Analysis of Ge-Si Heterojunction Nanowire Tunnel FET: Impact of Tunneling Window of Band-to-Band Tunneling Model

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Tunnel FET (TFET) has potential applications in the next generation ultra-low power transistor to substitute the conventional FETs. It can offer very steep inverse subthreshold slope to maintain a low leakage current, thus it can be very essential for limiting power consumption in MOSFETs. The carriers in TFET transport from source to channel by the band-to-band tunneling (BTBT) mechanisms. To realize high saturation currents of TFET, it critically depends on the transmission probability, \( T_{\text{WKB}} \). In indirect semiconductor, such as Si and Ge, the BTBT model is very crucial for designing and predicting the device performance. In this paper, we employed the nonlocal BTBT model applied to three-dimensional Ge-Si heterojunction TFET with gate length 10 nm compare with Si TFET by including quantum effects simulation. The results show that the Ge-Si TFET outperforms Si TFET because of the lower bandgap and larger tunneling windows. BTBT generation rates of Ge-Si TFET are higher than Si TFET in the on-state condition. The highest BTBT generation rates are located in the source and channel junction and its peaks close to the gate dielectric.

Power dissipation is a primary concern for future nanoelectronics devices and switching systems.1 Reducing supply voltage \( (V_{\text{dd}}) \), while keeping leakage current very low is very essential for limiting power consumption in MOSFETs.2 As \( V_{\text{dd}} \) is reduced, the overdrive factor \( (V_{\text{dd}}−V_{\text{th}}) \) must be remained high to meet performance requirements. On the other hand, reducing threshold voltage \( (V_{\text{th}}) \) can cause the off-state current \( (I_{\text{off}}) \) increase exponentially. Therefore, subthreshold swing \( (SS) \) must be reduced to maintain a low \( I_{\text{off}} \). However, conventional MOSFETs cannot provide \( SS \) lower than 60 mV/dec at room temperature because of fundamental thermal limits. Charge injection in the MOSFET occurs by thermionic emission over a potential barrier, is bound by an exponential tail of Fermi statistics.3,4

In the nanoscale transistor, the cylindrical nanowire is the promising candidate in the ultra-low power vertical devices due to high device density, its negligible trapping and leakage from buffer layer, wrap-gated structure and possibility of very short gate length (below 20 nm).5 Moreover, cylindrical shape tunnel field-effect transistor (TFET) can offer a very steep inverse subthreshold slope for maintain a low leakage current. The TFET is a gated p-i-n transistor with a gate voltage that causes large band bending at the source junction. Hence, the carriers can be transported from source to channel by the band-to-band tunneling (BTBT) mechanism.6 The carrier injection on the BTBT of electrons from a degenerate p+ source into the channel conduction band causes high-energy carrier are filtered out by the semiconductor bandgap. Thus, steeper subthreshold slopes can be achieved.

Recent studies have reported many complex fabrication issues of TFETs because of asymmetric doping concentration in source and drain of planar horizontal TFET. For the mature material process like germanium, the TFET fabrication process can be easily performed using top-down methods due to the maturity of etching and lithography technologies. Top-down methods have certain advantages in enabling fabrication of addressable, large area, and reproducible devices with good control of geometric dimension and dopant incorporation compared with bottom-up methods.7 Germanium material has a small effective bandgap, low-temperature process, relatively low cost, high symmetry, and easy integration on Si platform.8 In this paper, we employed BTBT model applied to three-dimensional Ge-Si heterojunction TFET compare with that Si TFET to understand the insight physics for predicting the device performance.

Band-to-Band Tunneling (BTBT) Theory

Band-to-Band Tunneling (BTBT) is a quantum mechanical process where electrons transport from the valence band to the conduction band (or vice versa) through the forbidden energy bandgap. Quantum mechanical tunneling occurs due to a non-zero probability for transition through a barrier. This tunneling current can generate electron-holes pairs. The transistor that operates based on this tunneling principle is called Tunnel FET (TFET). To realize high saturation currents of TFET, it critically depends on the transmission probability, \( T_{\text{WKB}} \), of the interband tunneling barrier.1 This barrier can be approximated by a triangular potential, so \( T \) can be calculated using the Wentzel–Krammer–Brillouin (WKB) approximation:

\[
T_{\text{WKB}} \approx \exp \left( \frac{4\lambda \sqrt{2m^*E_g^{3/2}}}{3\hbar(E_g + \Delta \Phi)} \right)
\]

where \( \lambda \) is the screening length; \( m^* \) is the effective mass; \( E_g \) is the energy bandgap of the source material, and \( \Delta \Phi \) is the energy difference between the valence band of the source and the conduction band of the channel.

To model tunneling adequately, this probability must be found and multiplied by the number of electrons in a given volume of space to find the net tunneling rate of electrons. Understanding the nature of this band-to-band tunneling is important for understanding the approximations made in various simulation models. There are several important models for Band-to-Band Tunneling (BTBT) models, such as Kane model,9 Schenck model,10 Hurkx model,11 and non-local path tunneling model.

a) Simple Model/Kane model: A general expression for these models can be written for the generation term as:

\[
G_{\text{BTBT}} = A_{\text{BTBT}}F \exp \left( -\frac{B_{\text{BTBT}}}{F} \right)
\]

where \( G_{\text{BTBT}} \) is the BTBT rate, \( A_{\text{BTBT}} \) is the prefactor, \( B_{\text{BTBT}} \) is the exponential factor, and \( F \) is the electric field. In Kane/simple model, even the electric field profile is not constant; a local \( G_{\text{BTBT}} \) is computed...
based on the local field. Since the BTBT rate only depends on $F$, we have current also for $V_{DS} = 0$ V.

b) Schenck model: Band-to-band tunneling is modeled using the expression:

$$R_{net}^{bb} = A_{bb} \left( \frac{F^{7/2}}{1 \text{ V/cm}} \right) \exp \left( -\frac{B_{bb} \left( F \right)^{3/2}}{E_g \left(300K\right)^{3/2} F} \right)$$

[3]

where the critical field strengths:

$$F^\pm = B \left( E_{g,ef} \pm \hbar \omega \right)^{3/2}$$

[4]

The upper sign refers to tunneling generation ($np < n^2_{i,ef}$) and the lower sign refers to recombination ($np > n^2_{i,ef}$). The quantity $\hbar \omega$ denotes the energy of the transverse acoustic phonon.

c) Hurkx model: The tunneling carriers are modeled by an additional generation–recombination process. Its contribution is expressed as:

$$R_{net}^{bb} = A_D \left( \frac{F}{1 \text{ V/cm}} \right)^p \exp \left( -\frac{B_D \left( F \right)^{3/2}}{E_g \left(300K\right)^{3/2} F} \right)$$

[5]

where:

$$D = \frac{np - n^2_{i,ef}}{\left( n + n_{i,ef} \right) \left( p + p_{i,ef} \right)} \left( 1 - |\alpha| \right) + \alpha$$

[6]

Here, specifying $\alpha = 0$ gives the original Hurkx model, whereas $\alpha = -1$ gives only generation ($D = -1$), and $\alpha = 1$ gives only recombination ($D = 1$). In this model, we can have both generation and recombination. It means that at $V_{DS} = 0$ (equilibrium), the net current will be zero. However, this model can largely overestimate the BTBT generation because the electric field is not uniform.

d) Nonlocal path tunneling model: The model implements the nonlocal generation of electrons and holes caused by direct and phonon-assisted band-to-band tunneling processes. In indirect semiconductors such as Si and Ge, the phonon-assisted tunneling process is more dominant than the direct tunneling process. If the energy differences between the conduction band valleys are small, it is possible that both the direct and the phonon-assisted tunneling processes are important.12 The model dynamically searches for the tunneling path that has a direction that is opposite to the gradient of the valence band. The model can be expressed as:

$$R_{net} = A \left( \frac{F}{F_0} \right)^p \exp \left( -\frac{B}{F} \right)$$

[7]

where $F_0 = 1 \text{ V/cm}, P = 2$ for the direct tunneling process, and $P = 2.5$ for the phonon-assisted tunneling process. Theoretically, the prefactor $A_{BTBT}$ and exponential factor $B_{BTBT}$ for direct and phonon-assisted tunneling process can be expressed by:

$$A_{direct} = \frac{g \pi m^*_{i,ef}^2 \left( q F_0 \right)^3}{9\hbar^4 E_g \left(300K\right) + \Delta_c}$$

[8]

$$B_{direct} = \frac{\pi^2 m^*_{i,ef}^2 \left( E_g \left(300K\right) + \Delta_c \right)^{3/2}}{\hbar q}$$

[9]

$$A_{phonon} = \frac{g \left( m_0 m_i \right)^{3/2} \left( 1 + 2N_{op} \right) D_{op}^3 \left( q F_0 \right)^{5/2}}{2^{11/4} \hbar^{5/4} m^*_{i,ef} \left( E_g \left(300K\right) + \Delta_c \right) \pi^2}$$

[10]

$$B_{phonon} = \frac{2^{11/4} \pi m^*_{i,ef}^2 \left( E_g \left(300K\right) + \Delta_c \right)^{3/2}}{3 \hbar}$$

[11]

where $g$ is a degeneracy factor; $m_i$ is the reduced tunneling mass; $q$ is the elementary charge; $h$ is Planck’s constant; ($m_i, m_0$) is the valence (conduction) band density of states effective mass; $N_{op} = \left[\exp\left(\epsilon_{i,op}/\kappa T\right) - 1\right]$ is the occupation number of the transverse acoustic phonon at temperature $T$, where $k$ is the Boltzmann constant; $D_{op}$ is the deformation potential of transverse acoustic phonons; $\rho$ is the mass density; $\tau_{op}$ is the transverse acoustic phonon energy; and $E_g$ is the minimum bandgap.

### Simulation Methods

Fig. 1 shows the device structure of Ge-Si heterojunction cylindrical nanowire TFET. The gate channel length ($L_g$) is set to 10 nm. The effective oxide thickness (EOT) is 0.6 nm. The source materials are high-doped germanium for Ge-Si TFET or silicon for Si TFET. The doping concentrations of the p-type source and the n-type drain are $1 \times 10^{20}$ and $1 \times 10^{19}$ cm$^{-3}$, respectively. The low-doped n-type silicon channel uses $1 \times 10^{17}$ cm$^{-3}$. The nanowire diameter ($D$) is set to 12 nm. The Sentaurus TCAD simulator was used to perform three-dimensional simulations, including the density-gradient solving model with quantum effects. This quantum effects is very important because the behavior of electron change in nanoscale devices. The band-gap narrowing model and SRH recombination with the doping dependent model were also considered. The Matthiessen’s rule was applied in the model used for device simulation, which included surface acoustic phonon scattering, surface roughness scattering, and bulk mobility with doping-dependent modification effect. Fermi statistics was also activated instead of Boltzmann statistics. Interface trap between Ge and Si material in Ge-Si is also considered with value of $10^{11}$ cm$^{-3}$. In this paper, we mainly focus on nonlocal path Band-to-Band tunneling model that employed in the comparison between Si homo-junction and Ge-Si hetero-junction nanowire TFET. The theoretical value of $\Delta_{BTBT} = 9.1 \times 10^{-6}$ cm$^{-1}$s$^{-1}$V$^{-2}$ and $\Delta_{BBT} = 4.9 \times 10^{-6}$ Vcm$^{-1}$ were adopted for Ge material.13 For Si TFET, the BTBT parameters of Si material are $\Delta_{BTBT} = 4 \times 10^{-6}$ cm$^{-1}$s$^{-1}$V$^{-2}$ and $\Delta_{BBT} = 19 \times 10^{-6}$ Vcm$^{-1}$.

### Results and Discussion

Fig. 2 shows the comparison of the transfer characteristics of Si homo-junction and Ge-Si hetero-junction nanowire TFET in the same gate length and nanowire diameter. This simulation reveals that Ge-Si TFET outperforms the Si TFET. The SS as low as 46 mV/dec and on/off current ratio as higher as $5 \times 10^6$ can be achieved in Ge-Si TFET. Increased leakage current in Ge-Si TFET is resulted from greater field-induced BTBT tunneling for small effective mass of Ge. When the gate-to-drain voltage becomes increasingly negative, a high electric field is created at the surface of the channel-to-drain overlap region. This results in a BTBT process that increases the gate-induced drain leakage (GIDL) current.14 The high electric field generates electron-hole pairs via band-to-band tunneling. As electrons drift toward the drain, the holes move into the channel region. If the transporting holes reach the source, the channel-to-source junction becomes forward biased, allowing the injection of electrons into the channel and represents the primary component of the increased leakage current. The leakage current also increases as $V_D$ increases due to
Figure 2. Transfer characteristics of Ge-Si TFET compared with Si TFET at \( L_G = 10 \text{ nm} \) and \( D = 12 \text{ nm} \) at \( V_D = 0.5 \text{ V} \).

the high electric field in the gate. Fig. 3 shows the transfer characteristics of Si TFET for different \( V_D \). It found that the Si TFET with \( L_G = 10 \text{ nm} \) and \( D = 12 \text{ nm} \) has steep \( SS \) below 60 mV/dec for \( V_D = 0.2–0.7 \text{ V} \). As \( V_D \) increases, the leakage current will increase.

Figs. 4a and 4b present simulated energy band diagrams of the Si homo-junction and Ge-Si hetero-junction nanowire TFET in the on-state (\( V_D = 0.5 \text{ V} \) and \( V_G = 0.5 \text{ V} \), solid line) and off-state condition (\( V_D = 0.5 \text{ V} \) and \( V_G = 0 \text{ V} \), dot line). The electrons will tunnel from the valence band of the source side to the conduction band of the channel side when the barrier width was enough reduced.

The energy difference between the valence band of the source and the conduction band of the channel can be represented by the tunneling window (\( \Delta \Phi \)). As depicted in Fig. 3, the tunneling window is larger in the Ge-Si TFET than in the Si TFET. This physical behavior can be explained by using the Wentzel-Kramers-Brillouin (WKB) approximation following Eq. 1. By increasing tunneling window, the BTBT tunneling probability will increase. Larger tunneling window results the saturation current of Ge-Si TFET outperforms Si TFET as seen in Fig. 2. The small effective tunnel gap of Ge materials can also result in high tunnel rates.

Figs. 5a and 5b present the BTBT generation rates (BTBT-GR) comparison of Si and Ge-Si nanowire TFET in the on-state. The highest BTBT generation rates are located in the source and channel junction and its peaks close to the gate dielectric. The Ge-Si TFET has a higher BTBT-GR compared to the Si TFET, which increases its on-current performance.

Figure 3. Transfer characteristics of Si-Si-Si cylindrical GAA TFET for different \( V_D \).

Figure 4. Simulated energy band diagram of a) Si and b) Ge-Si TFET in channel direction under on-state condition (\( V_D = 0.5 \text{ V} \) and \( V_G = 0.5 \text{ V} \), solid line) and off-state condition (\( V_D = 0.5 \text{ V} \) and \( V_G = 0 \text{ V} \), dot line).

Figure 5. Comparison of a) Ge-Si and b) Si TFET Band-to-Band Generation Rate (BTBT-GR) in the on-state (\( V_G = 0.5 \text{ V} \), \( V_D = 0.5 \text{ V} \)).
Figures 6a and 6b illustrate the influence of source and drain doping concentration on the subthreshold swing of Si and Ge-Si TFET, respectively. It shows that a high doping concentration in the source and low doping concentration in the drain enhances the SS below 60 mV/dec in Si TFET. For the heavily doped source, the voltage inside the source region is almost uniform because of the high hole concentration. Therefore, the electric field is concentrated on the source/channel junction. Because of high localized doping in the source, it can create large electric fields, which enhance tunnel rates. Figure 6b shows that the steep SS in the Ge-Si TFET was mainly determined by source doping concentration. The influence of n+ drain doping level on the SS is rather small. Thus, the n+ doping drain region is not as important as the p+ doped source region. The heavily n-type doped region is necessary for the ohmic metal-semiconductor contact at the drain of TFET.

Figures 7a and 7b show the influence of gate length ($L_g$) and diameter nanowire on the SS of Si and Ge-Si TFET, respectively. Decreasing the nanowire diameter degraded the SS due to size confinement effects. In addition, decreasing $L_g$, the SS will also decrease because of better electrostatic gate control. The SS variation in Ge-Si TFET is less sensitive to changes in gate length and the diameter nanowire compared with Si TFET.

Conclusions

In summary, this study of vertical Ge-Si cylindrical nanowire TFET demonstrated a very steep subthreshold slope and high on/off current ratio. Ge-Si heterojunction cylindrical tunnel-FET has better performance than Si TFET due to its smaller effective tunnel gap and its larger tunneling window. As larger tunneling window provides better tunneling which in turn reflects on the current ratio of the nanoscale devices. This device has promising applications in next-generation ultra-low power vertical transistors.
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