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Design of AlGaAs/InGaAs Heterojunction Tunneling Field-Effect Transistor for Low-Standby-Power and High-Performance Application

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1. Introduction

Increasing significance of power consumption in the nanoelectronic circuits calls for low standby power (LSTP) and low supply voltage (V_{DD}) operation have been required. Tunneling field-effect transistor (TFET) is a candidate with such capabilities due to excellent performance such as steep subthreshold swing (S) and low off-state current (I_{off}). Low on-state current (I_{on}) of silicon (Si) TFETs can be overcome by employing compound materials, high-κ dielectrics, and novel structuring [1-3]. Compound heterojunction TFETs with wide range of energy bandgap (E_g) can be designed to have higher I_{on} than conventional MOSFETs at a low V_{DD}. Also, TFETs should have a sharp band bending between source and channel to minimize the effective tunneling barrier width (W_T), since thinner W_T greatly improves both I_{on} and S. Compound semiconductors with various electron affinity (EA) and E_g have more chances to construct heterojunctions having steeper band bending [4]. AlGaAs/InGaAs can be also a candidate for hetero-structuring in TFETs. Even though GaAs has a larger energy bandgap (E_g = 1.42 eV) than that of Si (E_g = 1.12 eV), $Al_xGa_{1-x}As/In_yGa_{1-y}As$ heterojunction can form steep interfacial band bending by a large difference between EAs. In this work, we propose and characterize a TFET with $Al_xGa_{1-x}As/In_{1-y}Ga_yAs$ heterojunction achieving LSTP and high performance (HP) operations at as low V_{DD} as 0.5 V. 3-dimensional (3D) device simulations were performed for an optimal device design in terms of I_{on}, I_{off}, S, threshold voltage (V_{th}), and intrinsic delay time (τ).

2. Device Design and Performances

The design and characterization have been performed by device simulations (both TCAD and ATLAS) activating multiple models including non-local band-to-band tunneling (BBT) (spatial variations are taken into account) and trap-assisted tunneling (TAT) models for higher accuracy [5–6]. In incorporating higher Al and lower In fractions in $Al_xGa_{1-x}As$ and $In_yGa_{1-y}As$, respectively, they have a small lattice mismatch (for x = 0.7 and y = 0.2, respective lattice constants are 5.734 Å, 5.659 Å). In device simulations, doping concentrations of p^+ AlGaAs/p^- InGaAs/n^+ InGaAs (source/channel/drain) are 5×10^{19} cm^{-3}, 1×10^{16} cm^{-3}, and 1×10^{19} cm^{-3}, in sequence; The channel length, radius, and gate oxide thickness of a designed

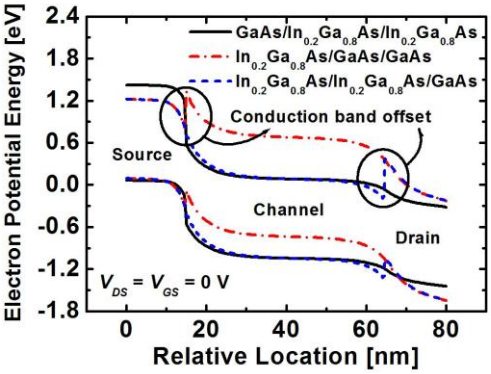


Fig. 1 Energy-band diagrams of TFETs having $GaAs/In_{0.2}Ga_{0.8}As$ heterojunctions.

device structure are 50 nm, 10 nm, and 3 nm, respectively; the workfunction of gate metal (Φ_m) was set to 4.75 eV.

Fig. 1 shows energy-band diagrams of TFETs having $GaAs/In_{0.2}Ga_{0.8}As$ heterojunctions of various arrangements. In case of $In_{0.2}Ga_{0.8}As/GaAs$ heterojunction TFET, the difference between EAs of $In_{0.2}Ga_{0.8}As$ and GaAs builds a discontinuous potential barrier seen either from source to channel (red dotted line) or from channel to drain (blue one) due to the conduction band offset which degrades I_{on}. On the other hand, when $GaAs/In_{0.2}Ga_{0.8}As$ heterojunction is deployed in the source-to-channel interface, a smooth conduction band is obtained due to smaller EA of GaAs.

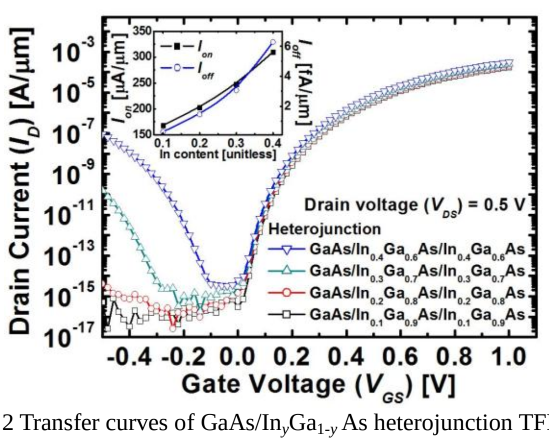
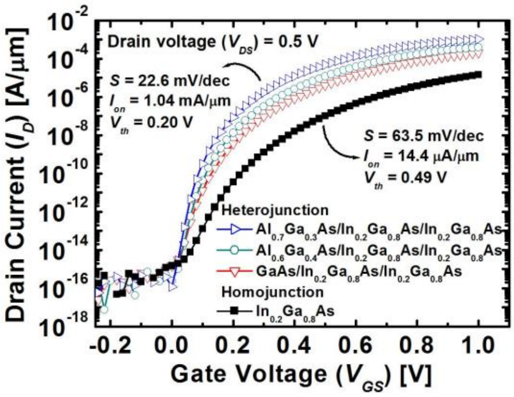


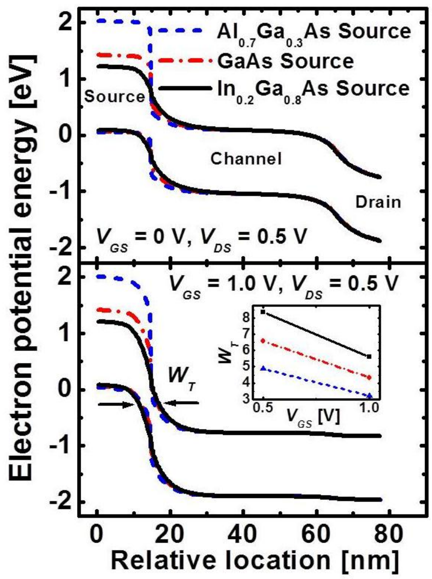
Fig. 2 Transfer curves of $GaAs/In_yGa_{1-y}As$ heterojunction TFETs.

Fig. 2 shows the drain current (I_D) vs. gate voltage (V_{GS}) transfer curves of $GaAs/In_yGa_{1-y}As$ heterojunction TFETs.

As In content in $In_yGa_{1-y}As$ increases, I_{on} prominently increases up to 300 μA/μm as depicted in the inset of Fig. 2, while I_{off} shows only a small amount of increase in a range of a few femto-amperes (fA). I_{on} and I_{off} are defined as the drain current at V_{GS} = 1 V and onset V_{GS}, both at V_{DS} = 0.5 V, respectively. As In content of $In_yGa_{1-y}As$ goes up to 0.3, a significant ambipolar behavior is observed due to the narrow bandgap initiating leakage current at the drain end. For this reason, a low enough In content of 0.2 is maintained in the InGaAs channel and drain for optimal design.



(a)



(b)

Fig. 3 DC characteristics. (a) I_D-V_{GS} transfer curves. (b) Energy-band diagram at different source material.

Fig. 3 demonstrates direct-current (DC) characteristics of $Al_xGa_{1-x}As/In_yGa_{1-y}As$ heterojunction TFETs with different source materials. $Al_{0.7}Ga_{0.3}As/In_{0.2}Ga_{0.8}As$ TFET shows improved I_{on} and S (average slope between two points of onset V_{GS} and V_{th} = [V_{GS} at $I_D = 10^{-7}$ A/μm]), and V_{th} = 0.2 V suitable to LSTP operation as confirmed in Fig. 3(a). The large difference between EAs of $Al_{0.7}Ga_{0.3}As$ (source) and $In_{0.2}Ga_{0.8}As$ (channel) thins W_T and eventually improves I_{on}, as proven in a more graphical manner by Fig. 3(b).

Fig. 4 depicts the intrinsic delay time (τ) as a function of V_{GS} at V_{DS} = 0.5 V ($\tau = C_{gg} \cdot V_{DD}/I_{on}$), where V_{DD} is the

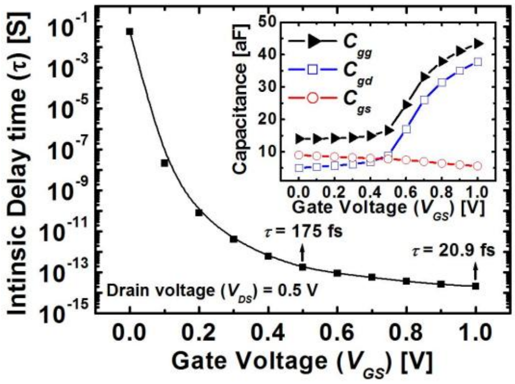


Fig. 4 Switching performance of $Al_{0.7}Ga_{0.3}As/In_{0.2}Ga_{0.8}As$ heterojunction TFETs as a function of V_{GS} (V_{DS} = 0.5 V).

supply voltage, which is V_{DS} in this work, gate capacitance (C_{gg}) is the sum of intrinsic gate-to-drain capacitance (C_{gd}) and gate-to-source capacitance (C_{gs}), and I_{on} is I_D at a given V_{DD}. $Al_{0.7}Ga_{0.3}As/In_{0.2}Ga_{0.8}As$ heterojunction TFET shows significantly short τ above V_{GS} = 0.5 V owing to the higher I_{on} as well as small C_{gg}. TFET has genuinely small C_{gg} since it is affected by mainly C_{gd} as shown in the inset of Fig. 4, unlike conventional MOSFETs where both C_{gd} and C_{gs} are comparably contributing factors [7].

3. Conclusions

A tunneling field-effect transistor based on AlGaAs/InGaAs heterojunction has been studied and evaluated for LSTP and HP applications. The large difference between electron affinities of materials is proven to have an practical effect of narrowing the effective tunneling barrier width. The $Al_{0.7}Ga_{0.3}As/In_{0.2}Ga_{0.8}As$ heterojunction TFET demonstrated superb performances including I_{on} of 1.04 mA/μm, S of 22.6 mV/dec, and τ of 20.9 fs by the help of band engineering.

Acknowledgements

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