Tunneling transistor theoretical model based on changed operating principles

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A tunneling transistor without heterojunction as a theoretical design is under consideration. The electrons from the conduction band of the source tunnel through the forbidden gap \( E_g \) of the channel to the conduction band of the drain. The tunneling current \( J \) calculations made for the Au-GaSe-Au and the InAs-InAs-InAs structures show that for a constant source-drain voltage, \( V_C \), of several mV, changes in the gate voltage, \( V_G \), applied to the channel within the voltage range of 0 - \( E_g / 2e \) change \( J \) by even 10 orders of magnitude at helium temperature. Unlike the existing solutions such as tunnel field-effect-transistor (TFET), the proposed device uses the change of \( V_C \), i.e. the change of the electrostatic potential in the channel, to modify the imaginary wave vector \( k_z \) of tunnel current electrons. Consequently, the gate voltage controls the damping force of the electrons wave functions and thus the magnitude of the tunneling current \( J \).

II. TUNNELING CURRENT IN METAL-INSULATOR-METAL STRUCTURE

Here we consider details of the general formula for the dependence of the current \( J \) on the applied voltage, \( V_C \), in the M-I-M structure (see Ref. [3]) as the source-channel-drain structure in our design. The elements of this structure are selected so that current electrons from

\[
E(k) = E_g - ((\Phi(z) - E_a) = \ldots
\]

FIG. 1: Diagram of the Metal-Insulator-Metal structure with applied voltage \( V_C \) between the metal A and the metal B, see e.g. Ref. [3]. The tunneling current flows along the \( z \) direction from the metal A through the forbidden gap of the insulator to the metal B. \( V_C \) and \( V_R \) are the band offsets between the conduction band of the insulator and the Fermi energy \( E_F \) in the metal A or the metal B, respectively. \( E_a \) is the energy of the electron.
where $E_g$ is the forbidden gap of the insulator, $k^2 = k_{\perp}^2 + k_z^2$, and wave vectors $k_{\perp}$ and $k_z$ have real and imaginary value in $E_g$, respectively. $E_a$ is the energy of the electron in the metal A, $m_0^*$ is the effective electron mass in the conduction-band edge of $m_e$ at the metal A conduction band edge, where $\Phi(z) = \Phi_B(z) + E_F$ is the energy of the M-I-M barrier potential relating to the metal A conduction band edge, where

$$\Phi_B(z) = V_b^L + (V_b^R - V_b^L - eV_c)z/d ,$$

where $V_b^L$ and $V_b^R$ are metal-insulator barrier energies and $E_F$ is the Fermi energy.

Hence,

$$|k_z(z)| = \left[ \left( 1 - \frac{\Phi(z) - E_a}{E_g} \right) (\Phi(z) - E_a) \frac{2m_0^*}{\hbar^2} + k_{\perp}^2 \right]^{1/2} .$$

or

$$|k_z(z)| = \left[ \left( 1 - \frac{E(z)}{E_g} \right) E(z) \frac{2m_0^*}{\hbar^2} + k_{\perp}^2 \right]^{1/2} .$$

The next step is a general expression for the elastic tunneling current $J(V)$ from the metal A to the metal B (e. g. Ref [5]),

$$J(V) = \frac{2eS}{h} \int_0^\infty dE_a (f_A(E_a) - f_B(E_a)).$$

or

$$\int_0^\infty \frac{d^2k_{\perp}}{(2\pi)^2} \exp \left[ -2 \int_0^d |k_z(k_{\perp}, \Phi(z) - E_a)dz \right] =$$

where $k_{\perp}^M = k_{\perp}^F$ for $E_F$ and $k_z = 0$ in the M-I-M system. Further, $d$ is the insulator thickness and $S$ is the area of the interface between the metal and the insulator. $f_A(E_a)$ and $f_B(E_a)$ are F-D distribution functions for the metal A and the metal B, $f_A(E_a) = 1/[1 + \exp(E_a - E_{F_a}^A)/kT]$ and $f_B(E_a) = 1/[1 + \exp(E_a - E_{F_a}^B - eV_c)/kT]$. For very low temperature one has

$$J(V) \left[ \frac{A}{cm^2} \right] = \frac{7.7483}{10^5} .$$

One can notice that the formula for $J(V)$ is dominated by the element with the exponential decay which is a result of the imaginary value of $k_z$ in the electron wave function for the insulator forbidden gap. It is also seen that all electrons in the metal A with energy in the range $E_F - (E_F - eV_c)$ form the tunneling current from the metal A to the metal B. Furthermore, the tunneling current of the electron is the bigger the smaller $|k_z|$ it has.

**III. DEPENDENCE OF CURRENT ELECTRONS ENERGY ON $k_z^2$ IN CHANNEL FORBIDDEN GAP**

Henceforth, the term Metal-Insulator-Metal is replaced by the term Source-Channel-Drain, source and drain are metals or $n$ type semiconductors and channel is a wide gap or narrow gap semiconductor.

The comparison of experimental data with theoretical calculations $J(V)$ in the structure under consideration shows that to describe the dispersion $E(k_z^2)$ of electronic states in the forbidden gap of a channel, for example GaSe or InAs, the two-band model is sufficient, see Refs [5] and [4]. The knowledge of the dependence $E$ on $k_z^2$ for $k_{\perp} = 0$ is the most important, because the greater the $k_{\perp}$, the greater the $|k_z|$ for keeping the electron energy unchanged. On the other hand, the tunneling energy changes.
current is determined by the electrons with \(|k_z|\) as small as possible, i.e. with damping of their wave function as little as possible.

If the effective masses of electrons \(m_e\) and holes \(m_v\) are not equal the use of the two band Franz model for band-to-band tunneling, see Refs [17] and [18], allows for a more detailed description of the tunneling process. It means replacing \(m_0^*\) in Eq. (1) by \(m_F\), the value of which depends on the energy of the electron \(E\) in the band forbidden gap. \(m_F\) has the form

\[
m_F(E) = \frac{m_e}{(E/E_g)(1 - m_e/m_v) + m_e/m_v},
\]

where \(E = E_g - \Phi(z) + E_a\), see Fig. 1. It is seen that for \(E = 0\) \(m_F = m_v\) and for \(E = E_g\) \(m_F = m_e\).

To calculate the energy dispersion \(E(k_z^2)\) in the forbidden gap of GaSe for \(k \parallel = 0\) we used Eq. (3) with \(m_0^* = m_F\) and GaSe parameters (Ref. [5]) \(E_g = 2\) eV \(m_C/m_0 = 0.35\) and \(m_V/m_0 = 0.07\). The curves calculated for \(m_0^* = m_F\), \(m_0^* = m_C\) and \(m_0^* = m_V\) are shown in Fig. 2. From comparison of the curves it follows that the use of \(m_F(E)\) is necessary. The results of similar calculations for InAs are shown in Fig. 3. InAs parameters are \(E_g = 0.417\) eV and \(m_0^*/m_0 = 0.026\). Fig. 2 and Fig. 3 show that a slight change in the energy of the electron in the band gap significantly changes the value of \(k_z^2\) of the electron, i.e. its importance in the formation of the tunnel current.

**IV. PRINCIPLES OF OPERATION OF THE PROPOSED TUNNELING TRANSISTOR**

The basis of the proposed transistor is the observation that the current that flows through the Source-Channel-Drain structure biased with the constant voltage \(V_C\) can be changed depending on the magnitude of the gate voltage \(V_G\) applied to the channel by electrode separated from the channel by the oxide layer. In other words, by increasing or lowering the potential energy of the channel in relation to the source, we can control \(k_z^2\) of the current electrons, and thus the magnitude of the tunneling current, see Figs. 2 and 3. So, the modified formula for the \(|k_z(z)|^2\) of an electron in the forbidden channel gap with the applied voltage \(V_G\) looks like this

\[
|k_z(z)|^2 = \left(1 - \frac{E(z) - eV_G}{E_g}\right)\left(E(z) - eV_G\right)^2\frac{2m_0^*}{\hbar^2} + k_{\perp}^2.
\]

In Fig. 4 is shown the dependence of the tunneling current \(J\) on the voltage \(V_G\) applied to the GaSe element with a width of \(d = 15\) nm in the Au-GaSe-Au structure with \(V_C = 10\) mV or 50 mV. A negative or positive value of \(V_G\) means reduction or increase of the virtual shift of \(V_{G}^{L}\) and \(V_{G}^{R}\) of the GaSe barrier with respect to the Au source, and thus the change \(k_z^2\) of current electrons. The dependence \(J\) is seen also in Figs. 5 and 6 for the InAs-InAs-InAs structure with a width of \(d = 50\) nm or 65 nm respectively, for different values of \(V_C\). The electrons tunnel through the forbidden gap along the entire length of the channel for the value of \(V_G\) within the range \(V_C - (E_g/e - V_C)\), see Fig. 7. The theoretical curves in the above cases are calculated using Eqs. 7 and 9. The
The comparison of Figures 5 and 6 shows a clear dependence of the current $J$ on the size of the electrons tunneling path $d$. The conclusion that can be drawn from the $J(V_G)$ curves in Figures 4, 5 and 6 is as follows: the smaller $V_C$, the greater the ratio of the maximum tunnel current $J_{MAX}$ to the minimum tunnel current $J_{MIN}$. The reason is that the smaller $V_C$ and, consequently, $J_C$, the fewer electrons forming the current and the smaller the difference between $|k_z|^2$ of these electrons. Thus, the highest ratio of $J_{MAX}$ to $J_{MIN}$ for a given width of $d$ will occur when the voltage $V_C$ will be extremely small, i.e. when the tunneling current will be formed exclusively from electrons of the same energy $E$. In this case, it is convenient to calculate the transmission coefficient $TC$ of electrons tunneling through the forbidden gap of the channel vs. $V_G$, (the procedure is included e.g. in Ref. [11]). Such a dependence $TC(V_G)$ for the InAs-InAs-InAs structure is shown in Fig. 8. It can be seen that the ratio of $TC_{MAX}$ to $TC_{MIN}$ and therefore $J_{MAX}$ to $J_{MIN}$ is indeed extremely large.
V. SUMMARY

The presented theoretical design of a tunneling transistor is a simple extension of the structure for studying the dependence of tunnel current on applied voltage. It has no heterojunction like TFET and is based on controlling the height of the potential barrier created by the channel biased with voltage $V_G$. Such a transistor would be extremely convenient in terms of technology. It is enough to apply a constant source-drain voltage $V_C$ of a few mV and then small change of the gate voltage $V_G$ applied to the channel changes the $J$ value by a few orders of magnitude. The maximum computed change in $J$ formed by tunneling electrons along the entire length of the channel is due to a change in $V_G$ in the range 0 - $(E_g/2e - V_C)$. For an InAs structure with $d = 65$ nm, this means a change in $V_G$ from 0 to about 200 mV and, consequently, a change in $J$ by 9 orders of magnitude at $V_C = 20$ meV and by more than 6 orders of magnitude at $V_C = 50$ meV. The intensity of the tunneling current $J$ can be additionally adjusted by changing the voltage $V_C$ and the width $d$ of the channel.

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