Penn State III-V Tunnel FET Model Manual
Version 1.0.1

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1 Introduction

We presented look-up table based Verilog-A models for III-V interband Tunnel Field Effect Transistors (TFETs) based on the calibrated TCAD Sentaurus [1] device simulations. The Verilog-A models can be further implemented to Spectre [2] circuit simulators. The calibrated TFET TCAD models serve as an approximation of full-band atomistic calculation of TFET band diagram and band-to-band tunneling current to generate the DC characteristics [3]. The gate-source and gate-drain capacitance characteristics obtained from the TCAD small-signal simulation has recently been validated with the measured transient characteristics of TFET [4, 5], which are employed for circuit-level transient analysis.

To improve the tunneling current, low bandgap materials (e.g. SiGe, Ge, InGaAs, InAs) have been widely explored for TFET prototype device design. The demonstrated double-gate III-V heterojunction TFET exhibits MOSFET-like on-current [6, 7, 8]. The improved gate-electrostatic control can further reduce the sub-threshold slope [9, 10]. Two types of III-V TFETs are considered for model development based on double-gate, ultra-thin body structure: InAs homojunction TFET and GaSb-InAs near-brokengap heterojunction TFET. Our Veriog-A models can capture TFET DC and transient operation for a wide range of operating voltages, which are suitable for various small-scale circuit designs and performance benchmarking (e.g. power consumption, energy-delay). Details of device calibration, look-up table generation and Verilog-A model implementation for circuit analysis are described in this manual.

2 III-V Tunnel FET (TFET) Device Simulation and Model Calibration

2.1 Tunnel FET Device Design and Simulation

TFETs have asymmetrical source/drain doping which operates as reverse-biased, gated p-i-n tunnel diodes. In TFETs, the on-off switching is enabled by the gate-voltage induced band-to-band tunneling (BTBT) at the source-channel tunnel junction. In conventional MOSFETs, only the carriers with energy exceeding the source-channel thermal barrier contribute to the on-state current. These carriers follow the Fermi-Dirac distribution with an energy slope of kT (where k is the Boltzmann constant, T is the absolute temperature), which induces a thermal limited sub-threshold slope of 60 mV/decade (~2.3kT/q at 300K, where q is the unite charge). In TFETs, the high energy carriers are filtered by the gate-controlled tunneling window. As a result, a sub-60 mV/decade SS, in principle, can be achieved in TFETs at the room temperature (300K) [11].

High on-state current ($I_{on}$), high on-off ratio and steep SS are critical aspects in TFET design, which allow the further scaling of the supply voltage ($V_{DD}$) for power consumption reduction without jeopardizing the performance. Tremendous progress has been made in TFET prototype demonstration with significant improvement of the tunneling limited $I_{on}$ and reduction of SS. The design of TFET involves the tunneling barrier reduction (e.g.
low bandgap materials, hetero-band-alignment), gate electrostatics improvement (e.g. multi-gate or gate-all-around, ultra-thin body, effective oxide thickness (EOT) reduction), and low interface states to suppress the trap-assisted tunneling (TAT) [6-10]. III-V semiconductors are attractive for TFET fabrication due to their direct band-gaps and wide range of compositionally tunable band-alignment for tunnel barrier reduction. Previous work in [6, 7, 8] demonstrated III-V heterojunction TFET (HTFET) with MOSFET-like on-current through the reduction of effective tunneling barrier width while preserving the band-gap of the channel material to achieve a simultaneous enhancement of the on-off ratio. Benchmarking on beyond CMOS logic devices in [12] shows significant energy efficiency advantages in HTFET, where over $10^{15}$ Integer Ops/s/cm$^2$ with power consumption less that 1W/cm$^2$ can be achieved.

For TFET device simulation, the full-band atomistic simulation provides an accurate calculation of the band-to-band tunneling (BTBT) [13] for ideal device performance evaluation (e.g. defect free case). TCAD simulation serves as an approximation for the BTBT generation calculation based on the dynamic non-local tunneling model, which requires calibration with atomistic full-band simulation. Figure 1 shows an example to obtain material characteristics from nextnano simulation [14] as parameter input for TCAD Sentaurus to account for the quantization effect. This section will be focusing on the TCAD simulation for InAs homojunction TFET and GaSb-InAs heterojunction TFET, which are used to generate the look-up tables in Verilog-A models.

**Figure 1.** Example of the effective bandgap of GaSb due to quantization obtained from nextnano [14] simulation.
2.2 InAs Homojunction TFET Model Calibration

![Double-gate InAs Homojunction Tunnel FET schematic](image1)

Figure 2. InAs Homojunction Tunnel FET schematic.

![InAs homojunction Tunnel FET DC characteristics calibration](image2)

Figure 3. InAs homojunction Tunnel FET DC characteristics calibration.

The double-gate InAs homojunction TFET schematic is shown in Figure 2 corresponding to the simulation structure in [22], which has a gate length ($L_G$) of 20 nm, ultra-thin body ($T_{Ch}$) of 5 nm, high-k dielectric thickness (HfO$_2$) of 5 nm at EOT of 1 nm with the source/drain doping of $4 \times 10^{19}$ cm$^{-3}$ (p+) and $6 \times 10^{17}$ cm$^{-3}$ (n+), respectively. The quantization induced bandgap broaden was obtained through nextnano simulation as described above in Figure 3. The calibrated DC characteristics show good agreement with the atomistic full-band simulation results [3].
2.3 GaSb-InAs Heterojunction TFET Model Calibration.

Figure 4 shows the GaSb-InAs heterojunction FET schematic, which is calibrated with simulated structure in [3] with a gate length ($L_G$) of 40 nm, ultra-thin body ($T_{Ch}$) of 5 nm, high-k dielectric thickness (HfO$_2$) of 5 nm at EOT of 1 nm with the source/drain doping of $4 \times 10^{19}$ cm$^{-3}$ (p+) and $2 \times 10^{17}$ cm$^{-3}$ (n+) respectively. The quantized bandgap are shown in Figure 5 which agrees well with the OMEN simulation in [13]. The effective barrier height ($E_{beff}$) is 0.065 eV.

Figure 5 shows the calibration of DC characteristics obtained from TCAD simulation with OMEN simulation results. The current at 0.5 V $V_{ds}$ shows good match at sub-threshold region and super-threshold region. Note that leakage current from TCAD simulation was 1 order lower. The Verilog-A model of GaSb-InAs HTFET uses 20 nm gate-length derived from this calibrated model.
Capacitance characteristics are critical for accurate device modeling. Due to the semi-classical simulation nature of TCAD, TFET gate-source $C_{gs}$ and gate-drain capacitance $C_{gd}$ characteristics obtained from the small signal simulation requires validation from transient measurements. [15] first reported the unique capacitance characteristics of TFET, which is known as enhanced on-state Miller capacitance effect, showing a dominant $C_{gd}$ among the total capacitance $C_{gg}$ at the device on-state ($V_{gs}=V_{DD}$). Such characteristics rises from the un-equal charge sharing between source and drain due to the tunnel-barrier, which results in a large “voltage spike” during transient analysis in TFET based inverter as compared to MOSFET case. Furthermore, Zhang et al [16] reported a Si TFET compact model based on the surface potential calculation, which shows the same observation (enhanced Miller capacitance effect) during transient analysis. Knoll et, al in [4] first reported the transient measurements of a Si nanowire TFET inverter, which further validates the effect of enhanced $C_{gd}$ contribution to overall $C_{gg}$. Recently, Bijesh et al in [7] reported the first measured RF characteristics of fabricated near-broken gap III-V HTFET, showing a good match of the capacitance characteristics from TCAD with the extracted capacitance values, transconductance ($g_m$) and cut-off frequency ($f_T$) from S parameter measurements. More works [17, 18] have recently explored this unique capacitance characteristic of TFET. Based on the experiment validation, we obtain the capacitance characteristics of $C_{gs}$ and $C_{gd}$ using calibrated TCAD model to construct the TFET Verilog-A model. The capacitance characteristics of InAs TFET and GaSb-InAs HTFET are shown in Figure 7 and Figure 8.
Due to the lack of experimental data, the simulation model validation of the 20 nm GaSb-InAs heterojunction Tunnel FET remains challenging. Here, we present the validation of our simulation models at a channel length of 200 nm with the fabricated near-broken gap heterojunction TFET from [7]. Figure 9 shows the In$_{0.9}$Ga$_{0.1}$As/GaAs$_{0.18}$Sb$_{0.82}$ material system and the vertical Tunnel FET schematic [7]. The device TEM cross-section is shown in Figure 10(a). Benefited from the near broken gap induced high band-to-band tunneling current density, a high drive current of 740 µA/µm is achieved at $V_{DS} = 0.5$ V (Figure 10(b-c)). The numerical simulation model has shown a good agreement with the measured $I_{DS}$-$V_{GS}$ characteristics at $T = 300$ K, $V_{DS} = 0.5$ V using interface states density ($D_i$) of $5 \times 10^{12}$ cm$^{-2}$ eV$^{-1}$ as shown in Figure 11(a-b).
Figure 9. The near-broken gap \text{In}_{0.9}\text{Ga}_{0.1}\text{As}/\text{GaAs}_{0.18}\text{Sb}_{0.82} heterojunction n-type Tunnel FET (a) material system and device schematic [7].

Figure 10. (a) Cross-section TEM image of the fabricated HTFET showing angled sidewall and gate-drain overlap. (b) Temperature dependent transfer characteristics of HTFET showing improved \text{I}_{\text{ON}}/\text{I}_{\text{OFF}} at low temperature (c) Output characteristics of HTFET at T=300K and T=77K [7].

To validate the capacitance characteristics of the TCAD models, the RF measurement has been carried out with a coplanar ground-signal-ground (GSG) waveguide structure. Figure 12(a-c) shows the measured and modeled scattering parameters (S-parameters) to extract the cut-off frequency (\text{F}_T) and capacitance values. The 200 nm HTFET exhibits a measured \text{F}_T of 10 GHz and 19 GHz at \text{V}_{\text{DS}}=0.3V and 0.5V respectively. TCAD simulation of the HTFET device structure matched to the TEM image has been used taking into account parasitic capacitances and resistances. The capacitance characteristics and \text{F}_T of the TCAD models are obtained from the small signal simulation. The simulated \text{C}_{\text{gs,extrinsic}}, \text{C}_{\text{gd,extrinsic}} values, as well as the \text{F}_T are in agreement with the measured values from RF measurements, as shown in Figure 13 [7]. The measured \text{I}_{\text{DS}}-\text{V}_{\text{GS}} characteristics and simulation results are available in the experiment data folder.
Figure 11. (a) TCAD simulation and measured characteristics at $T=300K$. (b) Simulated electron trap response time in In$_{0.9}$Ga$_{0.1}$As is used to estimate gate voltage pulse width required to suppress $D_{it}$.

Figure 12. (a-b) Modeled and measured s-parameters at $V_{DS} = 0.3$ V and 0.5 V respectively (c) Measured and modeled $H_{in}$ parameter at $V_{GS} = 0.5$ V and 0.3 V. After de-embedding, $F_T$ of 10GHz and 19 GHz are measured at $V_{DS}=0.3$ V and 0.5 V respectively [7].

Figure 13. (a) 2D schematic of the simulated HTFET with dimensions calculated from the TEM with parasitic capacitances and resistance illustration. Extraction of (b) gate-drain overlap capacitance $C_{gd,ov}$ (c) lateral gate-source overlap capacitance $C_{gs1,ov}$, (d) Measured $F_T$ is in agreement with the simulations. After de-embedding the overlap capacitances, HTFET with $L_{ch}=200nm$ is expected to achieve $F_T$ of 22GHz and 39GHz at $V_{DS}=0.3V$ and 0.5V respectively.
3 TFET Verilog-A Models

3.1 Look-up Table based Verilog-A Model

Lookup table-based Verilog-A model has been employed for TFET-based circuit designs in many literatures [3, 19, 20, 21]. Here we show the schematic of the Verilog-A transistor model in Figure 9 from [3]. It is a lookup table-based model composed of two-dimensional tables: the transfer characteristics $I_{ds}(V_{ds}, V_{gs})$, the gate-source capacitance $C_{gs}(V_{gs}, V_{ds})$ and the gate-drain capacitance $C_{gd}(V_{gs}, V_{ds})$ across a range of fine-step drain-source voltage bias $V_{ds}$ and gate-source voltage bias $V_{gs}$. The TCAD models used for lookup table generation are the same as those shown in the previous Section 2, except that the gate lengths are all set to $L_G = 20$ nm. The parasitic series resistance and parasitic external capacitance are not included in the TCAD model, which can be added at the circuit level as shown in the schematic above.

![Figure 9. Verilog-A model schematic.](image)

![Figure 10. Device characteristics comparison.](image)
Due to the ongoing efforts of p-type Tunnel FET development, we assume identical drive-currents for the n-channel and p-channel transistors in TFET Verilog-A models for the optimal circuit performance. We should notice that the Density-of-States (DoS) of electrons and holes can be quite different in III-V materials, such that the gate-capacitance characteristics need to be obtained from TCAD simulation for n-type and p-type TFET, respectively, to accurate modeling the circuit performance. We develop a symmetrical device structure as n-type TFET to obtain the capacitance characteristics for pseudo p-type TFET. The p-type and n-type device characteristics of GaSb-InAs TFET are shown in Figure 10.

### 3.2 Model Description (Ver. 1.0.1)

The Verilog-A model is coded in “.va” file, which contains the following files:

| Wrapper File | homotfet.va (for InAs Homojunction TFET); heterotfet.va (for GaSb-InAs Heterojunction TFET) |
| Master Model File | tfet_master.va |
| Look-up Tables | InAs Homojunction TFET |
| | IdVg-InAs-NTFET-Lg-20nm.tlb, CGS-InAs-NTFET-Lg-20nm.tlb, CGS-InAs-PTFET-Lg-20nm.tlb, CGD-InAs-NTFET-Lg-20nm.tlb, CGD-InAs-PTFET-Lg-20nm.tlb; |
| | GaSb-InAs Heterojunction TFET |
| | IdVg-GaSb-InAs-HNTFET-Lg-20nm.tlb, CGS-GaSb-InAs-HNTFET-Lg-20nm.tlb, CGS-GaSb-InAs-HPTFET-Lg-20nm.tlb, CGD-GaSb-InAs-HNTFET-Lg-20nm.tlb, CGD-GaSb-InAs-HPTFET-Lg-20nm.tlb; |

The key features of this model bundle are:

1. “tfet_master.va” combined all the model features for n-type and p-type homojunction and heterojunction TFETs. `ifdef has been used to enable HOMOJUNCTION and HETEROJUNCTION features.

2. “homotfet.va” and “heterotfet.va” recall “tfet_master.va” to enable different types of TFETs (e.g. “homotfet.va” enables “_HOMOJUNCTION_” for InAs Homojunction TFET in “tfet_master.va”, while “heterotfet.va” enables “_HETEROJUNCTION_” for GaSb-InAs Heterojunction TFET in “tfet_master.va”).

3. In “tfet_master.va”, a parameter, "type", has used to define n-type and p-type transistors, which needs to be specify in the circuit netlist.

The master model file “tfet_master.va” is as follows:
'include "constants.vams"
'include "disciplines.vams" // Header files, using Verilog-A language to describe a module function

module TFET(d,g,s);
inout d,g,s;
electrical g,d,s; // Device module name and terminal definition

real Ids, Cgs, Cgd, Qg, Qs, Qd; // Variables used in modeling.
parameter real W=1 from (0:inf); // Device width “W”, in micrometer unit.
parameter string type = "n" from ['"n", "p"]; // Parameter “type” to specify n-type or p-type TFET.
integer direction; // Variable to specify the current direction in n-type or p-type TFET.

//Verilog-A model main body
analog begin

`ifdef _HETEROJUNCTION_ // GaSb-InAs Heterojunction TFET
//n-type TFET, reading current Ids, capacitance Cgs and Cgd values from look-up tables (tables are generated from Sentaurus TCAD simulation), current direction is 1. Variable values assigned from the lookup tables in “.tbl” are according to terminal voltage condition. In each table, the 1st column is Vds, 2nd column is Vgs, 3rd column is the current or capacitance value.
if (type == "n") begin
Ids=$table_model(V(d,s), (V(g,s)), "IdVg-GaSb-InAs-HNTFET-Lg-20nm.tbl","1LL,1LL");
Cgd=$table_model(V(d,s), (V(g,s)), "CGD-GaSb-InAs-HNTFET-Lg-20nm.tbl","1LL,1LL");
Cgs=$table_model(V(d,s), (V(g,s)), "CGS-GaSb-InAs-HNTFET-Lg-20nm.tbl","1LL,1LL");
direction =1;
end

//p-type TFET, reading current Ids, capacitance Cgs and Cgd values from look-up tables (tables are generated from Sentaurus TCAD simulation), current direction is -1.
else if (type == "p") begin

// We assume that the PTFET and NTFET drive currents are similar
Ids=$table_model(-V(d,s), (-V(g,s)), "IdVg-GaSb-InAs-HNTFET-Lg-20nm.tbl","1LL,1LL");

endif

`else

   // Code for heterojunction TFET
endif

`endif // HETEROJUNCTION_
// We do not assume that the PTFET and NTFET gate capacitances are similar because the hole and electron DoS in InAs are significantly different
Cgd=$table_model(V(d,s), (V(g,s)), "CGD-GaSb-InAs-HPTFET-Lg-20nm.tbl","1LL,1LL");
Cgs=$table_model(V(d,s), (V(g,s)), "CGS-GaSb-InAs-HPTFET-Lg-20nm.tbl","1LL,1LL");
direction = -1;
end

`else `ifdef _HOMOJUNCTION_// InAs Homojunction TFET
//Similarly, reading variable values from look-up tables, specify the current direction according to the “type”.
if (type == "n") begin
Ids=$table_model(V(d,s), (V(g,s)), "IdVg-InAs-NTFET-Lg-20nm.tbl","1LL,1LL");
Cgd=$table_model(V(d,s), (V(g,s)), "CGD-InAs-NTFET-Lg-20nm.tbl","1LL,1LL");
Cgs=$table_model(V(d,s), (V(g,s)), "CGS-InAs-NTFET-Lg-20nm.tbl","1LL,1LL");
direction =1;
end
else if (type == "p") begin
Ids=$table_model(-V(d,s), (-V(g,s)), "IdVg-InAs-NTFET-Lg-20nm.tbl","1LL,1LL");
Cgd=$table_model(V(d,s), (V(g,s)), "CGD-InAs-PTFET-Lg-20nm.tbl","1LL,1LL");
Cgs=$table_model(V(d,s), (V(g,s)), "CGS-InAs-PTFET-Lg-20nm.tbl","1LL,1LL");
direction = -1;
end
`endif

//Calculate the charge Qgd, Qgs and Qg according to the capacitances, device width and the terminal voltages. Calculate the terminal current with respect to the charge.
Qd = (W*1*Cgd)*(V(g,d));
Qs = (W*1*Cgs)*(V(g,s));
Qg=1*(Qd+Qs);
I(d,s) <+ direction*Ids*W ;
I(g) <+ ddt(Qg);
I(s) <+ ddt(Qs);
I(d) <+ ddt(Qd);
end
endmodule
3.3 Terminal and Voltage Definition for Intrinsic Device

As shown in Figure 1, the intrinsic Tunnel FET (as shown in the dashed box in Figure 9) has 3 terminals: source (s), gate (g) and drain (d). No body terminal in this model due to the double-gate, ultra-thin-body device structure. The terminal voltage $V(g,s)$ and $V(d,s)$ identify the device operation and determine $I_{ds}$, $C_{gs}$ and $C_{gd}$ at such $V_{gs}$ and $V_{ds}$ bias through the look-up tables:

![Terminal Definition](image)

**Figure 11.** Terminal definition N-type TFET and p-type TFET and direction.

3.4 DC Characteristics

The device DC current is directly obtained from the table value and device width ($W$) definition, and current direction ($direction$):

```plaintext
parameter real W=1;
integer direction;
direction=1;
I(d,s) <+ direction*Ids*W;
```

3.5 Transient Characteristics

The device transient characteristics are obtained through charge models. Terminal charge of $Q_{gd}$ (drain charge) and $Q_{gs}$ (source charge) are calculated using $C_{gd}$ and $C_{gs}$ obtained from lookup tables and terminal voltages $V_{gd}$ and $V_{gs}$, respectively. Since the
DC component of $I_{gd}$ and $I_{gs}$ are negligible, the transient current $I_{gd}$ and $I_{gs}$ are calculated according to the time evolution of the terminal charges:

\[
\begin{align*}
Q_d &= (-1*W*C_{gd})*(V_{g(d)}); \\
Q_s &= (-1*W*C_{gs})*(V_{g(s)}); \\
Q_g &= -(Q_d+Q_s); \\
I(d,s) &= \text{direction} * I_{ds} * W; \\
I(d) &= \text{ddt}(Q_d); \\
I(s) &= \text{ddt}(Q_s); \\
I(g) &= \text{ddt}(Q_g); \\
\end{align*}
\]

### 3.6 Pseudo P-TFET

The pseudo P-TFET model uses the $I_{ds}$ table of NTFET with P-TFET Capacitance characteristics:

\[
\begin{align*}
&\text{if (type == "p") begin} \\
&\quad I_{ds} = \text{table_model}(V_{d(s)}, -(V_{g(s)}), "IdVg-NTFET-Lg-20nm.tbl", "1LL,1LL"); \\
&\quad C_{gd} = \text{table_model}(V_{d(s)}, V_{g(s)}, "CGD-PTFET-Lg-20nm.tbl", "1LL,1LL"); \\
&\quad C_{gs} = \text{table_model}(V_{d(s)}, V_{g(s)}, "CGS-PTFET-Lg-20nm.tbl", "1LL,1LL"); \\
&\quad \text{direction} = -1; \\
&\quad \text{end} \\
\end{align*}
\]

### 4 Example Circuits and Spectre Simulation Results

The TFET Verilog-A device model can be implemented in Spectre simulation. In order to execute the circuit simulations you need to have Virtuoso Spectre Circuit Simulator [2] installed. We present the following examples of using TFET Verilog-A model to obtain device $I_{d-Vg}$ characteristics, TFET based FO1 Inverter and Ring Oscillator simulation. The simulation projects are available with the model download as “.scs” files.

#### 4.1 $I_{d-Vg}$ simulation: DC Analysis Example

The $I_{d-Vg}$ simulation for NTFET is in ntfet_idvg.scs. Run by:

```
> spectre ntfet_idvg.scs
```

Note that, for InAs Homojunction TFET, use `ahdl_include “homotfet.va”`; for GaSb-Heterojunction TFET, use `ahdl_include “heterotfet.va”`.

```// Simulation language is Spectre.
simulator lang=spectre
global o```
Terminal voltages of VG and VD are defined as parameters. Device width is defined Width=1 um. Series resistance $R_{\text{Series}}$ of 55 Ohm-um is used as parameter.

- parameters VG=0.0
- parameters VD=0.3
- parameters Width=1
- parameters $R_{\text{Series}}$=55

3 dc voltage sources V1, V2 and V3 are defined and connected to source, gate, and drain node.

- V1 (source 0) vsource type=dc dc=0
- V2 (gate 0) vsource type=dc dc=VG
- V3 (drain 0) vsource type=dc dc=VD

R1 and R2 are the parasitic resistances. I1 is the instance of an intrinsic NTFET with a width W=Width, where nodes d1, gate and s1 are connected to the device d, g, s terminals respectively. Parasitic resistance R1 and R2 are connected to NTFET’s s and d, respectively.

- R1 (source s1) resistor r=$R_{\text{Series}}$/Width
- Specify type=n for NTFET

- I1 (d1 gate s1) TFET type=n W=Width
- R2 (drain d1) resistor r=$R_{\text{Series}}$/Width

dc dc param=VG start=0 stop=0.3 lin=100 oppoint=rawfile maxiters=150 maxsteps=10000 annotate=status

// Divide by two in order to report the current per micrometer. Since the simulator gives the double gate current

- print gate*1000, -(V3)*1e6/2, name=dc addto="idvg_heterotfet.out"
- print gate*1000, -(V3)*1e6/2, name=dc addto="idvg_homotfet.out" //Print to file

ahdl_include "heterotfet.va" //Using ahdl to compile Verilog-A model
ahdl_include "homotfet.va" //Using ahdl to compile Verilog-A model

The simulation results of InAs Homojunction TFET are plotted in Figure 12.
4.2 TFET based Inverter: Transient Analysis Example

The 5-stage FO1 inverter chain simulation using InAs TFET is in inverter_InAs_tfet_FO1.scs. Run by:
spectre inverter_tfet_FO1.scs

Note that, for InAs Homojunction TFET, use ahdl_include “homotfet.va”; for GaSb-Heterojunction TFET, use ahdl_include “heterotfet.va”.

**************************************************************************************

// Series resistance of 55 ohm-um and output parasitic capacitance 0.1 fF/um are included. Minimum device width W_min=20 nm is used for simulation at V_DD=0.3V.
parameters VSUPPLY=0.3 INPUT=0
parameters RSeries=55
parameters CParasitic=100e-18
parameters WMin=0.02

V1 (supply1 0) vsource type=dc dc=VSUPPLY
V2 (gnd 0) vsource type=dc dc=0
V3 (in1 0) vsource type=pwl wave=[0 0 1 0.05 0.3 0 0 0 3.5 0 5 0]

// 5-stage FO1 inverter chain
X1 (out1 in1 supply1 gnd) inv
X2 (out2 out1 supply1 gnd) inv
X3 (out3 out2 supply1 gnd) inv
X4 (out4 out3 supply1 gnd) inv
X5 (out5 out4 supply1 gnd) inv

// Sub-circuit definition for TFET inverter which has 4 terminals: out, in, supply, gnd. Series resistance is added to PTFET and NTFET. Parasitic capacitance is added to the inverter output.
subckt inv out in supply gnd

Figure 12. Id-Vg of InAs N-TFET with source/drain series resistance of 55 ohm at V_DS=0.3V.
// R1 R2 R3 and R4 are the parasitic resistances
R1 (o1 out) resistor r=RSeries/WMin
I1 (o1 in s1) TFET type=p W=1*WMin
R2 (s1 supply) resistor r=RSeries/WMin
R3 (o2 out) resistor r=RSeries/WMin
I2 (o2 in gnd2) TFET type=n W=1*WMin
R4 (gnd2 gnd) resistor r=RSeries/WMin

// C1 is the parasitic output capacitance
C1 (out o) capacitor c=CParasitic*WMin
ends

// Initial condition is given to inverter chain internal nodes.
ic out1=VSUPPLY out2=0 out3=VSUPPLY

tran tran stop=5n write="spectre.ic" writefinal="spectre.fc" annotate=status\maxiters=5 autostop=yes
print in1*1000,out1*1000,out2*1000,out3*1000,out4*1000, name=tran\addto="inv_tran.out"

//ahdl_include "heterotfet.va" //switch to heterotfet
ahdl_include "homotfet.va" //switch to homotfet
*******************************************************************************

The simulation results are plotted in Figure 13.

![InAs TFET FO1 Inverter Chain Test](image)

**Figure 13.** Input and Output Waveforms of InAs TFET inverter with minimum sizing at $V_{DS}=0.3V.$
The measurement simulation to obtain fall-delay, fall-energy, rise-delay and rise-energy for signal-stage inverter can be obtained by running:

```bash
> spectremdl -b inverter_tft Fet FO1.mdl -d inverter_tft Fet FO1.scs -measure inverter_tft Fet FO1.measure
```

The output results (energy vs $V_{DD}$, delay vs $V_{DD}$) of InAs Homojunction TFET are shown in Figure 14.

![Figure 14. InAs TFET FO1 Inverter Switching Energy and delay vs. supply voltage $V_{DD}$](image)

### 4.3 HTFET based Ring Oscillator: Transient Analysis Example

Similarly, the 15-stage FO1 inverter chain simulation using GaSb-InAs HTFET is in `ring_oscillator.scs`. Run by:

```bash
> spectre ring_oscillator.scs
```

The simulation results are plotted in Figure 15.

![Figure 15. Input and output waveforms of GaSb-InAs HTFET NAND based ring oscillator at $V_{DS}=0.3V$.](image)
The simulation results are plotted in Figure 16:

![Figure 16. Energy vs delay of the GaSb-InAs HTFET NAND based ring oscillator at different supply voltage $V_{DD}$.](image)

The simulation results are plotted in Figure 16:

![Figure 16. Energy vs delay of the GaSb-InAs HTFET NAND based ring oscillator at different supply voltage $V_{DD}$.](image)

5 References

[7] R. Bijesh et al, “Demonstration of In$_{0.5}$Ga$_{0.5}$As/GaAs$_{0.18}$Sb$_{0.82}$ near broken-gap tunnel FET with $I_{ON}$=740µA/$µm$, $Gm$=700µS/$µm$ and Gigahertz Switching Performance at $V_{DS}$=0.5V”, IEDM Tech. Digest., pp. 28.2.1–28.2.4, Dec. 2013.


