A UCSD analytic TFET model

Jianzhi Wu and Yuan Taur

Department of Electrical and Computer Engineering

University of California, San Diego, CA, USA, 92093

(Contact: jzwu@alumni.upenn.edu)

Last Update: Dec. 15, 2015

Model descriptions:

A continuous, analytic *I-V* model is developed for double-gate and nanowire tunnel FETs with 3D density of states, including depletion in the source. At the core of the model is a gate-controlled channel potential that satisfies the source and drain boundary conditions. Verified by numerical simulations, the model is able to generate I_{ds}-V_{gs} characteristics for any given staggered bandgap and channel length. I_{ds}-V_{ds} characteristics are also generated by building into the model the de-biasing effect of channel charge in the linear region. It is predictive in the sense that there are no ad hoc fitting parameters.

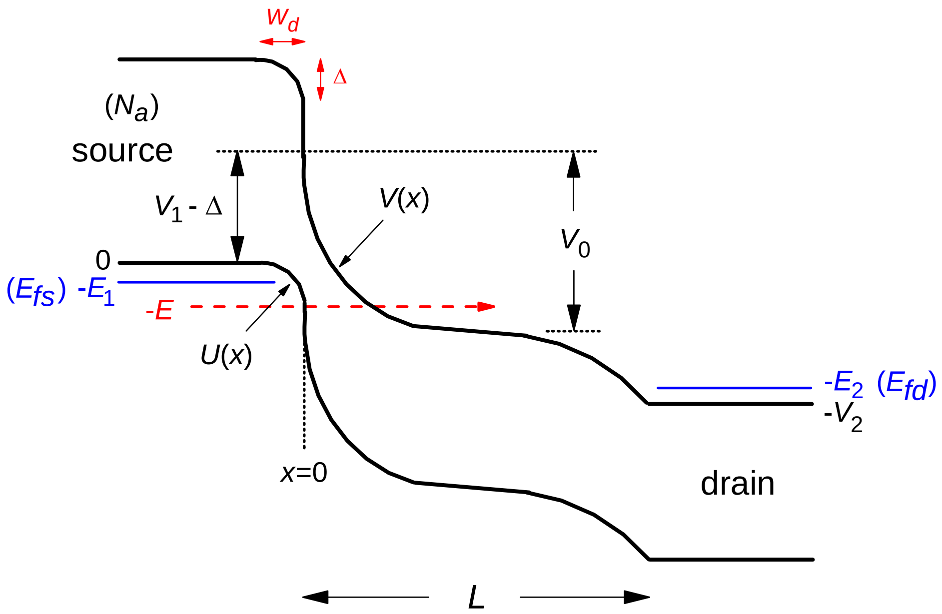

Fig. 1. Band diagram of a heterojunction TFET with p$^+$ source and n$^+$ drain.

Name	Parameter Description	Unit	Default
Material dependent parameters			
V_1	Staggered bandgap of the source to channel heterojunction	eV	0.23
m_c	Effective mass associated with conduction band	m_0	0.1
m_v	Effective mass associated with valence band	m_0	0.1
ε_s	Permittivity (assuming same in semiconductor and insulator)	ε_0	14.6

Device related parameters			
L	Channel length	nm	20
N_a	Density of source doping	cm^{-3}	3×10^{19}
N_d	Density of drain doping	cm^{-3}	3×10^{19}
N_v	Effective density of states in the valence band	cm^{-3}	1×10^{19}
N_c	Effective density of states in the conduction band	cm^{-3}	1×10^{18}
t_s	Semiconductor body thickness	nm	5
t_i	Insulator thickness	nm	2
λ	Scale length	nm	9
Bias dependent parameter			
V_{gs}	Gate bias	V	0.5
V_{ds}	Drain bias	V	0.5
Δ	Band bending	eV	calculated
W_d	Depletion width	nm	calculated
V_0	Controlled by the gate voltage	eV	calculated
d_1	Source degeneracy $F_{1/2}(d_1/kT) = (\pi^{1/2}/2)(N_a/N_v)$	eV	calculated
d_2	Drain degeneracy $F_{1/2}(d_2/kT) = (\pi^{1/2}/2)(N_d/N_c)$	eV	calculated
V_2	Drain conduction band	eV	calculated

$$V(x) = V_0 \frac{\sinh\left[\pi (L-x)/\lambda\right]}{\sinh(\pi L/\lambda)} - V_0 + V_1 - \Delta - (V_2 - V_0 + V_1 - \Delta)\frac{\sinh(\pi x/\lambda)}{\sinh(\pi L/\lambda)} \tag{1}$$

$$U(x) = -\frac{q^2 N_a}{2\varepsilon_s}\left(x + \sqrt{\frac{2\varepsilon_s \Delta}{q^2 N_a}}\right)^2 \tag{2}$$

$$Q_{inv} = \frac{4kT\varepsilon_s}{qt_s}\beta\tan\beta \tag{3}$$

$$\frac{q(V_{gs}-V_{ds}-d_1)}{2kT} - \ln\left[\frac{2}{t_s}\sqrt{\frac{2\varepsilon_s kT}{q^2 N_c}}\right] = \ln\beta - \ln[\cos\beta] + \frac{2\varepsilon_s t_i}{\varepsilon_i t_s}\beta\tan\beta \tag{4}$$

For given V_{gs} and V_{ds}, calculate Q_{inv} from Eqs. (3) and (4), then solve V_0 and Δ from Eqs. (5) and (6).

$$V_0 = (V_{gs} - Q_{inv}/C_{ox}) + (V_1 - \Delta), \quad V_2 = d_1 + d_2 + qV_{ds} \tag{5}$$

$$\frac{1}{q}\left|\frac{dV}{dx}\right|_{x=0} = \left(\frac{\pi}{q\lambda}\right)\frac{V_0\cosh(\pi L/\lambda) + (V_2 - V_0 + V_1 - \Delta)}{\sinh(\pi L/\lambda)} = \sqrt{\frac{2N_a\Delta}{\varepsilon_s}} \tag{6}$$

$$T(E, E_{\perp v}) = \exp\left\{-\frac{2\sqrt{2}}{\hbar}\left[m_v\int_{l_1}^{0}\sqrt{-U(x)-(E-E_{\perp v})}\,dx + m_c\int_0^{l_2}\sqrt{V(x)+E+E_{\perp c}}\,dx\right]\right\} \tag{7}$$

$$j = \frac{qm_v}{2\pi^2\hbar^3}\int_0^{V_2}(f_s - f_d)\left[\int_0^{E_{\perp m}} T(E, E_{\perp v})\,dE_{\perp v}\right]dE \tag{8}$$

Where $E_{\perp m}$ is the is the smaller of E and $(m_c/m_v)(V_2 - E)$

Model generated examples:

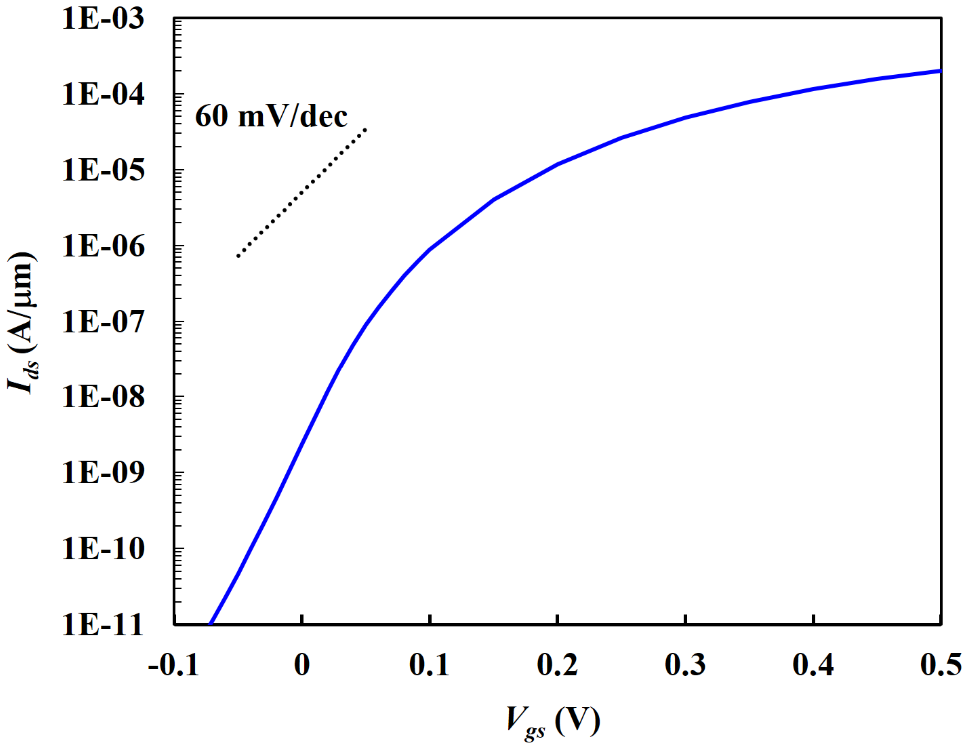

Fig. 2. Model generated I_{ds}-V_{gs} characteristics with default parameters (time: 33 seconds)

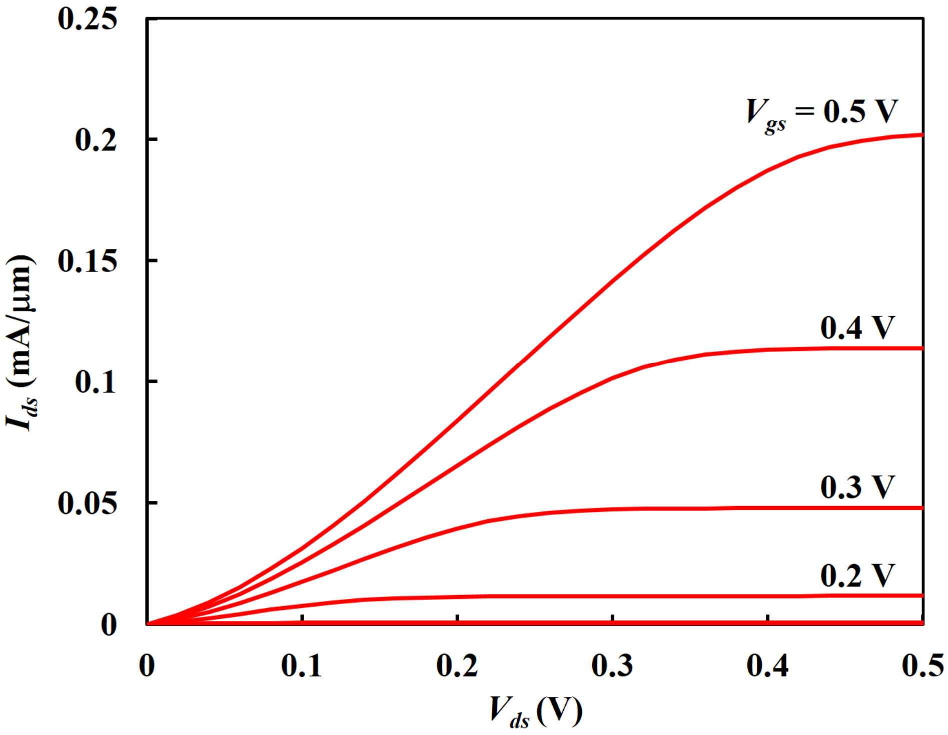

Fig. 3. Model generated I_{ds}-V_{ds} characteristics with default parameters (time: 170 seconds)

References:

[1] Yuan Taur, Jianzhi Wu and Jie Min, “An analytic model for heterojunction tunnel FETs with exponential barrier” *IEEE Transactions on Electron Devices*, vol. 62, no. 5, pp. 1399-1404, May 2015.

[2] Jianzhi Wu, Jie Min, and Yuan Taur, “Short channel effects in tunnel FETs”, *IEEE Transactions on Electron Devices*, vol. 62, no. 9, pp. 3019-3024, Sept. 2015.

[3] Jianzhi Wu, Jie Min, Jingwei Ji and Yuan Taur, “An analytic model for heterojunction and homojunction tunnel FETs with 3D density of states”, in *Proc. of 73rd Device Research Conference* (*DRC*) (pp. 249-250), Ohio, USA, June, 2015.

[4] Jie Min, Jianzhi Wu and Yuan Taur, “Analysis of source doping effect in tunnel FETs with staggered bandgap”, *IEEE Electron Device Letters*, vol. 36, no. 10, pp. 1094-1096, Oct. 2015.