \frac{1}{\exp\left(\frac{\varepsilon + \mu_p - E_g + qV}{kT}\right) + 1} \right) \sqrt{\varepsilon(qV_K - E_g - qV - \varepsilon)} \, d\varepsilon. \] (11)

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

\[ I_i = APT \int_0^{\mu_n + \mu_p - qV} \sqrt{\varepsilon(\mu_n + \mu_p - \varepsilon - qV)} \left( \frac{1}{\exp\left(\frac{\varepsilon - \mu_n}{kT}\right) + 1} - \frac{1}{\exp\left(\frac{\varepsilon + \mu_p + qV}{kT}\right) + 1} \right) \, d\varepsilon. \] (12)
where: $A = C^* C m_{\text{eff}} q^2 h^3$. For the transparency coefficient, we use the following formula [10, 17]:

$$P = \exp \left( - \frac{a h^2}{E} \right). \quad (13)$$

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

$$\vartheta = \mu E_x. \quad (14)$$

(Where, $m_{\text{eff}}$ 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:

$$F = qE_x. \quad (15)$$

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

$$P_1 = F \vartheta. \quad (16)$$

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

$$\frac{P_1 - P_0}{N} = F \vartheta. \quad (17)$$

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.

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

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

$$E_x = \frac{\sqrt{P_1 - P_0}}{Nq\mu}. \quad (19)$$

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

$$P = \exp \left( - \frac{a h^2}{E + E_x} \right) = \exp \left( - \frac{a h^2}{E + \frac{P_1 - P_0}{Nq\mu}} \right). \quad (20)$$

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

$$I_d = (I_0 \cdot \left( \frac{T}{T_0} \right)^3) \cdot \exp \left( \frac{E_x^2 q}{k T_0} \left( 1 - \frac{T}{T_0} \right) \right) \cdot \left( \exp \left( \frac{q \varphi - (\varphi - \varphi_0)}{k T} \right) - 1 \right). \quad (21)$$

It is known that the total current $I$ generated in a tunnel diode is the sum of the tunnel current, $I_{\text{CH}}$, 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:

$$I_{\text{CH}} = D P = \int_{\mu_0 + \mu_p}^{\mu_n + \mu_p} \sqrt{\mu_n + \mu_p - \varphi - qV} \left( \frac{1}{\exp \left( \frac{\mu_n + \mu_p - \varphi - qV}{k T} \right) \exp \left( \frac{1}{\exp \left( \frac{\mu_n + \mu_p - \varphi - qV}{k T} \right) + 1} \right) \right) \exp \left( - \frac{a h^2}{E + E_x} \right) \quad (22)$$

Here we have obtained the electric field strength as $E_x = \frac{V_k - V_{\text{m}} + V_{\text{m}}}{d}$, $V$ - external voltage, $V_k$ - contact potential difference, $d$ - potential barrier width, $V_{\text{m}}$ - 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:
\[ I = TA \exp \left( -\frac{aE_{g}^{2} \mu_{n} + \mu_{p} - qV}{E + \sqrt{\frac{P_{1} - P_{0}}{Nq\mu}}} \right) \times \]
\[ \times \int_{0}^{\mu_{n} + \mu_{p} - qV} \left( \sqrt{\mu_{n} + \mu_{p} - \varepsilon - qV} \left( \frac{1}{\exp\left( \frac{\varepsilon - \mu_{n}}{kT} \right) + 1} - \frac{1}{\exp\left( \frac{\varepsilon - \mu_{n} + qV}{kT} \right) + 1} \right) \right) d\varepsilon + \]
\[ + I_{0} \left( \frac{T}{T_{0}} \right)^{3} \exp \left( \frac{q\phi}{kT} \left( 1 - \frac{7a}{7c} \right) \right) \left( \exp\left( \frac{q\phi - q(\phi - V)}{kT} \right) - 1 \right) \]
\[ \int_{\mu_{n} + \mu_{p} - qV}^{\mu_{n} + \mu_{p} + qV} \left( \frac{1}{\exp\left( \frac{\varepsilon - \mu_{n}}{kT} \right) + 1} - \frac{1}{\exp\left( \frac{\varepsilon - \mu_{n} + qV}{kT} \right) + 1} \right) d\varepsilon \exp \left( -\frac{aE_{g}^{2}}{E + E_{g}} \right) \] (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].

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:

\[ \rho_{c}(\varepsilon) = \frac{1}{4\pi^{2}} \left( \frac{2m}{\hbar^{2}} \right)^{3} \hbar\omega_{H}^{C} \sum_{n}^{N_{C}} \frac{1}{\sqrt{\varepsilon - \varepsilon_{C} - \left( n + \frac{1}{2} \right) \hbar\omega_{H}^{C}}} d\varepsilon; \]
\[ \rho_{v}(\varepsilon) = \frac{1}{4\pi^{2}} \left( \frac{2m}{\hbar^{2}} \right)^{3} \hbar\omega_{H}^{V} \sum_{n}^{N_{V}} \frac{1}{\sqrt{\varepsilon - \varepsilon_{V} - \left( n + \frac{1}{2} \right) \hbar\omega_{H}^{V}}} d\varepsilon. \] (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]:

\[ U_{XX} = \frac{ieB}{2n}. \] (25)

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

\[ R_{XX} = \frac{A(n_{e} - n_{h})}{q(2n_{e})^{2}} \] (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:
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\[ \rho(\varepsilon) = \rho_C(\varepsilon) = \frac{1}{4\pi^2} \left( \frac{2m}{\hbar^2} \right)^3 \hbar \omega_H \sum_0^{N_C} \frac{1}{\sqrt{\varepsilon - \varepsilon_C - \left( n + \frac{1}{2} \right) \hbar \omega_H}} d\varepsilon \times \]

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

\[ f(\varepsilon) d\varepsilon = \left( \frac{1}{\exp\left(\varepsilon - \mu_T\right) + 1} - \frac{1}{\exp\left(\varepsilon - \mu_T + qV\right) + 1} \right) d\varepsilon \] (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:

\[ I = I_t(E_x, B) + I_{Ch}(E_x, B) + I_{d}(E_x, B), \]

(28)

\[ I_T(E_x, B) = AT \exp\left( - \frac{\alpha E_g^3}{E + \frac{P_0}{qNq\mu}} \right) \int_0^{\mu_T + \mu_T - qV} \frac{1}{4\pi^2} \left( \frac{2m}{\hbar^2} \right)^3 \hbar \omega_H \sum_0^{N_C} \frac{1}{\sqrt{\varepsilon - \varepsilon_C - \left( n + \frac{1}{2} \right) \hbar \omega_H}} d\varepsilon \times \]

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

\[ I_x(E_x, B) = \exp\left( - \frac{\alpha E_g^3}{E + \frac{P_0}{qNq\mu}} \right) \int_0^{\mu_T + \mu_T - qV} \left( \frac{1}{4\pi^2} \left( \frac{2m}{\hbar^2} \right)^3 \hbar \omega_H \sum_0^{N_C} \frac{1}{\sqrt{\varepsilon - \varepsilon_C - \left( n + \frac{1}{2} \right) \hbar \omega_H}} d\varepsilon \times \right) \]

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

\[ I_d(E_x, B) = I_0 \left( \frac{T}{T_0} \right)^3 \exp\left( \frac{E_g q}{K_T} \right) \left( \exp\left( \frac{q\phi - qV - U_{xx}}{K_T} \right) - 1 \right) \]

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 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.

**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.

**REFERENCES**


Розрахунок повного струму, що генерується в тунельному діоді під дією мікрохвильового та магнітного полів

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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