Dependence of Short-Channel Effects on Semiconductor Bandgap in Tunnel Field-Effect Transistors

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Abstract. Scaling down the bandgap is considered as an essential approach to enhance the performance of tunnel field-effect transistors (TFETs). Using two-dimensional simulations, this study examines the dependence of short-channel effects on the semiconductor bandgap in TFETs. It is shown that the short-channel effect is more severe with using lower bandgap materials although the supply voltage is scaled in parallel with the bandgap. For a given bandgap material, the short-channel effect can be well evaluated by the increase of drain-induced barrier thinning (DIBT) with decreasing the channel length. For different bandgap TFETs, however, their short-channel effects cannot be compared properly by comparing the DIBTs. Adequately considering the effect of bandgap on the TFET scalability is necessary in designing scaled integrated circuits.

1. Introduction

Tunnel field-effect transistors (TFETs) with a steep subthreshold swing of sub-60 mV/decade [1], [2] have attracted much attention since the demand of low power consumption becomes a key factor in designing electronic devices. However, the conduction mechanism based on band-to-band tunneling (BTBT) does not allow the TFET on-current as high as that of conventional MOSFETs [3]. Over the past decade, many advanced techniques involving new materials and structures have been suggested to ameliorate the on-current of TFETs [4]-[7]. Among proposed solutions, using low-bandgap materials has been demonstrated as the most effective method to improve the on-current [4] since the tunneling probability depends exponentially on the bandgap which is treated as the height of tunnel barrier [8].

With the continuous trend of decreasing the feature size of transistors to keep the pace of Moore’s law, the length scaling of TFETs is also one of the most important problems that need to be addressed. Since TFETs are operated in reverse-biased condition, valence electrons in the source can directly tunnel to the drain at off-state to cause severe short-channel effects in sub-30 nm uniform TFETs [9], [10]. Some sophisticated techniques have been developed to scale TFETs into sub-10 nm regimes.
Figure 1. Typical p-i-n structure of tunnel field-effect transistors used in this study.

While the scaling of bandgap is critical to boost the on-current, its effects on the short-channel effect have not been clearly understood. Our recent work has pointed out that the bandgap parameter should be taken into account in studying the short-channel effect of TFETs [12]. Therefore, an adequate understanding on the role of bandgap in determining the short-channel performance is important in applying low-bandgap materials for scaled TFETs.

In this paper, we examined the dependence of short-channel effects on the bandgap of semiconductors in TFET devices. Two-dimensional simulations [15] based on the nonlocal approach of direct and indirect Kane’s BTBT models [8] were performed to produce their electrical characteristics. The total tunneling current in TFETs was determined by the BTBT generation rate ($G_{\text{BTBT}}$) which was modeled in the Kane’s formalism as:

$$ G_{\text{BTBT}} = A \frac{E_g \gamma}{E_s^{3/2}} \exp \left( -B \frac{E_s^{1/2}}{\xi} \right), $$

(1)

where $E_g$ is the semiconductor bandgap, $E_s$ is the nonlocal electric field which is the average of electric field along the tunnel path. In the formula of tunneling rate (1), $\gamma = 2$ was applied for direct tunneling and $\gamma = 2.5$ was used for indirect tunneling. Input factors $A$ and $B$ depend on material parameters and their values can be manually adjusted in the simulator. To investigate the bandgap dependence of short-channel effects, three different bandgap materials including high-bandgap Si (1.12 eV), low-bandgap Ge (0.8 eV) and InAs (0.36 eV) were adopted. These low-bandgap semiconductors were demonstrated as excellent candidates for TFET devices because of their CMOS-compatible fabrication technology [16]. The indirect BTBT model was used for Si-based TFETs, whereas the direct BTBT model was applied for Ge and InAs devices. In the simulations, we used the values of $A$ and $B$ that were theoretically calculated and experimentally verified for Si in [17], Ge and InAs in [18]. For more realistic simulations, the Fermi-Dirac distribution and the Shockley-Read-Hall recombination were also enabled. To exactly evaluate the bandgap dependence of short-channel effects, however, the process-sensitive trap-assisted tunneling and the bandgap narrowing due to heavy doping were not included.

2. Short-channel effects

Figure 1 shows the schematic view of a typical p-i-n TFET used in this study. The uniform structure was utilized to exclude any effects of structure parameters on short-channel effects, which may create difficulties for the studying purpose. The source region was heavily doped by a p-type impurity of $10^{20}$ cm$^{-3}$ to enhance the on-current, whereas a medium donor concentration of $5 \times 10^{18}$ cm$^{-3}$ was employed for the drain to diminish the ambipolar off-current [19]. A very low n-type doping concentration of
$10^{15}$ cm$^{-3}$ was defined for the channel and a practical doping gradient of 2 nm/decade was applied at source/drain junctions. A reasonable equivalent oxide thickness of 1 nm was specified for the gate insulator layer and the gate workfunction was set at 4.25 eV for all TFETs.

To investigate the dependence of short-channel effects on the bandgap, figure 2 shows the current-voltage characteristics of TFETs using Si, Ge and InAs. Because the drain voltage must be scaled in parallel with the bandgap to eliminate the ambipolar off-leakage [18], the supply voltage ($V_{dd}$) for drain in each case of material is slightly smaller than their bandgap voltage ($E_g/q$), namely 1, 0.7 and 0.3 V for Si, Ge and InAs TFETs, respectively. Moreover, setting the drain voltage in the scale of bandgap is also to ensure the appropriate and significant evaluation of short-channel effects because the smaller bandgap is suitable for lower power applications. For easily comparing short-channel effects in the three cases, the gate voltage is normalized by the bandgap voltage. Generally, the short-channel effects are clearly observed in all Si, Ge and InAs TFETs at very short channel lengths. In particular, the on-off characteristics start deteriorating because of substantial short-channel effects when the channel lengths are scaled below 30 nm for Si, 60 nm for Ge, and 80 nm for InAs TFETs. It means that with the same channel length of 40 nm, the short-channel effect is negligible in the Si TFET, but it is considerable in the Ge TFET and severe in the InAs TFET. Notably, the channel length limit, which separates the two regimes of negligible and severe short-channel effects, increases when going from high- to low-bandgap TFETs. To exactly explain the differences of the length limits, it is noted that there are only two factors that are different among the TFETs, including the bandgap and

![Figure 2. Current-voltage characteristics of TFET devices based on (a) Si, (b) Ge, and (c) InAs.](image-url)
Drain voltage. Logically, because decreasing the drain voltage helps to decrease the short-channel effect of TFETs [20], the increase in the length limit is obviously attributed to the decrease in the bandgap of semiconductors. Physically, the increase in short-channel effect with decreasing the bandgap is due to the exponential dependence of tunneling probability on the bandgap. More specifically, the increase of tunneling probability is much more rapid than the decrease of drain voltage when scaling down the bandgap.

### 3. Drain-induced barrier thinning

In traditional MOSFETs, if the channel length is short enough, the electric field of drain can penetrate deeply into the region of the source-channel junction. The partial merge of the source and drain fields leads to the lowering of thermal barrier to deteriorate the on-off characteristics of short-channel devices. This drain-induced barrier lowering (DIBL) can be used to directly measure the short-channel effect of MOSFETs because the larger the DIBL, the stronger the short-channel effect is. In TFET devices, similarly, the drain field can encroach upon the source-channel region to thin the tunnel barrier. Therefore, this drain-induced barrier thinning (DIBT) also degrades the on-off switching of TFETs. However, the current of TFETs is controlled not only by the tunnel barrier width, but also by the tunnel barrier height. Merely using DIBT is not enough to estimate the short-channel performance of TFETs [12]. In this section, the bandgap dependence of DIBT and its role in explaining the short-channel effect of TFETs are considered by investigating different bandgap materials.

Figure 3 shows the DIBT as a function of channel length for Si, Ge and InAs TFETs. For fair comparisons, the threshold voltage used in the DIBT calculation is defined separately for each case of material using the constant current method. The current level used for each material is determined by the 100nm TFET at the gate voltage of 0.4E_g/q higher than the onset voltage. The calculation of DIBT is based on the threshold voltages attracted at V_{dd} and 0.1V_{dd}. Overall, the DIBT tends to increase as the channel length decreases for all materials. The DIBT starts increasing significantly when the channel lengths are decreased below 30 nm for Si, 60 nm for Ge, and 80 nm for InAs TFETs. These values of channel lengths are identical to those observed in figure 2. Importantly, only the variation trend of the DIBT, but not its magnitude, depends on the bandgap similarly to that of the short-channel effect. It implies that for a given semiconductor bandgap, the DIBT variation with scaling the channel length can be used as a good indicator to measure the short-channel effect of TFETs. However, the DIBT magnitude cannot be used to compare short-channel effects between different bandgap devices.

As seen in the figure, for the same channel length of 40 nm, the DIBT of the Si TFET is considerably higher than that of the Ge TFET, whereas the short-channel effect of the Si TFET is much weaker than...
that of the Ge TFET. For longer channel lengths, the DIBT of the Si TFET is even considerably greater than that of the Ge and InAs devices. Finally, it is seen at the short-channel regimes that the increase of DIBT is more rapid in TFETs with lower bandgap materials, which is a direct consequence of enhanced tunneling probability due to decreased bandgap. In other words, the short-channel performance of low-bandgap TFETs degrades at a faster rate than that of high-bandgap counterparts with aggressive channel length scaling.

In order to understand the increase of DIBT when scaling the channel length, figures 4(a)-(b) plot the energy-band diagrams at threshold state of Ge TFETs with different channel lengths. For the 60nm TFET, the conduction band at the region of the shortest tunnel path in case of $V_{ds} = 0.7$ V is very close to that in case of $V_{ds} = 0.07$ V because the drain field does not penetrate significantly into the channel. Therefore, the minimum barrier widths in the two cases are almost equal to produce a small DIBT. For the 20nm TFET, however, the deep encroachment of the drain field on the channel at the high drain voltage pulls down the channel conduction band significantly. Consequently, the shortest tunnel path regions are clearly separated and the minimum barrier width is appreciably decreased at the high drain voltage to get a large DIBT. Here, only the energy-band diagrams of Ge-based TFETs are exampled for illustrating the explanations because the similar mechanism of DIBT trends also occurs in higher-bandgap Si and lower-bandgap InAs TFETs. For explaining the large DIBT at long-channel regime in high-bandgap Si TFETs compared to low-bandgap Ge TFETs (and similarly to InAs TFETs), figure

Figure 4. Energy-band diagrams at threshold state of (a) long-channel Ge, (b) short-channel Ge, and (c) long-channel Si TFETs.
4(c) shows the energy-band diagrams at threshold state of the 60nm Si TFET at low and high drain voltages. Although the long channel can effectively prevent the drain field encroachment on the channel, the high drain voltage associated with the small carrier density in the channel pulls the channel conduction band down largely. As a result, the minimum barrier width at the high voltage is much smaller than that at the low voltage, which results in the large DIBT.

4. Conclusion
The dependence of short-channel effects on the semiconductor bandgap in TFETs have been examined to show that the device scalability is poorer with using lower bandgap materials. For a given bandgap, the variation of drain-induced barrier thinning with scaling the channel length can serve as a good indicator to evaluate the short-channel effect of TFETs, but its magnitude cannot be used to compare short-channel effects between different bandgap devices. With the necessity of decreasing the bandgap for enhancing the on-current, the bandgap dependence of short-channel effects should be properly considered in scaling TFET devices.

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