Analytical Modeling of Triple-Material Trigate Junctionless Tunnel Field Effect Transistor

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Abstract. An analytical two-dimensional (2D) model is developed to obtain expressions for various parameters of triple-material trigate junctionless tunnel field-effect transistors (TMTG-JTFETs). The 2D Poisson’s equation uses the superposition approximation method to calculate the sum of potentials arising from different point charges. The electric field distribution in the channel is obtained from the gradient of the electric potential. The drain current of the device is calculated using the Kane’s model in the presence of an electric field and a band structure. The TMTG-JTFET, with a channel length of 40nm, exhibits significant electrical characteristics with very low off-current (Ioff) and high on-current compared to a dual-material double-gate TFET. To validate the model, analytical results are confirmed via comparison with technology computer-aided design simulation results.

Keywords: Two-dimensional (2D) model •Triple-material trigate junctionless TFET (TMTG-JTFET)•Poisson’s equation• Superposition method • Kane model• TCAD.

1. Introduction

Short-channel effects have pronounced implications for the scaling of conventional-bulk-planar metal-oxide-semiconductor field-effect transistors (MOSFETs) and drive us to investigate multigate structures and other novel devices (junctionless devices, tunneling devices, etc.). Scaling down MOSFETs to nanometer dimensions exponentially increases the leakage current (Ioff) via the scaling of the threshold voltage and oxide thickness. Reducing the subthreshold swing is necessary to reduce the power without excessively increasing the leakage current. Because of the nonscalability of the threshold voltage in MOSFETs, the subthreshold slope cannot be reduced below 60mV/dec. To reduce
the subthreshold slope, a band-to-band tunneling (BTBT) current mechanism is used rather than a thermionic current mechanism in MOSFETs [1–3]. Tunnel FETs (TFETs) are expected to operate at voltages as low as 300mV and achieve a subthreshold swing of <60mV/dec via the BTBT mechanism [4]. TFETs are the most promising device for ultralow-power applications because they are steep-slope devices that give the lowest $I_{on}$ and largest $I_{on}/I_{off}$ at a reduced $V_{DD}$. Because TFET structures suffer from lower $I_{on}$ compared to MOSFET structures owing to the tunneling current transport phenomenon, various structures have been investigated to improve the $I_{on}/I_{off}$ ratio—e.g., single gates[5], double gates[6], dual-material double gates[7], gate all around FETs[8], vertical gates[9], heterojunctions [10], stacked gate oxides[11], and junctionless TFETs (JTFETs)[12]. The TFET on-current can also be boosted by employing bandgap engineering[13], doping engineering[14], geometry engineering[15], and gate work function engineering[16].

An analytical TFET model is essential to provide insight into the working of the steep subthreshold switch and its switching behavior for low-power circuits. Several two-dimensional (2D) analytical models for different TFET structures have been investigated to solve Poisson’s equation using the parabolic approximation[17–20] and the superposition approximation[21,22] to compute the surface potential, electric field, and tunneling rate generation of TFETs. The superposition approximation has been used by Lee et al.[21] and Gholizadeh et al.[22] to develop a 2D analytical model that predicts the impacts of structural parameters and includes the influences of the mobile charges on the potential profile and the drain bias on the current. In this paper, we have modeled the triple-material trigate JTFET (TMTG-JTFET) and derived an analytical expression for the drain current using the superposition approximation method. When the analytical results are compared with technology computer-aided design (TCAD) results [23], the device model using the superposition approximation is shown to be more effective than the parabolic approximation.

2. Model derivation

The structure of a TMTG-JTFET is shown in Fig.1. The channel length ($L$) is 40nm, and the uniform channel doping $n_i = 8 \times 10^{18} \text{cm}^{-3}$. The thicknesses of the gate dielectric ($T_{g}$) and the junction depth ($T_{j}$) are considered to be 3 and 8 nm, respectively. The junctionless transistors are turned on by varying the middle gate voltage from 0 to 1 V and by fixing $V_{G1}$ as positive and $V_{G2}$ as negative, tunneling occurs in the source–channel junction [23]. The workfunctions for gate 1, gate 2, and the middle gate are considered to be 4.26, 4.6, and 4.28eV, respectively. The gate voltage determines the transistor operation, and Vadivukkarasi et al.[24] investigated the optimal combination of gate 1 voltage $V_{G1}$ and gate 2 voltage $V_{G2}$.

![Fig.1. Cross-sectional view of a TMTG-JTFET](image)

The 2DPoisson’s equation in the channel region is written as

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = \frac{q}{\varepsilon_{si}} n_i \exp\left(\frac{\psi - V}{V_t}\right)$$

(1)

where $\varepsilon_{si}$ is the permittivity of the silicon, $q$ is the electronic charge, $V_t = 0.025\text{V}$ is the energy gained by the electrons to jump to the conduction band energy level, and $V$ indicates the population of electrons in the energy band resulting from the voltage applied at the source and drain. The
The electrostatic potential $\psi(x, y)$ of the device is estimated from (1), and its solution is obtained using the superposition approximation method[25]:

$$\psi(x, y) = \psi(y) + \psi(x, y)$$  \hspace{1cm} (2)$$

where $\psi(y)$ and $\psi(x, y)$ are the solutions of the one-dimensional (1D) Poisson’s equation in (3.1) and the 2D Laplace equation in (3.6), respectively. As per Pao-Sah’s gradual channel approximation [26], the potential in the intrinsic region is given as

$$\psi(x, y) = V_l \ln \left( \frac{2\varepsilon_{si} V_l}{q n_i} \right)$$  \hspace{1cm} (3)$$

The solution to the 1D Poisson’s equation is obtained by integrating (3) twice as described by Taur et al.[5]:

$$V_l = \beta - \ln(\cos(\beta)) - \frac{2\varepsilon_{si} T_{si}}{\varepsilon_i T_{si}} \beta \tan(\beta)$$  \hspace{1cm} (5)$$

After simplifying (5), we obtain $\beta = 1.5$, where $V_l$ and $q$ are the thermal voltage and electron charge, respectively; the permittivity of silicon is $\varepsilon_{si} = 11.68 \text{ F/m}$; the permittivity of the insulator is $\varepsilon_i = 3.9 \text{ F/m}$; the thickness of the silicon is $T_{si} = 8 \text{ nm}$; the thickness of the insulator is $T_i = 3 \text{ nm}$; the intrinsic carrier density is $n_i = 8 \times 10^{18} \text{ cm}^{-3}$; $\Delta \phi = 0.026 \text{ eV}$ is the work function difference between $\phi_M$ (metal) and $\phi_S$ (semiconductor) used to control the behaviour of the JTFET; and the potential $V$ is equal to the drain-to-source voltage $V_{DS}$, varies at the source–channel junction, and remains constant in the channel.

The 2D Laplace equation is given as

$$\frac{\partial^2 \Psi(1)}{\partial x^2} + \frac{\partial^2 \Psi(1)}{\partial y^2} = 0$$  \hspace{1cm} (6)$$

and its solution is

$$\psi_1(x, y) = U_L(x, y) + U_R(x, y)$$  \hspace{1cm} (7)$$

where the eigenfunctions $U_R$ and $U_L$ can be written as $U_R = \sum_{n=1}^{\infty} U_{Rn}(x, y)$ and $U_L = \sum_{n=1}^{\infty} U_{Ln}(x, y)$, where the first-order coefficients $U_{Rn}$ and $U_{Ln}$ can be evaluated from[27] and capture the electrostatic potential in the channel region[28]:

$$U_{Rn}(x, y) = c_n \frac{\sinh(\pi y/\lambda_n)}{\sinh(\pi L/\lambda_n)} \sin \left( \frac{n\pi x}{2} + \frac{\pi x}{\lambda_n} \right)$$  \hspace{1cm} (8)$$
\( \lambda_n \) is the scale length of the JTFET structure, which is mathematically defined as

\[
\varepsilon_{si} \tan \left( \frac{nT_i}{\lambda_n} \right) = \varepsilon_{si} \tan \left( \frac{n\pi - \pi T_{si}}{2\lambda_n} \right)
\]

(10)

Upon solving (10), for a trigate \( n = 3 \), the eigenvalues \( \lambda_1 = 2.596 \times 10^{-8} \), \( \lambda_2 = 1.298 \times 10^{-8} \), and \( \lambda_3 = 0.864 \times 10^{-8} \) are obtained from

\[
\varepsilon_{si} \tan \left( \frac{nT_i}{\lambda_1} \right) = \varepsilon_{si} \tan \left( \frac{n\pi - \pi T_{si}}{2\lambda_1} \right)
\]

(11.a)

\[
\varepsilon_{si} \tan \left( \frac{nT_i}{\lambda_2} \right) = \varepsilon_{si} \tan \left( \frac{n\pi - \pi T_{si}}{2\lambda_2} \right)
\]

(11.b)

\[
\varepsilon_{si} \tan \left( \frac{nT_i}{\lambda_3} \right) = \varepsilon_{si} \tan \left( \frac{n\pi - \pi T_{si}}{2\lambda_3} \right)
\]

(11.c)

where \( T_i \) and \( T_{si} \) are the thicknesses of the insulator and silicon, respectively. The eigenvalues \( \lambda_1 \), \( \lambda_2 \), and \( \lambda_3 \) are used in the calculation of first-order coefficients \( b_n \) and \( c_n \).

Upon solving for the basic characteristics of Bessel and Neuman functions[27], the values of first-order coefficients \( b_n \) and \( c_n \) are found to be

\[
b_n = \frac{2\lambda_n^2 \tan \left( \frac{\pi T_i}{\lambda_n} \right) \sin \left( \frac{\pi T_{si}}{2\lambda_n} \right)}{\pi^2 T_i + \frac{\sin \left( \frac{\pi T_{si}}{\lambda_n} \right)}{\sin \left( \frac{2\pi T_i}{\lambda_n} \right)}} (\psi_{SC} - V_{GS} + \Delta \phi_n)
\]

(12)
From (12) and (13), the first-order coefficients \( b_1 = 0.156, b_2 = 0.207, b_3 = 0.375, c_1 = 2.239, c_2 = 2.232, \) and \( c_3 = 3.578 \) are obtained for the trigate by substituting \( n = 3, \) where \( \Delta \Phi_1 = 0.6eV, \Delta \Phi_2 = 0.28eV, \) and \( \Delta \Phi_3 = 0.26eV \) represent the work function differences among the three regions, respectively; \( V_{GS} \) is the gate-to-source voltage; \( V_D \) is the drain-to-source voltage; \( E_{\alpha} \) is the bandgap energy in electron volts; and \( q \) is the magnitude of electronic charge in coulombs.

The first-order eigenfunction is used to calculate the potential in the channel and is expressed as

\[
\Psi(x, y) = v(x) + \cos(\pi x / \lambda_1) \left[ \left( b_1 \sinh(\pi (L - y) / \lambda_1) \right) / \sinh(\pi L / \lambda_1) + c_1 \sinh(y / \lambda_1) \right] \tag{14}
\]

Substituting the values of the 1D Poisson’s equation into the above equation, we obtain \( \Psi(x, y) = 2.86V \) for a mesh point in the middle of the channel.

The lateral electric field \( E_{x}(x, y) \) resulting from the applied gate bias voltage is calculated as the derivative of the potential per unit length from (14) and is

\[
E_x(x, y) = -\frac{\pi}{\lambda_1} b_1 \cosh(\pi (L - y) / \lambda_1) + 2 \frac{\pi}{\lambda_1} c_1 \cosh(\pi y / \lambda_1) \cos \left( \frac{\pi x}{\lambda_1} \right) \tag{15}
\]

From (15), the maximal value of \( E_{x}(x, y) \) can be obtained at the middle of the channel. In contrast to the results of [29] and [30], the field is maximized along the source–channel junction and decreases to a minimal value along the channel. To obtain accurate results, we can consider higher-order terms to capture a sharper potential in the tunneling region. A Taylor series expansion is used to calculate the electric field and is written as

\[
E_{x_n}(x, y) = \sum_{n=1}^{\infty} \left( -\frac{\pi}{\lambda_n} b_n \frac{\cosh(\pi (L - y) / \lambda_n))}{\sinh(\pi L / \lambda_n)} + 2 \frac{\pi}{\lambda_n} c_n \frac{\cosh(\pi y / \lambda_n))}{\sinh(\pi L / \lambda_n)} \right) \cos \left( \frac{n \pi x}{\lambda_n} \right) \tag{16}
\]

From (16), the electric field \( E_{x}(x, y) \) of the TMTG-JTFT can be obtained as \( 0.128 \times 10^6 \text{V/cm} \) by taking the root mean square of vector components \( E_{y_1}, E_{y_2}, \) and \( E_{y_3}. \)

3. Drain current derivation

The drain current expression for the JTFT is derived from Kane’s model [31] using a dynamic nonlocal tunneling model based on the band structure and electric field. The drain current along the channel is expressed as

\[
I = q \int AEE_{\text{avg}} \left[ \frac{-B}{E_{\text{avg}}} \right] \, dv \tag{17}
\]

where \( A \) and \( B \) are the process-dependent parameters of Kane’s model (because Kane’s model has been used in an analytical model, the same values of \( A = 0.18 \times 10^{-16} \text{V/cm} \) and \( B = -3.38 \times 10^{-16} \text{V/cm} \) have been included in the simulation), \( D = 2.5 \) for an indirect tunneling process, and the average electric field can be calculated as

\[
E_{\text{avg}} = \frac{E_g}{qL_{\text{path}}} \tag{18}
\]
where $l_{\text{path}} = 40 \text{ nm}$ is the tunneling path length and $E_g = 1.1 \text{ eV}$ is the bandgap energy. By substituting the electric field from (16) into (17), the drain current is obtained as $1.68 \times 10^{-8} \text{ A/µm}$.

4. Results and discussion

In this section, the analytical results for a TMTG-JTFET with three gates are compared with the device simulator results from Sentaurus TCAD. The device parameters for the simulated structure are given in Table I. The middle gate acts as a controlling gate $V_G$; its voltage is varied from 0 to 2 V to turn the device on. The gate 2 voltage ($V_{G2}$) near the source and the gate 1 voltage ($V_{G1}$) near the drain region convert the junctionless device into a P-i-N structure. Because the operation of the device is based on the gate voltage, side gate voltages are fixed to establish the band structure of the device. Fig.2 illustrates the effect of variation of $I_{\text{ON}}$ on $V_{G1}$ for different values of $V_{G2}$. It is evident that the maximal value of $V_{G1}$ is chosen in the range of 0.7 to 1.3 V if $I_{\text{ON}}$ is constrained. The energy band diagram of the JTFET with $V_{G2} = -0.7 \text{ V}$ for $V_{G1} = 0.7$ and 1.3 V is illustrated in Fig.3, which shows the BTBT rate as $V_{G1}$ increases.

| Parameter                        | Value          |
|----------------------------------|----------------|
| Gate 1, gate 2 lengths           | 50, 50 nm      |
| Channel length ($L$)             | 40 nm          |
| Thickness of gate dielectric ($T_g$) | 3 nm          |
| Thickness of silicon ($T_s$)     | 8 nm           |
| Doping ($N_d$)                   | $8 \times 10^{11} \text{ cm}^{-2}$ |
| Gate voltage for gate 1 near drain | $1 \text{ V}$  |
| Gate voltage for gate 2 near source | $-0.7 \text{ V}$ |
| Gate bias ($V_{G0}$)             | $1 \text{ V}$  |
| Drain bias ($V_{D0}$)            | $2 \text{ V}$  |
| Gate 1 work function             | $4.26 \text{ eV}$ |
| Middle gate work function        | $4.28 \text{ eV}$ |
| Gate 2 work function             | $4.6 \text{ eV}$ |
| Permittivity of high-$k$ dielectric ($Si_3N_4$) | $k = 7.5$      |
| Permittivity of low-$k$ spacer ($SiO_2$) | $k = 3.5$      |

**Table I.** Simulated TMTG-JTFET device parameters

Fig.2. $V_{G1}$ versus $I_{\text{ON}}$ for different values of $V_{G2}$
Fig. 3. Energy band diagram with $V_{G2}$ as $-0.7$ V for different values of $V_{G1}$.

Fig. 4 shows the effect of varying $I_{ON}$ on $V_{G2}$ for different values of $V_{G1}$. It can be observed that $I_{ON}$ increases when $V_{G2}$ becomes more negative. The energy band diagram, with $V_{G2}=-0.7$ V for $V_{G1}=-0.7$ and $0.7$ V is illustrated in Fig. 5, which shows that the BTBT rate increases as $V_{G2}$ becomes more negative.

Fig. 4. $V_{G2}$ versus $I_{ON}$ for different values of $V_{G1}$.

Fig. 5. Energy band diagram with $V_{G1}$ as $0.7$ V for different values of $V_{G2}$.

In this model, for each mesh point, nonlocal BTBT is used by the TCAD simulator to determine the tunneling rate by using Kane’s model considering the band structure and electric field. Fig. 6 illustrates the contour plot of the electrostatic potential of the JTFET. It is evident that there is a
potential drop in the source–channel junction as defined by (14), which increases the electric field in the tunneling region.

As shown in Fig. 7, the first-order eigenfunction works well to describe the channel potential, and higher-order approximations of the Taylor series expansion are used to capture the potential in the source–channel junction. In the middle of the channel, the electrostatic potential \( \psi(x,y) \) is constant and is obtained as 2.86V from (14) by using the superposition approximation method, and the analytical result is validated with the results of the TCAD device simulator. To model the electric field distribution along the channel, we have considered only the lateral electric field, because the tunneling path follows the channel direction. It is evident from Fig. 8 that the highest electric field is obtained in the source–channel junction and drops to its minimal value in the middle of the channel owing to constant potential, as shown in Fig. 7. A maximal electric field of \( 0.128 \times 10^6 \) V/cm has been derived by using the superposition approximation method with (16), and the analytical result is compared with the simulator result.
The drain current behavior for the JTFET device is shown in Fig. 9. The proposed analytical model offers an on-current of $1.68 \times 10^{-8}$ A/m for $V_G = 1$ V at fixed side voltages of $V_{G1} = 0.7$ V and $V_{G2} = -1.1$ V. It is evident from Fig. 9 that the drain current increases with increasing gate voltage, owing to the presence of a high-$k$ material for the gate (Si$_3$N$_4$, $k = 7.5$) and low-$k$ spacers (SiO$_2$, $k = 3.9$). A low off-current of $\sim 10^{-12}$ A/m is observed in Fig. 9 owing to the ultrastep doping profile. This model can also be applied to other materials such as III–V compound semiconductors. A higher drain current and a steeper subthreshold slope can be obtained by reducing the thickness of silicon, using high-$k$ dielectrics such as HfO$_2$, ZrO$_2$, and TiO$_2$ as gate material and by work function engineering.

5. Conclusion

In this paper, the electrostatic potential of a TMTG-JTFET has been developed from the 2D Poisson’s equation using the superposition approximation method; its derivative gives the electric field. The drain current is obtained by integrating the BTBT generation rate over the channel thickness. Maximal $I_{on}$ is achieved by giving a positive voltage to the drain and a negative voltage to
the source. The JTFET device with three gates offers an $I_{ON}$ of $1.68 \times 10^{-8}$ A/μm at $V_G=1$ V, $V_{G1} = 0.7$ V, and $V_{G2} = -1.1$ V. Analytical results for the electrostatic potential, electric field, and drain current obtained using the superposition approximation method are in good agreement with the TCAD results.

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