A Surface-Potential-Based n-MOSFET Gate Tunneling Current Model

Xin Gu, Gennady Gildenblat, Gennady Gildenblat, Xin Gu
Department of Electrical Engineering
The Pennsylvania State University

Glen Workman, Surya Veeraraghavan
DigitalDNA Laboratories, Motorola

Shye Shapira and Kevin Stiles
Agere Systems
Outline

- Introduction
- Tunneling current density
- Gate tunneling current
- Drain bias dependence and partition
- Model Verification
- Conclusions
Aggressive scaling of $t_{ox}$ (below 30Å) ⇒ substantial $I_g$ in MOSFETs

First principle approach is not suited for compact models

Most of the existing compact models don’t include the physics-based carrier statistics ⇒ unphysical results i.e. $I_g \neq 0$ when $V_{gs} = V_{bs} = V_{ds} = 0$

$I_g$ in the overlap regions is significant, requiring the physics-based modeling

In n-MOSFET, only the tunneling of the electrons in the conduction band needs to be considered
**Introduction – SP Gate Current Model**

- \( I_g = I_{gc} + I_{gsov} + I_{gdov} \); the overlap components are modeled using physics-based approach
- \( I_{gc} = I_{gcs} + I_{gcd} \); partition is achieved using a physics-based approach
- The physically correct carrier statistics included in the Esaki-Tsu formula is implemented efficiently
- The same form of model and identical parameters are used in all the three components
- No scaling parameters are required to fit the data
Tunneling Current Density

- Esaki-Tsu formula
  \[ J_g = J_0 \int D(E) F_s(E) dE \]
- \( D(E) \) and \( F_s(E) \) are the transmission coefficient and the supply function at the given kinetic energy \( E \), respectively.

\[ F_s = \ln \left( \frac{1 + \Delta_{\text{Si}}}{1 + \Delta_{\text{Poly}}} \right) \]
\[ \Delta_{\text{Si}} = \exp \left[ \frac{(E_f^{\text{Si}} - E)}{k_B T} \right] \]
\[ \Delta_{\text{Poly}} = \exp \left[ \frac{(E_f^{\text{Poly}} - E)}{k_B T} \right] \]

- At equilibrium
  \[ E_f^{\text{Si}} = E_f^{\text{Poly}} \Rightarrow F_s = 0 \Rightarrow J_g = 0 \]
Tunneling Current Density (II)

- Numerical integration in the Esaki-Tsu formula prohibits it to be included in compact models.
- Assuming that all the tunneling takes place at a constant energy, $E_T$, yields an analytical expression:

$$J_g = J_0 D(E_T) F_s(E_T)$$

- The assumption reflects the fact that the most of electrons only occupy the states close to the band edge.
In WKB approximation,

\[
D(E_T) = \exp \left[ B \left( 1 - \frac{|V_{ox}|/\chi_B}{|\chi_B|} \right)^{3/2} - 1 \right]
\]

\[
\approx \exp \left\{ -B \left[ G_1 + G_2 \frac{|V_{ox}|}{\chi_B} + G_3 \left( \frac{|V_{ox}|}{\chi_B} \right)^2 \right] \right\}
\]

Ideally, \(G_1\), \(G_2\), and \(G_3\) can be obtained by the second order Taylor expansion; here they are changed into model parameters to absorb the numerical difference as well as the uncertainties of the effective electron mass, etc.

Comparison reveals that the approximation faithfully reproduces the original integral.
Tunneling Current Density (IV)

- When $V_{gb} > V_{fb}$, $E_T = \text{the conduction band edge in the Si surface}$
- When $V_{gb} \leq V_{fb}$, $E_T = \text{the conduction band edge in the Poly surface}$
- Smoothing function is used to provide the asymptotic transition

$$E_T = E^{Si}_{Cs} + \frac{1}{2} \left[ \sqrt{(V_{ox} - G_0 \phi_t)^2 + 10^{-3}} - (V_{ox} - G_0 \phi_t) \right]$$

- $G_0$ is used to mode the band misalignment between the polysilicon and silicon
Gate Tunneling Current – Overlap

- $J_g$ in the overlap region is uniform
  
  \[ I_{gsov} = W L_{ov} J_g (V_{gs}) \]
  
  \[ I_{g dov} = W L_{ov} J_g (V_{gd}) \]

- In scaled devices, $L_{ov}$ is comparable to $L_{eff}$
  \[ \Rightarrow \text{significant overlap component} \]

- In large devices, for small gate biases, $V_{ox}$ in the overlap region is larger than in the channel region
  \[ \Rightarrow \text{significant overlap component} \]
Gate Tunneling Current – Channel

- $V_{ds}$ induces the position dependence of $J_g$ along the channel

$$I_{gc} = W \int_0^L J_g(y) \, dy; \quad J_g(y) = J_0 F_s(y) D(\phi_m) \exp \left( -\frac{u}{u_0} \right)$$

$$\phi_m = (\phi_{ss} + \phi_{ss})/2; \quad u = \phi_s - \phi_m; \quad u_0 = \frac{\chi_B}{B[G_2(1 - 2G_3|\text{Vox}|/\chi_B)]}$$

- The integrals are evaluated analytically using the symmetric linearization method (Gildenblat and Chen WCM2002)

\[
\frac{dy}{du} = \frac{L(H - u)}{H\phi}
\]

$L$: channel length; $H$: constant along the channel; $\phi = \phi_{sd} - \phi_{ss}$

$$I_{gc} = I_{gc0} \left[ (1 - b) \sinh(x) / x + b \cosh(x) \right]$$

$$I_{gc0} = I_{gc} \bigg|_{V_{ds}=0}; \quad x = \phi/2u_0; b = u_0/H$$

Shi et al. IEDM 2001 and van Langevelde et al. IEDM 2001
Gate Tunneling Current – Channel

Symbols: numerical integration
Solid Lines: analytical result

$W/L = 10 \mu m/10 \mu m \quad V_{bs} = 0 \text{ V}$

$V_{gs} = 1.5 \text{ V}$

$t_{ox} = 30 \text{ Å} \quad N_{sub} = 5 \times 10^{17} \text{ cm}^{-3} \quad V_{fb} = -1 \text{ V}$

$V_{ds}$ (V)
Gate Tunneling Current – Partition

Partition of $I_{gc}$ into the source and drain components, $I_{gcs}$ and $I_{gcd}$, is crucial to compact models

$$I_{gd} = W \int_0^L J_g(y) \frac{y}{L} dy; \quad I_{gcs} = I_{gc} - I_{gcd}$$

Repeating the algebra yields

$$I_{gcd} = \frac{I_{gc}}{2} - \frac{I_{gc0}}{2} \sinh(x) \left\{ \left( 1 - 3b + 3b^2 \right)x - b(1-b) \left[ \coth(x) - \frac{1}{x} \right] \right\}$$

When $V_{ds} \to 0$ or in subthreshold region,

$$I_{gcd} \to \frac{I_{gc}}{2}$$

Shi et al. IEDM 2001 and van Langevelde et al. IEDM 2001
Model Verification

W/L=10µm/0.17µm

Symbols: Experiment
Lines: Model

W/L=10µm/10µm

V_{bs} = 0.3 V

V_{ds} = 0 V
Model Verification

$W/L = 70 \mu$m/10 $\mu$m

Symbols: Experiment
Lines: Model

$I_g$ (A)

$V_{ds} = 0.3$ V

$V_{bs} = 0$ V
Model Verification

Symbols: I_g
Solid line: I_gov
Broken lines: I_gc

Vgs (V)
Vbs = -0.3 V
Vds = 0 V
W/L = 10µm/0.17µm
W/L = 10µm/0.17µm

Gate Current Components (A)

Vgs (V)
Vbs = -0.3 V
Vds = 0 V
Vds = 0 V
Vbs = -0.3 V
Conclusions – SP Gate Current Model

- Using surface-potential-based approach increases the physical content of the gate tunneling current model
- Physics-based carrier statistics are included efficiently, leading to physically correct results
- Overlap components are modeled sophisticatedly
- Drain bias dependence and source-drain partition of the channel component are accounted for using a physics-based approach
- All the three components have the same form of model and identical parameters
- Bias and geometry dependence of experimental data are reproduced without using scaling parameters

more information about SP model – gildenblat@psu.edu