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

Young Jun Yoon¹, Seongiae Cho², Jae Hwa Seo¹, Eou-Sik Cho³, Shin-Won Kang¹, Jin-Hyuk Bae¹, Jung-Hee Lee¹, Byung-Gook Park⁴, James S. Harris, Jr.², and In Man Kang¹

¹School of Electronics Engineering, Kyungpook National University, Buk-gu, Daegu 702-701, Republic of Korea
²Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA
³Department of Electronics Engineering, Gachon University, Seongnam, Kyunggi-do 461-701, Republic of Korea
⁴Inter-university Semiconductor Research Center (ISRC) and Department of Electrical Engineering and Computer Science, Seoul National University, Gwanak-gu, Seoul 151-742, Republic of Korea
Phone: +82-53-950-5513, Fax: +82-53-950-5505, E-mail: imkang@ee.knu.ac.kr

1. Introduction

Increasing significance of power consumption in the nanoelectronic circuits calls for low standby power (LSTP) and low supply voltage (VDD) 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 (Ioff). Low on-state current (Ion) 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 (Eg) can be designed to have higher Ion than conventional MOSFETs at a low VDD. Also, TFETs should have a sharp band bending between source and channel to minimize the effective tunneling barrier width (Wt), since thinner Wt greatly improves both Ion and S. Compound semiconductors with various electron affinity (EA) and Eg 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 (Eg = 1.42 eV) than that of Si (Eg = 1.12 eV), AlGaAs/InGaAs heterojunction can form steep interfacial band bending by a large difference between EAs. In this work, we propose and characterize a TFET with AlGaAs/InGaAs heterojunction achieving LSTP and high performance (HP) operations at as low VDD as 0.5 V. 3-dimensional (3D) device simulations were performed for an optimal device design in terms of Ion, Ioff, S, threshold voltage (Vth), 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 AlGaAs and InGaAs, 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 5x10¹⁹ cm⁻³, 1x10¹⁹ cm⁻³, and 1x10¹⁸ cm⁻³, in sequence. The channel length, radius, and gate oxide thickness of a designed 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/In₀.₂Ga₀.₈As heterojunctions. In case of In₀.₂Ga₀.₈As/GaAs heterojunction TFET, the difference between EAs of In₀.₂Ga₀.₈As 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 Ion. On the other hand, when GaAs/In₀.₂Ga₀.₈As heterojunction is deployed in the source-to-channel interface, a smooth conduction band is obtained due to smaller EA of GaAs.

![Energy-band diagrams of TFETs having GaAs/In₀.₂Ga₀.₈As heterojunctions.](image_url)

Fig. 1

Fig. 2 shows the drain current (I_D) vs. gate voltage (VGS) transfer curves of GaAs/In₀.₂Ga₀.₈As heterojunction TFETs.

![Transfer curves of GaAs/In₀.₂Ga₀.₈As heterojunction TFETs.](image_url)

Fig. 2
As In content in In$_x$Ga$_{1-x}$As increases, $I_{on}$ prominently increases up to 300 $\mu$A/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$_x$Ga$_{1-x}$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.

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$_{0.3}$Ga$_{0.7}$As/In$_{0.2}$Ga$_{0.8}$As heterojunction TFETs with different source materials. Al$_{0.3}$Ga$_{0.7}$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 $V_{th} = V_{GS} at I_D = 10^{-8} A/µm$), and $V_{th} = 0.2$ V suitable to LSTP operation as confirmed in Fig. 3(b). The large difference between EAs of Al$_{0.3}$Ga$_{0.7}$As (source) and In$_{0.2}$Ga$_{0.8}$As (channel) thins $W_f$ and eventually improves $I_{on}$ as proven in a more graphical manner by Fig. 3(b).

Fig. 4 depicts the intrinsic delay time ($\tau$) as a function of $V_{GS}$ at $V_{DS} = 0.5$ V ($\tau = C_{gg}V_{DS}/I_{on}$), where $V_{DS}$ is the supply voltage, which is $V_{GS}$ 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$_{0.3}$Ga$_{0.7}$As/In$_{0.2}$Ga$_{0.8}$As heterojunction TFET shows significantly short $\tau$ 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$_{0.3}$Ga$_{0.7}$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 $\tau$ of 20.9 fs by the help of band engineering.

Acknowledgements
This research was supported by the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (MEST) under Grants 2011-0025701, 2012-000619 and 2012-0005671, the Center for Integrated Smart Sensors funded by MEST as the Global Frontier Project (CISS-2012M3A6A6054186), and in part by Samsung Electronics Corporation.

References