III-V Heterojunction TFET with Bandgap Engineering for Performance Enhancement and Ambipolar Leakage Suppression

Chiu-Ting Wang and Vita Pi-Ho Hu
Department of Electrical Engineering, National Central University, Taoyuan, Taiwan
Phone: +866-3-4227151 Email: vitalahu@ee.ncu.edu.tw

Abstract
GaAs$_x$Sb$_{1-x}$/In$_x$Ga$_{1-x}$As heterojunction TFETs with bandgap engineering by using non-uniform channel thickness (Tch) are analyzed comprehensively for improving Ion and suppressing ambipolar leakage. Quantum confinement induced bandgap widening as a function of Tch is considered. For non-uniform Tch TFETs, the thick source/channel junction thickness (Ts) with small bandgap maintains small tunneling barrier and large on current, while the thin drain/channel junction thickness (Td) with large bandgap reduces the ambipolar leakage. With the same Ioff, type II non-uniform TFET exhibits 4 times larger Ion (238 μA/μm) than the type-II uniform TFET, and type III non-uniform TFET shows 63% improvement in Ion ($538 μA/μm$) compared with the type-III uniform TFET. The optimized non-uniform TFETs are designed with Ts = 9nm and Td = 4–5nm. Ion degradation is observed for non-uniform Tch TFETs with thin Td = 3nm due to extra energy barrier.

Introduction
Tunnel FET (TFET) with steep switching characteristics has been intensely studied as a promising candidate for ultra-low-power applications. The major challenges for TFET have been achieving high drive current and suppressing the ambipolar leakage. Compared with Si TFET, III-V TFETs are attractive due to low effective mass and small bandgap, which improving the band-to-band tunneling probability and tunneling current densities. The effective bandgap (E$_{gap}$) is adjustable for further increasing the on current of III-V GaAs$_x$/Sb$_{1-x}$/In$_x$Ga$_{1-x}$As heterojunction TFET by changing the compositions x and y [1-3]. GaSb/InAs TFETs with broken gap band alignment has been studied for suppressing the ambipolar leakage by using non-uniform channel thickness [4]. In other words, reducing the drain/channel junction thickness offers a large bandgap due to quantum confinement and suppresses the ambipolar tunneling leakage at off-state, meanwhile retaining a relatively large source/channel tunnel junction thickness without compromising the large tunnel probability. However, the impact of source/channel and drain/channel junction thickness on the on-current (Ion) has rarely been examined. The structure of heterojunction TFETs with uniform and non-uniform channel thickness (Tch) are shown in Fig. 1(a) and 1(b). Non-uniform TFET with thick source/channel junction thickness (Ts) and thin drain/channel junction thickness (Td) suppresses the ambipolar leakage, while introducing extra energy barrier and degrading Ion if Td is too thin. In this paper, we optimized the non-uniform channel thickness for type-II and type-III GaAs$_x$/Sb$_{1-x}$/In$_x$Ga$_{1-x}$As TFETs with bandgap engineering are analyzed comprehensively compared with the Si DG MOSFET.

Simulation Methodology and Device Parameters
In this work, double gate structure with gate length = 25 nm and high-k gate dielectric (Tox = 3nm with H102) is analyzed for type-II (GaAs$_x$/Sb$_{1-x}$/In$_x$Ga$_{1-x}$As) and type-III (GaAs$_x$/Sb$_{1-x}$/In$_x$Ga$_{1-x}$As) heterojunction TFETs, and their band diagrams are shown in Fig. 2. As can be seen, type-III TFET with the broken gap shows ultra-thin tunneling barrier. In the TFET simulations [5], effective mass, affinity and the bandgap widening due to quantum confinement with various Tch are calibrated [6] as shown in Fig. 3. We use nonlocal tunneling model which is applicable to account for the arbitrary tunneling barrier with non-uniform electric field. Tunneling parameters including A$_{path}$ and B$_{path}$ as a function of bandgap and R$_{crit}$ are calibrated [7].

Non-uniform Tch TFETs with Bandgap Engineering
Fig. 4 shows the impact of drain and source doping concentrations on the Id-Vg characteristics of type-II TFETs with uniform Tch. TFET with low drain doping concentration suppresses the ambipolar leakage due to the increased tunneling barrier across the drain/channel junction. However, TFET with high source doping concentration improves Ion due to decreased tunneling barrier across the source/channel junction. In the following part, the source, drain, and channel doping concentrations of TFETs are designed with $3E19$ cm$^{-3}$, $1E17$ cm$^{-3}$, and $1E15$ cm$^{-3}$, respectively. Fig. 5 shows the Id-Vg characteristics of type-II and type-III TFETs with uniform Tch. Compared with TFET with uniform Tch = 9 nm, TFET with uniform Tch = 3 nm exhibits larger Eg (shown in Fig. 3) resulting in smaller Ion and Ioff. Fig. 6 shows the impact of uniform Tch on the Ion, Ioff, and Ioff/Ion ratio for type-II and type-III TFETs. As can be seen, for Tch scaling from 9nm to 2nm, the Ion degrades significantly for both type-II and type-III TFETs due to bandgap widening and increased tunneling barrier across the source/channel junction. Therefore, the relatively large source/channel junction thickness (Ts) should be used to maintain high Ion. Type-III TFET with ultra-thin tunneling barrier across the source/channel junction and smaller Eg across the drain/channel junction exhibits larger Ion and larger Ioff than the type-II TFET. Therefore, the small drain/channel junction thickness (Td) should be used for suppressing the ambipolar leakage. TFET with small Tch shows excellent Ion/Ioff ratio, however, Ion is significantly degraded at small Tch. In other words, TFETs with uniform Tch design exhibit conflicting improvements in Ion and Ioff.

Fig. 7 compares the Id-Vg characteristics of type-II and type-III TFETs with non-uniform Tch and uniform Tch. Type-II TFET with non-uniform Tch (Ts = 9nm, Td = 5nm) shows larger Ion ($238μA/μm$) than that with uniform Tch = 5nm ($538 μA/μm$) and maintain the same Ioff (7F-9μA/μm). Type-III TFET with non-uniform Tch (Ts = 9nm, Td = 5nm) exhibits 63% improvements in Ion compared with TFET with uniform Tch = 5nm. Besides, TFETs with non-uniform Tch exhibit better subthreshold swing than TFETs and Si DG MOSFETS with uniform Tch. Fig. 8 shows the impact of thicker channel length (Lw = 15nm) on the Id-Vg characteristics of non-uniform type-II TFETs, and results show that non-uniform Tch TFET with Lw = 4nm exhibits slightly larger Ion. Fig. 9 shows the impact of Td on the Id-Vg characteristics for type-II and type-III TFETs. The Ioff of non-uniform Tch TFETs can be significantly reduced as Td changes from 5nm to 3nm. This is because the tunneling barrier across the drain/channel junction increases as Td changes from 5nm to 3nm. However, non-uniform Tch TFETs show significant degradations in Ion as Td scales down to 3nm. For non-uniform Tch TFETs, Td is reduced for suppressing the ambipolar leakage, however, small Td may introduce an extra energy barrier across the source/channel junction which degrades the Ion as can be seen in Fig. 10. Fig. 11 compares the Ion and Ioff among type-II and type-III TFETs with non-uniform Tch, and Si DG MOSFETs. For non-uniform type-III TFETs, Ioff can be improved by 77% as Td changes from 5nm to 3nm, and for non-uniform type-II TFETs, Ioff can be improved by over two orders of magnitude as Td changes from 5nm to 3nm. However, for non-uniform Tch type-III (type-II) TFETs, compared with Td = 5nm, Td = 4nm and 3nm show 2.2% (6%) and 36% (44.5%) degradation in Ion, respectively. Therefore, for non-uniform Tch type-II and type-III TFETs with Ts = 9nm, Td cannot be smaller than 4nm in order to maintain high Ion and suppress the ambipolar leakage.

In summary, non-uniform Tch type-II and type-III GaAs$_x$/Sb$_{1-x}$/In$_x$Ga$_{1-x}$As heterojunction TFETs with bandgap engineering can enhance the Ion and suppress the ambipolar leakage by using large Ts and small Td. The optimized non-uniform Tch design for type-II and type-III TFETs are proposed. For non-uniform Tch TFETs, Ts should be equal to or larger than 9nm to avoid the significant Ion degradation due to band-gap widening, while Td is designed at 4–5nm for ambipolar leakage suppression, and Td should not be smaller than 4nm to avoid extra energy barrier induced Ion degradations.

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References
Fig. 1. Ga$_{1-x}$Sb$_x$/In$_{1-y}$Ga$_y$As TFETs with (a) uniform channel thickness ($T_{ch}$) and (b) non-uniform $T_{ch}$, where $T_s$ ($T_d$) is the source/channel (drain/channel) junction thickness. The oxide thickness and gate length are the same for uniform $T_{ch}$ and non-uniform $T_{ch}$ TFETs.

Fig. 2. The energy band diagrams of (a) type-II and (b) type-III (broken-gap) GaAs$_{1-x}$Sb$_x$/In$_{1-y}$Ga$_y$As heterojunction TFETs with uniform channel thickness.

Fig. 3. Impact of channel thickness on bandgap of various III-V materials. The quantum confinement effect along the channel thickness direction is considered.

Fig. 4. The $I_d$-$V_g$ characteristics of type-II TFETs with (a) various drain doping concentration ($N_d$) and (b) various source doping concentration ($N_s$). TFET with lower $N_d$ and higher $N_s$ shows lower ambipolar leakage and higher on current ($I_{on}$).

Fig. 5. The $I_d$-$V_g$ characteristics of (a) type-II and (b) type-III TFETs with uniform channel thickness ($T_{ch}$) structure as shown in Fig. 1(a). Type-II and type-III TFETs show larger $I_{on}$ and ambipolar leakage as $T_{ch}$ changes from 3nm to 9nm.

Fig. 6. Impact of $T_{ch}$ on (a) $I_{on}$, (b) $I_{off}$, and (c) $I_{on}$/$I_{off}$ ratio for type-II and type-III TFETs with uniform $T_{ch}$. As $T_{ch}$ changes from 10nm to 2nm, $I_{on}$ degrades significantly and $I_{off}$ is reduced due to bandgap widening resulting from quantum confinement effect. Type-II TFET with small $T_{ch}$ shows excellent $I_{on}$/$I_{off}$ ratio, however, $I_{on}$ is significantly degraded at small $T_{ch}$.

Fig. 7. Id-$V_g$ characteristic comparisons of non-uniform $T_{ch}$ TFET, uniform $T_{ch}$ TFET, and Si DG MOSFET. Non-uniform $T_{ch}$ TFET with bandgap engineering exhibits larger $I_{on}$ and lower $I_{off}$ compared with the uniform $T_{ch}$ TFET.

Fig. 8. Impact of $L_w$ on the $I_d$-$V_g$ characteristics of type-II TFET with non-uniform $T_{ch}$ as shown in Fig. 3(b) ($T_s = 9nm$ and $T_d = 5nm$).

Fig. 9. Impact of drain/channel junction thickness ($T_d$) on the $I_d$-$V_g$ characteristics of type-II/type-III TFETs with non-uniform $T_{ch}$. $T_{ch}$ = 9nm and $L_w$ = 4nm. $I_{off}$ can be reduced by decreasing $T_d$. However, $I_{on}$ also degrades as $T_d$ decreases.

Fig. 10. Band diagrams of non-uniform $T_{ch}$ type-II TFETs with $T_d = 5nm$ and 3nm, respectively ($T_s = 9nm$, $L_w = 4nm$). TFET with smaller $T_d$ and larger bandgap introduces an extra barrier between source/channel junction which results in $I_{on}$ degradation compared to TFET with larger $T_d$.

Fig. 11. (a) $I_{on}$ and (b) $I_{off}$ comparisons among non-uniform $T_{ch}$ type-II TFETs, non-uniform $T_{ch}$ type-III TFETs, and uniform $T_{ch}$ Si DG MOSFETs with various $T_d$ and $T_{ch}$. Non-uniform $T_{ch}$ type-III TFETs exhibit larger $I_{on}$ than the non-uniform type-II TFET and Si DG MOSFET.

Fig. 12. Band diagrams of non-uniform $T_{ch}$ type-II TFETs with $T_d = 5nm$ and 3nm, respectively ($T_s = 9nm$, $L_w = 4nm$). TFET with smaller $T_d$ and larger bandgap introduces an extra barrier between source/channel junction which results in $I_{on}$ degradation compared to TFET with larger $T_d$. 

Fig. 13. Impact of drain/channel junction thickness ($T_d$) on the $I_d$-$V_g$ characteristics of type-II/type-III TFETs with non-uniform $T_{ch}$. $T_{ch}$ = 9nm and $L_w$ = 4nm. $I_{off}$ can be reduced by decreasing $T_d$. However, $I_{on}$ also degrades as $T_d$ decreases.

Fig. 14. Band diagrams of non-uniform $T_{ch}$ type-II TFETs with $T_d = 5nm$ and 3nm, respectively ($T_s = 9nm$, $L_w = 4nm$). TFET with smaller $T_d$ and larger bandgap introduces an extra barrier between source/channel junction which results in $I_{on}$ degradation compared to TFET with larger $T_d$. 

Fig. 15. Impact of drain/channel junction thickness ($T_d$) on the $I_d$-$V_g$ characteristics of type-II/type-III TFETs with non-uniform $T_{ch}$. $T_{ch}$ = 9nm and $L_w$ = 4nm. $I_{off}$ can be reduced by decreasing $T_d$. However, $I_{on}$ also degrades as $T_d$ decreases.