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

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Abstract

$GaAs_{1-x}Sb_x/In_{1-y}Ga_yAs$ 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/um) than the type-II uniform TFET, and type III non-uniform TFET shows 63% improvement in Ion (538 μA/um) 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 ($E_{g,eff}$) is adjustable for further increasing the on current of III-V $GaAs_{1-x}Sb_x/In_{1-y}Ga_yAs$ 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 source 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, the optimized non-uniform channel thickness for type-II and type-III $GaAs_{1-x}Sb_x/In_{1-y}Ga_yAs$ 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 HfO_2) is analyzed for type-II ($GaAs_{0.4}Sb_{0.6}/In_{0.65}Ga_{0.35}As$) and type-III ($GaAs_{0.1}Sb_{0.9}/InAs$) 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_{path} 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 Ion/Ioff 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/um) than that with uniform Tch = 5nm (53μA/um) and maintain the same Ioff (7E-9μA/um). 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 shown in Fig. 1(b)) 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 and suppress the ambipolar leakage.

In summary, non-uniform Tch type-II and type-III $GaAs_{1-x}Sb_x/In_{1-y}Ga_yAs$ 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.

Acknowledgments

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References

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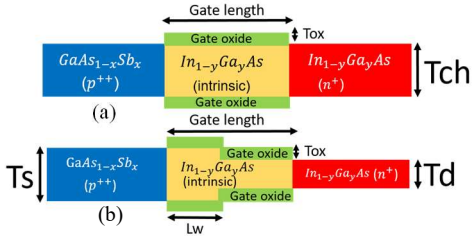

Fig. 1. $GaAs_{1-x}Sb_x/In_{1-y}Ga_yAs$ TFETs with (a) uniform channel thickness (Tch) and (b) non-uniform Tch, where Ts (Td) is the source/channel (drain/channel) junction thickness. The oxide thickness and gate length are the same for uniform Tch and non-uniform Tch TFETs.

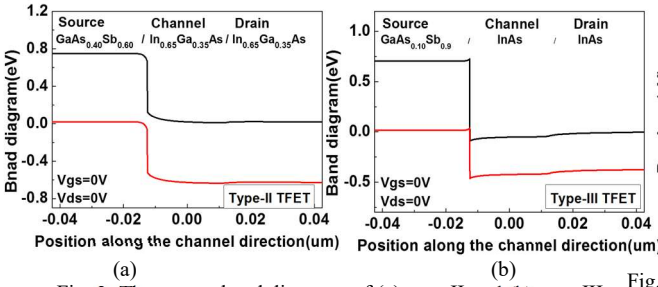

Fig. 2. The energy band diagrams of (a) type-II and (b) type-III (broken-gap) $GaAs_{1-x}Sb_x/In_{1-y}Ga_yAs$ heterojunction TFETs with uniform channel thickness.

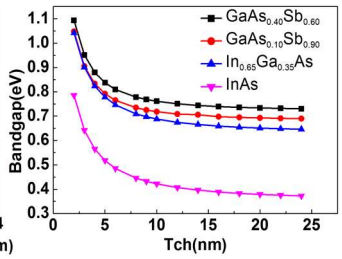

Fig. 3. Impact of channel thickness on bandgap of various III-V materials. The quantum confinement effect along the channel thickness direction is considered.

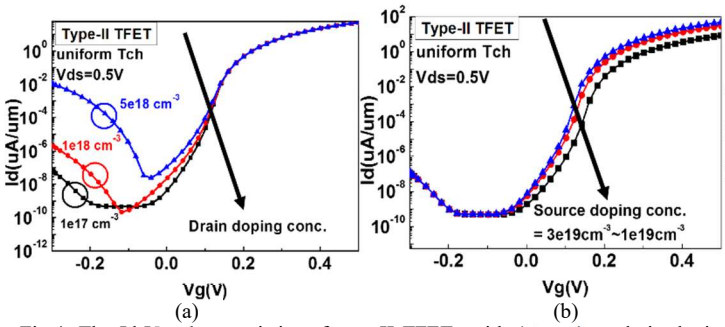

Fig.4. The Id-Vg characteristics of type-II TFETs with (a) various drain doping concentration (Nd) and (b) various source doping concentration (Ns). TFET with lower Nd and higher Ns shows lower ambipolar leakage and higher on current (Ion).

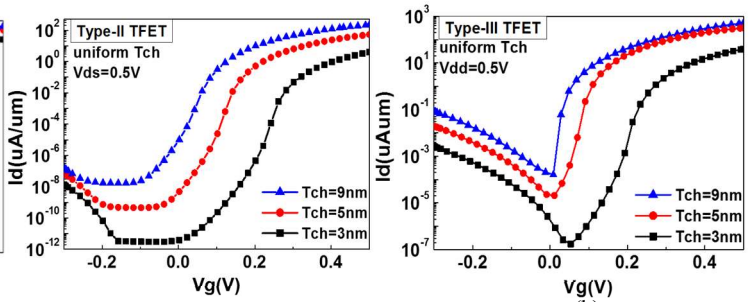

Fig.5. The Id-Vg characteristics of (a) type-II and (b) type-III TFETs with uniform channel thickness (Tch) structure as shown in Fig. 1(a). Type-II and type-III TFETs show larger Ion and ambipolar leakage as Tch changes from 3nm to 9nm.

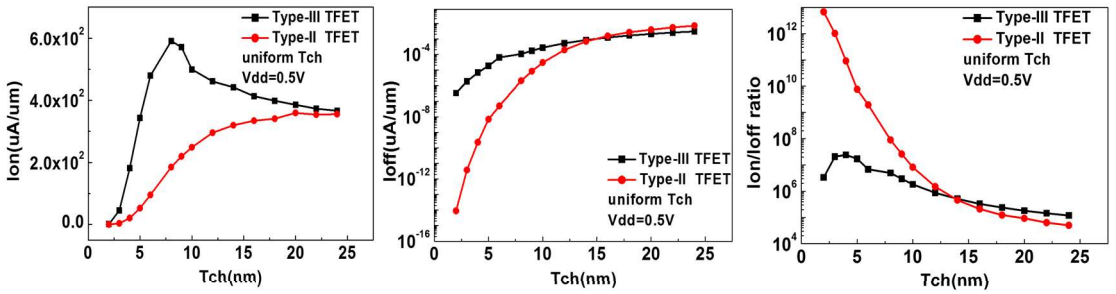

Fig. 6. Impact of Tch on (a) Ion, (b) Ioff, and (c) Ion/Ioff ratio for type-II and type-III TFETs with uniform Tch. As Tch changes from 10nm to 2nm, Ion degrades significantly and Ioff is reduced due to bandgap widening resulting from quantum confinement effect. Type-II TFET with small Tch shows excellent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

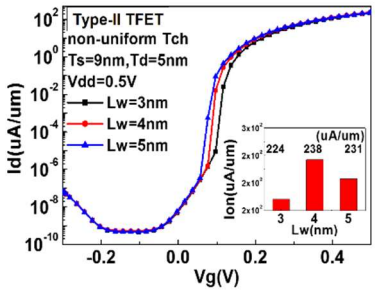

Fig.8. Impact of Lw on the Id-Vg characteristics of type-II TFET with non-uniform Tch as shown in Fig. 3(b) (Ts = 9nm and Td = 5nm).

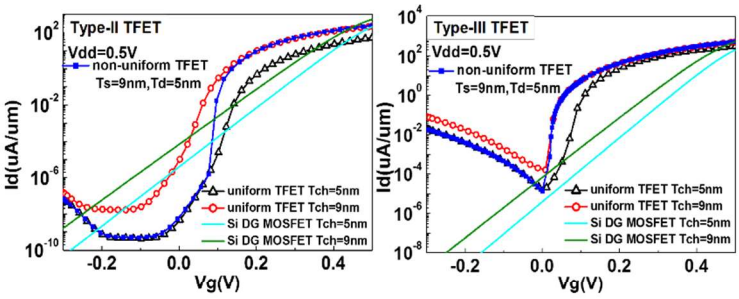

Fig.7. Id-Vg characteristic comparisons of non-uniform Tch TFET, uniform Tch TFET, and Si DG MOSFET. Non-uniform Tch TFET with bandgap engineering exhibits larger Ion and lower Ioff compared with the uniform Tch TFET.

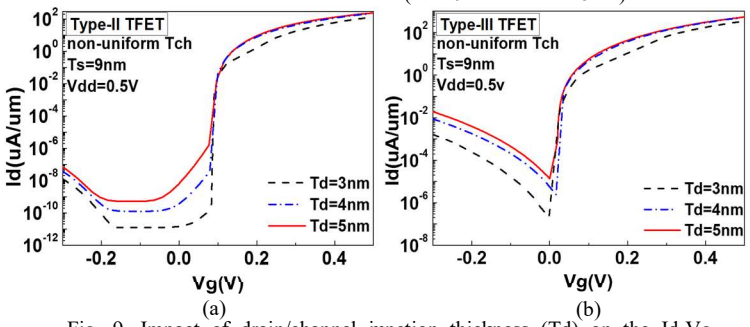

Fig. 9. Impact of drain/channel junction thickness (Td) on the Id-Vg characteristics of type-II/type-III TFETs with non-uniform Tch. (Ts = 9nm and Lw = 4nm). Ioff can be reduced by decreasing Td. However, Ion also degrades as Td decreases.

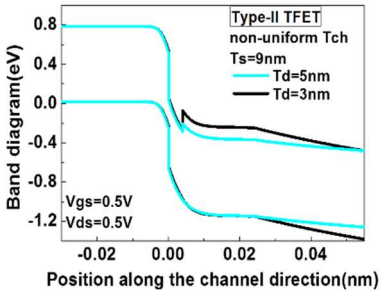

Fig.10. Band diagrams of non-uniform Tch type-II TFETs with Td = 5nm and 3nm, respectively (Ts = 9nm, Lw = 4nm). TFET with smaller Td and larger bandgap introduces an extra barrier between source/channel junction which results in Ion degradation compared to TFET with larger Td.

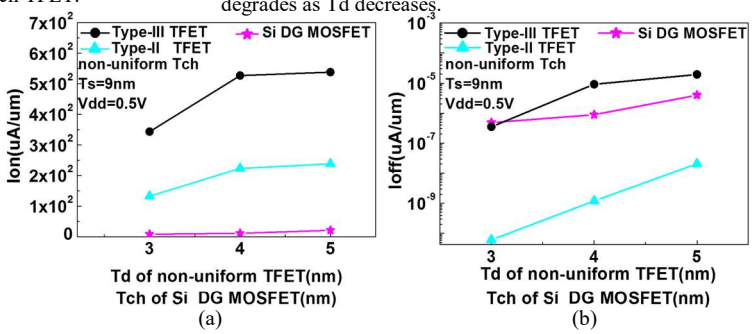

Fig. 11. (a) Ion and (b) Ioff comparisons among non-uniform Tch type-II TFETs, non-uniform Tch type-III TFETs, and uniform Tch Si DG MOSFETs with various Td and Tch. Non-uniform Tch type-III TFETs exhibit larger Ion than the non-uniform type-II TFET and Si DG MOSFET.