Dependency of Tunneling Field-Effect Transistor (TFET) Characteristics on Operation Regions

Min Jin Lee and Woo Young Choi

Abstract—In this paper, two competing mechanisms determining drain current of tunneling field-effect transistors (TFETs) have been investigated such as band-to-band tunneling and drift. Based on the results, the characteristics of TFETs have been discussed in the tunneling-dominant and drift-dominant region.

Index Terms—Tunneling field-effect transistor, band-to-band tunneling, drift, tunnel resistance, channel resistance

I. INTRODUCTION

A TFET is considered as one of the most promising candidates to replace a MOSFET. It is because the subthreshold swing (SS) of the TFET can be smaller than 60 mV/dec at room temperature, which is the physical limit of the MOSFET [1-4]. However, the TFET has suffered from smaller on current ($I_{ON}$) than the MOSFET at the same channel length ($L_{CH}$). It is originated from the fact that the SS of the TFET is a function of the gate voltage ($V_{GS}$) unlike that of the MOSFET [2] and the physical reason is the large tunneling barrier. Fig. 1 shows that the TFET has a smaller instantaneous SS than the MOSFET at low overdrive voltage ($V_{OV}$). $V_{OV}$ is defined as the difference between $V_{GS}$ and threshold voltage ($V_T$). In this work, $V_T$ of TFETs is defined as $V_{GS}$ when drain current ($I_{DS}$) is $10^{-15}$ A/μm. However, at high $V_{OV}$, the instantaneous SS of the TFET increases more abruptly than that of the MOSFET. It is problematic in that $I_{ON}$ of the TFET cannot exceed that of the MOSFET.

Fig. 2 compares the on resistance ($R_{ON}$) of the MOSFET and TFET. The $R_{ON}$ of the MOSFET consists of source resistance ($R_S$), drain resistance ($R_D$) and channel resistance ($R_{CH}$). On the other hand, the $R_{ON}$ of the TFET has an additional tunnel resistance ($R_{TUN}$). $R_{CH}$ is determined by drift mechanism which is related to channel mobility. $R_{TUN}$ is determined by band-to-band tunneling mechanism which is related to the tunneling barrier between the source and channel region. It should be noted that $R_{ON}$ of the TFET has both $R_{CH}$ and $R_{TUN}$. It means that $I_{DS}$ of the TFET is determined by both drift and band-to-band tunneling while $I_{DS}$ of MOSFETs is determined only by drift mechanism. Thus, it can be inferred that TFETs can have two different operating regions depending on the values of $R_{CH}$ and $R_{TUN}$. When $R_{TUN}$ is dominant, TFETs are operated in the tunneling-dominant region where band-to-band tunneling determines $I_{DS}$. When $R_{CH}$ is dominant, TFETs are operated in the

Fig. 1. Instantaneous SS of a 1-μm MOSFET and TFET. Inset figure provides fine-scale resolution.

Manuscript received Aug. 2, 2011; revised Oct. 18, 2011.
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In this paper, we have adjusted $R_{\text{TUN}}$ and $R_{\text{CH}}$ by performing device simulation in order to investigate the electrical characteristics of tunneling-dominant and drift-dominant TFETs. This paper consists of two parts. First, the extraction method of $R_{\text{ON}}$ components is explained. In the first place, Fig. 3 shows the extraction method of $R_{\text{CH}}$. $R_{\text{ON}}$ is plotted by dividing $I_{DS}$ by the drain voltage ($V_{DS}$) from TFETs with various $L_{\text{CH}}$'s. $V_{OV}$ and $V_{DS}$ are fixed at 1 and 0.1 V, respectively. The line slope in Fig. 3 indicates $R_{\text{CH}}$ per $L_{\text{CH}}$ ($\rho_{\text{CH}}$). However, the problem of this method is that the line slope is too small to measure because the ratio of $R_{\text{CH}}$ to $R_{\text{ON}}$ is extremely small. It makes the accurate extraction of $R_{\text{CH}}$ difficult. Thus, for higher accuracy, we have decreased channel mobility by a factor of 1, 0.1, 0.05 and 0.01. Those factors are defined as mobility factor ($MF$) in this paper. It means that $R_{\text{CH}}$ increases by a factor of 1, 10, 20 and 100 because $R_{\text{CH}}$ is inversely proportional to channel mobility. By adjusting $MF$, $\rho_{\text{CH}}$ can be extracted accurately as shown in Fig. 4.

For example, at the same $V_{OV}$, when channel mobility decreases by a factor of 10, $\rho_{\text{CH}}$ becomes 10x larger. In order to extract the genuine value of $\rho_{\text{CH}}$ which is defined as $\rho_{\text{CH}}$ when $MF$ is 1, the extracted $\rho_{\text{CH}}$ needs to be calibrated by the reciprocal of $MF$. Fig. 5 shows extracted $\rho_{\text{CH}}$'s with various $MF$'s. When calibrated by the reciprocal of $MF$'s, genuine $\rho_{\text{CH}}$'s are located in the tunneling-dominant and drift-dominant region.

**II. EXTRACTION METHOD OF $R_{\text{ON}}$ COMPONENTS**

Single-gate silicon-on-insulator (SOI) TFETs have been simulated by using Silvaco ATLAS [5]. Nonlocal band-to-band tunneling [6], doping and temperature dependent mobility model, band-gap narrowing, Fermi-Dirac and Shockley-Read-Hall recombination model have been used in the simulation. The simulated TFET has a gate oxide thickness of 2 nm, a channel width ($W_{\text{CH}}$) of 1 mm, a buried oxide thickness of 150 mm and an SOI layer thickness of 50 nm. N+ poly-Si gate is used. The doping concentrations of the channel ($N_{B}$), source ($N_{S}$) and drain region ($N_{D}$) are $5 \times 10^{17}$, $1 \times 10^{19}$ and $1 \times 10^{19}$ cm$^{-3}$, respectively. Quantum mesh has been used at the surface of the SOI layer.

For quantitative analysis, each component of $R_{\text{ON}}$ has been extracted. In the first place, Fig. 3 shows the extraction method of $R_{\text{CH}}$. $R_{\text{ON}}$ is plotted by dividing $I_{DS}$ by the drain voltage ($V_{DS}$) from TFETs with various $L_{\text{CH}}$'s. $V_{OV}$ and $V_{DS}$ are fixed at 1 and 0.1 V, respectively. The line slope in Fig. 3 indicates $R_{\text{CH}}$ per $L_{\text{CH}}$ ($\rho_{\text{CH}}$). However, the problem of this method is that the line slope is too small to measure because the ratio of $R_{\text{CH}}$ to $R_{\text{ON}}$ is extremely small. It makes the accurate extraction of $R_{\text{CH}}$ difficult. Thus, for higher accuracy, we have decreased channel mobility by a factor of 1, 0.1, 0.05 and 0.01. Those factors are defined as mobility factor ($MF$) in this paper. It means that $R_{\text{CH}}$ increases by a factor of 1, 10, 20 and 100 because $R_{\text{CH}}$ is inversely proportional to channel mobility. By adjusting $MF$, $\rho_{\text{CH}}$ can be extracted accurately as shown in Fig. 4.

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same curve as shown in the inset of Fig. 5. It confirms the validity of the proposed extraction method. Next, $R_{SD}$ is extracted. We use the fact that $MF$’s affect $R_{CH}$ and $R_{SD}$ regardless of $R_{TUN}$. Depending on the value of $MF$, $R_{ON}$’s are written as

$$R_{ON}(MF=1.0) = R_{CH}(MF=1.0) + R_{SD}(MF=1.0) + R_{TUN} \quad (1a)$$

$$R_{ON}(MF=0.5) = R_{CH}(MF=0.5) + R_{SD}(MF=0.5) + R_{TUN} - 2R_{CH}(MF=1.0) + 2R_{SD}(MF=1.0) + R_{TUN} \quad (1b)$$

When Eq. (1a) is subtracted from Eq. (1b), $R_{TUN}$ disappears while $R_{CH}$ and $R_{SD}$ remain as follows:

$$R_{ON}(MF=0.5) - R_{ON}(MF=1.0) = R_{CH}(MF=1.0) + R_{SD}(MF=1.0) \quad (2)$$

$R_{SD}$ is derived as

$$R_{SD}(MF=1.0) = R_{ON}(MF=0.5) - R_{ON}(MF=1.0) - R_{CH}(MF=1.0) \quad (3)$$

Fig. 6 shows that the average value of extracted $R_{SD}$ is $588 \, \Omega$ and constant regardless of $V_{OV}$. Also, as $V_{OV}$ increases, $R_{CH}$ decreases, which makes $R_{SD}$ larger than $R_{CH}$. Finally, $R_{TUN}$ is extracted as follows:

$$R_{TUN} = R_{ON} - R_{CH} - R_{SD} \quad (4)$$

Based on the abovementioned results, we defined intrinsic $R_{ON}$ ($R_{ON\_int}$), which excludes $R_{SD}$ as

$$R_{ON\_int} = R_{ON} - R_{SD} = R_{TUN} + R_{CH} \quad (5)$$

Fig. 7 shows $R_{ON\_int}$ as a function of $L_{CH}$ for the extraction of $R_{TUN}$. Unlike Fig. 3, every line meets at one $y$-intercept which indicates $R_{TUN}$ because $MF$’s only affect $R_{CH}$ rather than $R_{TUN}$. In order to confirm the validity, we compared extracted $R_{TUN}$ with theoretical values which is calculated by the following equation [7]:

$$R_{TUN} = A \times \frac{4\pi^3 h^2 W_{TUN} E_G}{\sqrt{2m^* q^3}} \exp\left(\frac{4\sqrt{2m^* W_{TUN} E_G}}{3qh}\right) \quad (6)$$

where $A$ is constant, $q$ is elementary charge, $m^*$ is electron tunneling effective mass, $W_{TUN}$ is tunneling barrier width, $E_G$ is bandgap energy and $h$ is Dirac constant. For the calculation of theoretical values, As $V_{OV}$ increases, $W_{TUN}$ decreases and its decreasing rate becomes smaller as shown in Fig. 8(a). $W_{TUN}$ have been extracted automatically at each $V_{OV}$ by using device simulation as follows. From the simulated energy band diagrams, the minimum distance between valence band and conduction band has been extracted as shown in inset of Fig. 8(a). $A$ and $m^*$ have been calibrated carefully to fit extracted $R_{TUN}$ with the theoretical value. Fig. 8(b) shows
that the extracted $R_{\text{TUN}}$ fits theoretical $R_{\text{TUN}}$ within 5.4%. Thus, it is confirmed that $R_{\text{TUN}}$ is related only to tunneling mechanism rather than drift mechanism. Although $R_{\text{TUN}}$ is not a function of $V_{\text{TUN}}$ from Eq. (6), $V_{\text{TUN}}$ affects $W_{\text{TUN}}$ and $R_{\text{TUN}}$ actually. $V_{\text{TUN}}$ means the voltage drop across the tunneling junction which is defined as

$$V_{\text{TUN}} = \frac{R_{\text{TUN}}}{R_{\text{CH}} + R_{\text{TUN}} + R_{\text{CH}}} V_{\text{DS}} \quad (7).$$

As $MF$ decreases, $R_{\text{CH}}$ increases and $V_{\text{TUN}}$ decreases. It increases $W_{\text{TUN}}$ and $R_{\text{TUN}}$. In order to further confirm the validity of the extraction method, we have observed $\Delta V_{\text{TUN}}$, $\Delta W_{\text{TUN}}$ and $\Delta R_{\text{TUN}}$ with the variation of $MF$ at $V_{\text{OV}} = 1$ V. Inset figure shows the definition of $W_{\text{TUN}}$. (b) $R_{\text{TUN}}$ compared with theoretical values and inset figure shows the ratio of $R_{\text{TUN}}$ to $R_{\text{CH}}$ with the variation of $V_{\text{OV}}$ at $V_{\text{DS}} = 0.1$ V.

![Fig. 8.](a) Extracted $W_{\text{TUN}}$ with the variation of $V_{\text{OV}}$ at $V_{\text{DS}} = 0.1$ V. Inset figure shows the definition of $W_{\text{TUN}}$. (b) $R_{\text{TUN}}$ compared with theoretical values and inset figure shows the ratio of $R_{\text{TUN}}$ to $R_{\text{CH}}$ with the variation of $V_{\text{OV}}$ at $V_{\text{DS}} = 0.1$ V.

III. TUNNELING-DOMINANT TFETS VS. DRIFT-DOMINANT TFETS

From now on, the electrical characteristics of TFETs will be investigated in the tunneling-dominant and drift-dominant region. In the first place, tunneling-dominant TFETs will be discussed because most of TFETs from literature are classified into tunneling-dominant TFETs. Simulation conditions of tunneling-dominant TFETs are summarized in Table 1. It is observed that in the case of tunneling dominant TFET, $R_{\text{TUN}}$ is ~2000x larger than $R_{\text{CH}}$ as shown inset of Fig. 8(b). In the case of tunneling-dominant TFETs, $R_{\text{TUN}}$ is a dominant factor determining $R_{\text{ON}}$ and instantaneous $SS$ becomes larger as $V_{\text{OV}}$ increases. It means that the tunneling-dominant TFET may have lower $I_{\text{ON}}$ than the MOSFET even if the former has lower instantaneous $SS$ than the latter at low $V_{\text{OV}}$.

![Fig. 9.](b) $\Delta W_{\text{TUN}}$, $\Delta R_{\text{TUN}}$ and $\Delta R_{\text{TUN}}$ with the variation of $MF$. As shown in Fig. 8(a), $W_{\text{TUN}}$ shows little change with the variation of $V_{\text{TUN}}$. Thus, $\Delta R_{\text{TUN}}$ is 1% and it confirms the validity of the proposed extraction method.

| Table 1. Simulation conditions of tunneling-dominant and drift-dominant TFET |
|-------------------------------------------------|-------------------------------------------------|
| $MF$                                            | 1                                              |
| $m^2$ factor                                    | 1                                              |
| $15\mu m$                                      | 15 nm                                          |
| Gate oxide thickness                            | 2 nm                                           |
| Channel width                                   | 1 $\mu m$                                      |
| Buried oxide thickness                          | 150 nm                                         |
| SOI layer thickness                             | 50 nm                                          |
| Gate material                                   | N⁺ poly-Si                                     |
| $N_0$, $N_1$ and $N_0$                         | $5 \times 10^{17}$, $1 \times 10^{19}$ and $1 \times 10^{19}$ cm⁻³ |
same $L_{CH}$, which due to $R_{TUN}$ rather than $R_{CH}$ because $I_{DS}$ of the tunneling-dominant TFET is determined only by band-to-band tunneling. Fig. 10 shows that $I_{DS}$ matches the tunneling current ($I_{TUN}$) well which is defined as

$$I_{TUN} = \frac{V_{DS}}{R_{TUN}} \quad (8).$$

As explained in Eq. (6), $R_{TUN}$ is a strong function of $W_{TUN}$. As $V_{OV}$ increases, $W_{TUN}$ decreases and its decreasing rate becomes smaller as shown in Fig. 8a. It makes $R_{TUN}$ and $R_{ON}$ decrease less abruptly as $V_{OV}$ increases, which causes $I_{DS}$ saturation at high $V_{OV}$.

Conventional TFETs have suffered from low $I_{ON}$ because they are operated in the tunneling-dominant region. Thus, the best way of boosting $I_{ON}$ is reducing $R_{TUN}$. Some pioneering research results have been reported for the purpose of low $R_{TUN}$ [3, 8]. As a result, recently, $I_{ON}$ of TFETs have risen at a steady pace [9, 10]. In particular, III–V TFETs may achieve larger tunneling current compared with Si TFETs due to their smaller bandgap energy and smaller electron mass [11, 12]. Further, TFETs with gate-drain overlap structures to suppress ambipolar behavior will have larger $R_{CH}$ than MOSFETs, which makes drift-dominant TFETs more feasible [13]. If $R_{TUN}$ is reduced successfully down to the $R_{CH}$ in the future, TFETs will be operated in the drift-dominant region where $I_{DS}$ is determined by drift mechanism unlike tunneling-dominant TFETs. In the drift-dominant region, TFETs show electrical characteristics similar to MOSFETs. For the investigation of drift-dominant TFETs, $m^*$ has been 1x, 0.8x, 0.6x, 0.4x, 0.2x and 0.15x decreased. Fig. 11 shows that $R_{TUN}$ decreases as $m^*$ factor decreases while inset of Fig. 11 shows that $\rho_{CH}$ is constant regardless of $m^*$ factor. According to simulation results, when $m^*$ factor is 0.15, the ratio of $R_{TUN}$ to $R_{CH}$ is $\sim$10. It implies that $I_{DS}$ is greatly affected by drift mechanism. Thus, in this work, the TFET whose $m^*$ factor is less than 0.15 is defined as a drift-dominant TFET as shown in Table 1.

Drift-dominant TFETs are distinguished from tunneling-dominant TFETs in three viewpoints. First, drift-dominant TFETs are dominated by $R_{CH}$. Fig. 12(a)
compare $R_{TUN}$ with $R_{ON}$ in the case of tunneling-dominant and drift-dominant TFETs. The drift-dominant TFET shows considerable difference which is equal to $R_{CH}$ as shown in Fig. 12(b). It proves that drift mechanism plays an important role in determining $I_{DS}$ in the case of drift-dominant TFETs. Second, $I_{DS}$ of tunneling-dominant TFETs is independent of $L_{CH}$ while $I_{DS}$ of drift-dominant TFETs is dependent on $L_{CH}$ as shown in Fig. 13. Finally, tunneling-dominant and drift-dominant TFETs show different temperature dependence [14]. Fig. 14 shows that $I_{DS}$ of tunneling-dominant TFETs increases as temperature increases. It is because of $E_G$ reduction at elevated temperature. On the other hand, $I_{DS}$ of drift-dominant TFETs decreases as temperature increases. It is because channel mobility is reduced with increasing temperature.

To sum up, currently, the best way of achieving large $I_{ON}$ is the reduction of $R_{TUN}$ because most of TFETs operate in the tunneling-dominant region. However, continuous reduction of $R_{TUN}$ makes tunneling-dominant TFETs drift-dominant. Thus, for more $I_{ON}$ boosting of drift-dominant TFETs, higher channel mobility will be necessary as in the case of conventional MOSFETs. Fig. 15 shows that channel mobility has no influence on $I_{DS}$ in the tunneling-dominant TFET. However, in the case of the drift-dominant TFET, $I_{ON}$ is affected by channel mobility.

**IV. SUMMARY**

The extraction method of $R_{CH}$ and $R_{TUN}$ has been proposed for TFETs. Based on the results, we classified the operation region of TFETs into two categories: the tunneling-dominant and drift-dominant region. In the tunneling-dominant region, because $I_{DS}$ is dominated by $R_{TUN}$ rather than $R_{CH}$, the instantaneous $SS$ increases with increasing $V_{OV}$ which is related to $W_{TUN}$ saturation. The reduction of $R_{TUN}$ makes tunneling-dominant TFETs drift-dominant. In the drift-dominant region, like MOSFETs, mobility engineering will be necessary for higher $I_{ON}$.

**ACKNOWLEDGMENTS**

This work was supported in part by the National Research Foundation (NRF) of Korea funded by the Ministry of Education, Science and Technology (MEST) under Grants 2011-0019107 (Development of Future-Oriented Technology) and 2011-0027471 (Mid-Career Researcher Program), in part by the Ministry of Knowledge Economy (MKE) of Korea under Grant NIPA-2011-C1090-1101-0003 (University ITRC support
program supervised by the National IT Industry Promotion Agency), in part by the IT R&D program of MKE/KEIT under Grant 10039174 (Technology Development of 22 nm level Foundry Device and PDK) and in part by the Sogang University Research Grant of 2010.

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