Compact model for ultra-short channel four-terminal DG MOSFETs for exploring circuit characteristics

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1. Introduction – background and what has been achieved
2. Modeling issues – double charge-sheet, mobility, velocity saturation
3. Modeling – rigorous vs. empirical approach for velocity saturation
4. Results – comparison of two approaches, comparison with ATLAS
Two gates sandwich the Si channel. The additional gate can be used as
-the gate **electrically tied** with the other, or
-the gate **electrically independent** of the other.

It was originally proposed by one of the present authors.
Four-Terminal DG MOSFET


- CMP-line
- Stopper
- $H_{\text{fin}} = 80$ nm
- $t_{\text{ox}} = 1.7$ nm
- $T_{\text{Si}} = 8.5$ nm
- $G_1$, $G_2$
- Poly-Si
- 50 nm
- BOX
Three- vs. Four-Terminals

Advantages

Three-terminal structure
- minimum short-channel effect
- high current drivability
- ideal S factor

Four-terminal structure
- minimum short-channel effect
- ‘body bias’ by the gate
- signal mixing by two gates

Disadvantages

Four-terminal transistors can be used as three terminal transistors by externally connecting two gates.

Four-terminal structure usually means additional process to separate two gates.

Advantages of the four-terminal structure will be clarified only at the circuit level.

Compact model for DG MOSFET LSI needed now.
Modeling Issues

Conventional MOSFET
- Substrate doping
- Space charge partition
- Wide depletion layer of the drain
- Large drain capacitance
- Higher inversion electric field

DG MOSFET
- Drift-diffusion transport
- Variable surface mobility
- Mobility saturation
- Quantum size-effect
- Two interacting charge sheets
- Nonvanishing surface scattering
- Limited source current
- Mutual gate capacitance
Modeling Issues

Issues change their implications.

- **Conventional MOSFET**
  - Complicated - space charge
  - To fit within the limited range
  - Replacement of the mobility
  - Strong surface quantum size-effect

- **Drift-diffusion transport**
  - Variable surface mobility
  - Mobility saturation
  - Quantum size-effect

- **DG MOSFET**
  - Simpler - no space charge
  - Need to fit from zero electric field
  - Can include the transport equation
  - Surface and volume quantum size-effect
Double charge-sheet model - A compact model for 4-terminal DG MOSFETs that we proposed at WCM 2003

T. Nakagawa, T. Sekigawa, T. Tsutsumi, E. Suzuki, and H. Koike,
“Primary Consideration on Compact Modeling of DG MOSFETs with Four-terminal Operation Mode,”

In the model, we calculate source-end charge rigorously, separate it into two at the potential maximum, and re-calculate potential profile assuming the charge is only at the interfaces.
Drift-diffusion model

Since two charge sheets have different mobility, 
two charge sheets should be solved independently

Drain current is calculated by using drift diffusion model, assuming 
gradual channel approximation, 
\( \Delta \psi_{s1} = -\frac{q n_1}{C_{11}} - \frac{q n_2}{C_{12}} \) \quad \Delta \psi_{s2} = -\frac{q n_1}{C_{21}} - \frac{q n_2}{C_{22}} 

no current mixing between two channels,
\( I_1(y) = I_1(0) \quad I_2(y) = I_2(0) \) 

---small deviation proved by ATLAS 
and charge proportionality between two channels.
\( n_1(y)/n_1(0) = n_2(y)/n_2(0) \) 

---only for simplicity, but accurate enough

\[
I_i = q \left[ -\mu_i \frac{\partial \psi_{s_i}(y)}{\partial y} n_i(y) + D_i \frac{\partial n_i(y)}{\partial y} \right] 
\]

\[
= q \left[ \mu_i q \left( \frac{1}{C_{ii}} + \frac{n_j(0)/n_i(0)}{C_{ij}} \right) \frac{\partial n_i(y)}{\partial y} n_i(y) + D_i \frac{\partial n_i(y)}{\partial y} \right] 
\]
Mobility Modeling

Strategy: Keep the number of fitting parameters as small as possible
- Limited number of device data

Surface mobility
Replace $\mu_0$ (bulk mobility) to $\mu$ (surface mobility)
$\mu$ varies in position, but treat as a constant

$$\mu^{-1} = \mu_0^{-1} + \mu_{PH}^{-1} + \mu_{SR}^{-1}$$

$$\mu_{PH} = 5.85 \times 10^4 \times E_{tr}^{-1/3}$$

$$\mu_{SR} = 4 \times 10^{15}\left( E_{tr} + kT/qT_{Si} \right)^{-2}$$

It expresses nonvanishing surface scattering
Velocity Saturation

\[ \mu \rightarrow \left( 1 + \frac{|E_{AV}|}{E_c} \right)^{1/2} \mu \]

**\( \mu_{cons} \) approach**
- Replace \( \mu \) to effective mobility
- It does not vary in position.
- Fast, but inaccurate.

**\( \mu_{var} \) approach**
- Replace \( \mu \) to effective mobility
- It varies in position.
- Solve it rigorously
- Slow, but accurate.

**Electric Field**

**Velocity**
Transport Equation
with Velocity Saturation

\[-q\mu \left( q \frac{dn}{Cd} n + \frac{kT \frac{dn}{dy}}{q \frac{dy}{dx}} \right) = I_D\]

\[\mu \rightarrow \left( 1 + \frac{E}{E_c} \right)^{1/2} \mu\]

\[-q\mu \left( q \frac{dn}{Cd} n + \frac{kT \frac{dn}{dy}}{q \frac{dy}{dx}} \right) = I_D \left( 1 + \left| \frac{E}{E_c} \right|^2 \right)^{1/2}\]

Solution

\[-\beta E_c n_b L_{tr} = \frac{1}{2} \left( n_{aL} \sqrt{n_{aL}^2 - n_b^2} - n_{a0} \sqrt{n_{a0}^2 - n_b^2} \right) - \frac{1}{2} n_b^2 \log \left( \frac{n_{aL} + \sqrt{n_{aL}^2 - n_b^2}}{n_{a0} + \sqrt{n_{a0}^2 - n_b^2}} \right)\]

\[n_{aL} = n_a(L_{tr}), \quad n_{a0} = n_a(0),\]

\[n_a = n/(CkT/q^2) + 1, \quad n_b = (I_D/q\mu E_c)/(CkT/q^2)\]
At the point where the drain electric field becomes dominant, we assume
\[
\frac{d^2n}{dy^2} / \frac{dn}{dy} = \frac{1}{\lambda}
\]

This condition guarantees most smooth transition across the point. We call the point, ‘transition point.’

$L$ is the endpoint of the model, and is not necessarily the gate length.
Algorithm for $\mu_{\text{var}}$ approach

1. Compute $n_1(0)$ and $n_2(0)$

2. Suppose $I_1$

3. Compute $n_1(L_{tr})$

4. Find $L_{tr}$
   
   - If $L_{tr} > L$?
     - Assume $L_{tr} = L$
     - Calculate $V_{D\text{cal}}$
     - If $V_{D\text{cal}} = V_D$?
       - Calculate $I_1$
     - Output $I = I_1 + I_2$

5. Suppose $I_2$

6. Compute $n_2(L_{tr})$

7. Find $L_{tr}$
   
   - If $L_{tr} = L$?
     - Assume $L_{tr} = L$
     - Calculate $V_{D\text{cal}}$
     - If $V_{D\text{cal}} = V_D$?
       - Calculate $I_2$
Long Channel characteristics

Comparison of $\mu_{\text{var}}$ and $\mu_{\text{cons}}$ approach with ATLAS data. Only three parameters are used to fit the curve.

$V_{G1}=V_{G2}=1.0V$

$0.6V$

$0.2V$

$LG=200\text{nm}$

$TOX1=TOX2=2\text{nm}$

$T_{Si}=5\text{nm}$
Comparison of $\mu_{\text{var}}$ and $\mu_{\text{cons}}$ approach with ATLAS data. Only three parameters are used to fit the curve, and these parameters are fixed common with the long channel case.

- $L_G = 50\text{nm}$
- $T_{\text{ox1}} = T_{\text{ox2}} = 2\text{nm}$
- $T_{\text{Si}} = 5\text{nm}$
Comparison of $\mu_{\text{var}}$ and $\mu_{\text{cons}}$ approach with ATLAS data.

Output conductance behave well in the case of $\mu_{\text{cons}}$ approach.

$V_{G1}=V_{G2}=1.0\text{V}$

$V_{G1}=0.6\text{V}$

$V_{G1}=0.2\text{V}$

$\mu_{\text{var}}$ approach

$\mu_{\text{cons}}$ approach

ATLAS result

$L_G=50\text{nm}$

$T_{Ox1}=T_{Ox2}=2\text{nm}$

$T_{Si}=5\text{nm}$
Drain current and so-called pinch-off point for 20nm DG MOSFET. Pinch-off point moves drastically when the drain voltage increases. However the drain current hardly increase, because of carrier velocity saturation.

Transition Point for 20nm DG MOSFET

$V_{G1} = V_{G2} = 1.0\text{V}$

$L_G = 20\text{nm}$

$T_{OX1} = T_{OX2} = 2\text{nm}$

$T_{Si} = 5\text{nm}$
Summary

Mobility modeling, starting from the bulk mobility, with only three fitting parameters, was proposed.

Two approaches, $\mu_{\text{var}}$ and $\mu_{\text{cons}}$ approach, were compared to handle the carrier velocity saturation.

These results are compared each other, and with the device simulator results.

Better agreement with device simulator was obtained when the velocity saturation effect is included as a variable in the transport equation.