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INVESTIGATION OF PARAMETERS CHARACTERIZING A TUNNEL DIODE UNDER THE ACTION OF A SUPERHIGH-FREQUENCY (MW) FIELD IN THE TSU-ESAKI MODEL

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Abstract
It has been theoretically studied that a sharp increase in the electron temperature strongly affects the current-voltage characteristic of a tunnel diode, at high temperatures causing a decrease in the area with negative differential resistance in the current-voltage characteristic and is the cause of an increase in diffusion capacitance. In addition, it has been observed that an increase in diffusion capacitance leads to a decrease in the quality factor of a tunnel diode.

Keywords: Tsu-Esaki model, quality factor, differential resistance, diffusion capacitance.

The study of the current-voltage characteristics of tunnel diodes, high tunnel current, the ability of a tunnel diode to work even at very high temperatures, the dependence of a tunnel diode on the internal structure, that is, its preparation with various chemical elements by the heterostructure method, is a very important factor. Based on the analysis of the work presented above and the available literature [1], we analyzed according to the theory of Nott and De Mass and in the Tsu-Esaki model and found that in the case of a germanium diode (Ge-diode), when the tunnel junctions are direct, the current increases with time at different temperatures, depending on the diffusive capacitance and differential resistance. According to the Tsu-Esaki theory, the direct current flowing through a tunnel diode, is determined on the basis of the product of the distribution function - $N(E_X)$ on the transfer coefficient $-T_C(E_X)$ [2]

$$I_T = \frac{4\pi m_{eff} q}{h^3} \int_{min}^{max} T_C(E_X) \cdot N(E_X) dE_X \quad (1)$$

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In a tunnel flow, the currents passing from region p to region n and from region n to region p are determined by the following expressions:

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

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

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

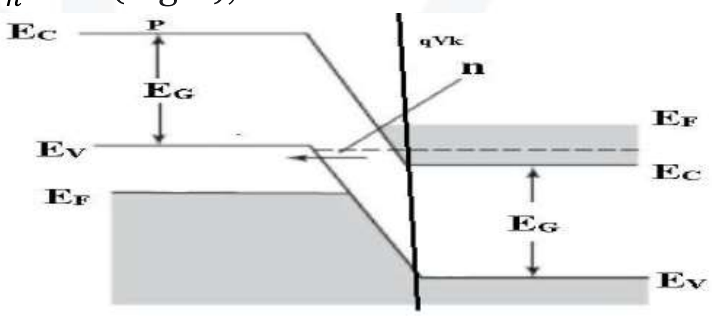
$$I = A\int_{\varepsilon_n}^{\varepsilon_p} \rho_p(\varepsilon)\,\rho_n(\varepsilon)P[f_n(\varepsilon)-f_p(\varepsilon)]d\varepsilon \quad (4)$$

- transfer coefficient $- T_C(E_X)$ and distribution functions $- N(E_X)$ can be specified as follows [3]:

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

$$T_C(E_X) = \int_{min}^{max} P\cdot\rho_p(\varepsilon)\cdot\rho_n(\varepsilon)d\varepsilon \quad (6)$$

where, $\varepsilon_n$and ε_p - respectively, the minimum energy that electrons can accept in the conduction band of the n-semiconductor, and the maximum energy that electrons can accept in the valence band of the 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),



Picture 1. Scheme for the formation of the current-voltage characteristic of a tunnel diode.

and based on this figure for the energy ε_p below [4]:

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$$\varepsilon_{\mathrm{p}} = qV_k - E_g = \mu_n + \mu_p \quad (7)$$

where, μ_n and μ_p are the chemical potentials (Fermi level) for the fields n and p, respectively. Also, when an external voltage is applied, we have:

$$\varepsilon_{\mathrm{p}} = qV_k - E_g - qV \quad (8)$$

And the distribution function is determined by the expressions:

$$f_n(\varepsilon) = \frac{1}{e^{\frac{\varepsilon-\mu_n}{k\cdot T}} + 1} \quad (9)$$

$$f_p(\varepsilon) = \frac{1}{e^{\frac{\varepsilon+\mu_{p-q\cdot V_k+E_g+q\cdot V}}{k\cdot T}} + 1} \quad (10)$$

The density of states of electrons and holes is equal to $\rho_n(\varepsilon) = C\sqrt{\varepsilon}$, $\rho_p(\varepsilon) = C'\sqrt{qV_k - E_g - qV - \varepsilon}$, here C and C' are constant numbers. Taking into account the above, using expression (12), we derive the following expression for the tunnel current [5]:

$$I_T = \frac{4\pi P m_{eff} q}{h^3} \int_0^{qV_k - E_g - q\cdot V} \left(\frac{1}{e^{\frac{\varepsilon-\mu_n}{kT}} + 1} - \frac{1}{e^{\frac{\varepsilon+\mu_{p-qV_k+E_g+qV}}{kT}} + 1} \right) \sqrt{\varepsilon\left(qV_k - E_g - qV - \varepsilon\right)} d\varepsilon \quad (11)$$

Using expressions (9) and (10), we find qV_k and substituting expression (12), we obtain the following expression for the tunnel current:

$$I = A \int_0^{\mu_n+\mu_p-qV} \sqrt{\varepsilon(\mu_n + \mu_p - \varepsilon - qV)} \left(\frac{1}{\exp\left(\frac{\varepsilon - \mu_n}{kT}\right)} - \frac{1}{exp\left(\frac{\varepsilon - \mu_n + qV}{kT}\right) + 1} \right) d\varepsilon, \quad (12)$$

Here $A = \frac{4\cdot P\cdot \pi\cdot m_{eff}\cdot q}{h^3}$ will be

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For the 1st term in the expression for the total tunneling current given in expression (1) above, using the given expression (12), the Tsu-Esaki model, ignoring the 2nd term due to its smallness compared to the other terms , and instead of 3rd term for the diffusion current using the Shockley expression, we have the following expression for the tunneling current:

$$I = A\int_0^{\mu_n+\mu_p-qV}\sqrt{\varepsilon(\mu_n+\mu_p-\varepsilon-qV)}\left(\frac{1}{\exp\left(\frac{\varepsilon-\mu_n}{kT}\right)}-\frac{1}{exp\left(\frac{\varepsilon-\mu_n+qV}{kT}\right)+1}\right)d\varepsilon + I_0\left(exp\left(\frac{-qV}{kT}\right)-1\right) \quad (13)$$

Taking into account this expression (13), we derive the formula for the diffusion capacity according to expression (2):

$$C_1 = \frac{\tau}{2}\cdot R^{-1} = \frac{\tau}{2}\Bigg(-TA\sqrt{(\mu_n+\mu_p-qV)V}\Bigg(\Bigg\{\lim_{\varepsilon\to\infty}\Bigg(kTln\left(e^{-\frac{-\varepsilon+\mu_n}{kT}}+1\right)+kTln\left(e^{-\frac{-\varepsilon+\mu_n}{kT}}\right)+kTln\left(e^{\frac{\varepsilon-\mu_n+qV}{kT}}+1\right)-kTln\left(e^{\frac{\varepsilon-\mu_n+qV}{kT}}\right)+kTln\left(e^{\frac{-\mu_n}{kT}}+1\right)-kTln\left(e^{\frac{-\mu_n}{kT}}\right)-kTln\left(e^{\frac{-\mu_n+qV}{kT}}+1\right)+kTln\left(e^{\frac{-\mu_n+qV}{kT}}\right)\Bigg),\ 0<I\pi kT+\mu_n \text{ ва } 0<I\pi kT-qV+\mu_n\Bigg\}\Bigg)+TA\int_0^{\mu_n+\mu_p-qV}\left(\sqrt{\varepsilon(\mu_n+\mu_p-\varepsilon-qV)d\varepsilon}\right)\Bigg)\Bigg(\Bigg\{\lim_{\varepsilon\to\infty}\left(\frac{e^{\frac{\varepsilon-\mu_n+qV}{kT}}}{e^{-\frac{-\varepsilon+\mu_n}{kT}}+1}-\frac{e^{-\frac{-\varepsilon+\mu_n}{kT}}}{e^{\frac{-\mu_n}{kT}}+1}\right),0<I\pi kT+\mu_n \text{ ва } 0<I\pi kT-qV+\mu_n\Bigg\}\Bigg)\text{-}\left(I_0 q e^{\frac{-qV}{kT}}\right)\frac{\tau}{2} \quad (14)$$

and using this expression, we get a plot of capacitance versus voltage (Figure-2).

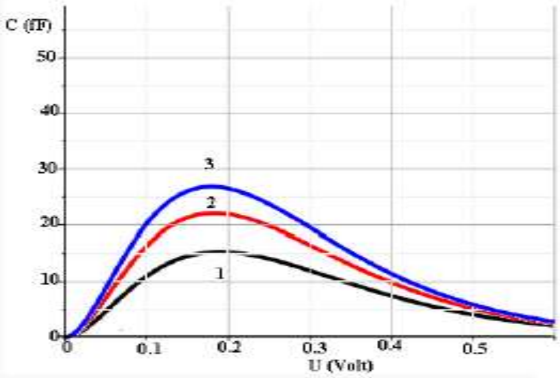

Figure-2. Graph of dependence of capacitance on voltage determined using expression (13). 1. T_e=300K 2. T_e=350K 3. T_e=400K

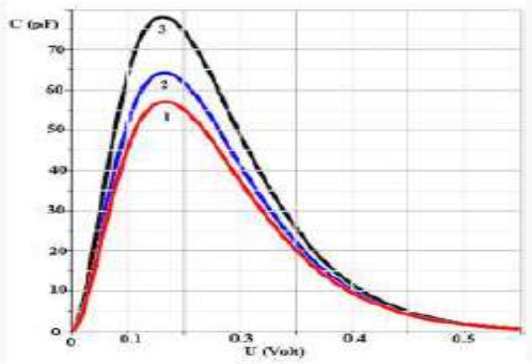

Figure-3. Graph of the dependence of the capacitance on the voltage determined using the expression (16). 1. T_e=300K 2. T_e=350K 3. T_e=400K

Now let's determine the quality factor "K_1" of a tunnel diode based on germanium-Ge by expression (14):

$$K_1 = \frac{I_P}{C_1} = \frac{I_0 S e^{BE_g\sqrt{\frac{\epsilon m(N_A N_D)}{N_A+N_D}}}}{C_1} \quad (15)$$

Here E_g- is the band gap for elements-Ge, I_0 is the saturation current, S is the contact surface, B is a constant expression, ϵ- is the electrical constant for Ge, N_A and N_D is the number of charge carriers in the n and p field.

Instead of the term - 3 of the diffusion current in expression (13), i.e., in the place of the term of the unheated diffusion current, substituting the expression for the diffusion current for electrons heated under the action of an extremely high frequency field, we obtain the expression for the current for a heated electron tunnel diode with a semiconductor - Ge :

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

$$+ I_0\left(\frac{T}{T_0}\right)^3 exp\left(\frac{E_g q}{kT}\left(1-\frac{T_0}{T}\right)\right)\left(e^{\frac{q\varphi}{kT}-\frac{q(\varphi-q)}{kT_e}}-1\right) \quad (16)$$

Using this expression, we derive the formula for the diffusion capacitance of a tunnel diode, taking into account the heating of electrons, and we present a graph (Figure-3):

$$C_2 = \frac{\tau}{2}\cdot R^{-1} = \frac{\tau}{2}\Bigg(-TA\sqrt{(\mu_n+\mu_p-qV)V}\Bigg(\Bigg\{\lim_{\varepsilon\to\infty}\Bigg(kTln\left(e^{-\frac{-\varepsilon+\mu_n}{kT}}+1\right)+$$

$$kTln\left(e^{-\frac{-\varepsilon+\mu_n}{kT}}\right)+kTln\left(e^{\frac{\varepsilon-\mu_n+qV}{kT}}+1\right)-kTln\left(e^{\frac{\varepsilon-\mu_n+qV}{kT}}\right)+kTln\left(e^{\frac{-\mu_n}{kT}}+1\right)-$$

$$kTln\left(e^{\frac{-\mu_n}{kT}}\right)-kTln\left(e^{\frac{-\mu_n+qV}{kT}}+1\right)+kTln\left(e^{\frac{-\mu_n+qV}{kT}}\right)\Bigg)\ ,\ 0 < I\pi kT+\mu_n \text{ ва } 0 < I\pi kT -$$

$$qV+\mu_n \quad \Bigg\}\Bigg)+TA\int_0^{\mu_n+\mu_p-qV}\left(\sqrt{\varepsilon(\mu_n+\mu_p-\varepsilon-qV)d\varepsilon}\right)\Bigg)\Bigg(\Bigg\{\lim_{\varepsilon\to\infty}\Bigg(\frac{e^{\frac{\varepsilon-\mu_n+qV}{kT}}}{e^{-\frac{-\varepsilon+\mu_n}{kT}}+1}-$$

$$\frac{e^{-\frac{-\varepsilon+\mu_n}{kT}}}{e^{\frac{-\mu_n}{kT}}+1}\Bigg), 0 < I\pi kT + \mu_n \text{ ва } 0 < I\pi kT - qV + \mu_n \Bigg\}\Bigg) + \left(\frac{I_s \cdot q \cdot T^3 \cdot e^{\frac{E_g \cdot e\left(1-\frac{T_0}{T}\right)}{k \cdot T_0}} \cdot e^{\frac{q\varphi}{kT} - \frac{q\cdot(\varphi - V)}{k\cdot T_e}}}{T_0^{\,3} \cdot k \cdot T_e} \right) \frac{\tau}{2}$$

(17)

From here, there is a sharp increase in the diffusion capacity due to heated electrons (Figure-3) in relation to the diffusion capacity determined without electron heating (Figure-2). For an electron heated under the action of a microwave field, the quality factor K_2 of a semiconductor tunnel diode-Ge is determined as follows:

$$K_2 = \frac{I_P}{C_2} = \frac{I_0 S e^{BE_g \sqrt{\frac{\epsilon m (N_A N_D)}{N_A + N_D}}}}{C_2} \quad (18)$$

Bring out

In contrast to the theory of Knott and De Mass, according to the Tsu-Esaki model for any heterojunction or heavily doped semiconductor tunnel diode for the total current consisting of the sum of diffusion and tunnel currents in heated and unheated states of electrons, a theoretical expression for the total current is obtained based on the Tsu-Esaki model . Here, as well as in the theory of Knott and De Mass, a sharp increase in the diffusion capacity was observed due to heated electrons compared to the unheated state of electrons. It has been observed that an increase in the diffusion capacitance leads to a change in the quality factor of the tunnel diode.

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