Fundamentals, Computer Implementation and Applications of the Advanced Compact MOSFET (ACM) Model

O. Franca Siebel, M. C. Schneider, and C. Galup-Montoro

Federal University of Santa Catarina
http://eel.ufsc.br/~lci/
Contents

1. Pao-Sah model
2. Capacitive model of the field-effect
3. Advanced Compact MOSFET
4. Computer Implementation
5. Benchmark tests
6. Simulation times
7. Conclusions
Gradual channel approximation

Considering \( \frac{\partial F_x}{\partial x} \gg \frac{\partial F_y}{\partial y} \)

We can separate one 2-D problem into two 1-D problems.

Vertical 1-D field electrostatics control conduction charge

Longitudinal 1-D field controls current flow
Pao-Sah current expression

### Drain current expression

\[
I_D = -\mu WQ'_I \frac{dV_C}{dy} \quad \Rightarrow \quad I_D = \frac{W}{L} \int_{V_D}^{V_S} \mu (-Q'_I) dV_C
\]

\[
I_D = \frac{W}{L} \int_{V_D}^{V_S} \mu (-Q'_I) dV_C \left\{ \begin{array}{l}
I_D = -\mu \frac{W}{L} \int_{\phi_s}^{\phi_s L} Q'_I(\phi_s) \frac{dV_C}{d\phi_s} d\phi_s \\
I_D = -\mu \frac{W}{L} \int_{Q'_{ID}}^{Q'_{IS}} Q'_I \frac{dV_C}{dQ'_I} dQ'_I
\end{array} \right.
\]

### Small-signal output conductance

\[
g_d = \left. \frac{\partial I_D}{\partial V_D} \right|_{V_G,V_S} = -\mu \frac{W}{L} Q'_I(V_D, V_G)
\]
Capacitive model of the field-effect

\[ V_G \]

\[ \frac{dQ'}{d\phi_s} \]

\[ C'_i \]

\[ C'_b \]

\[ C'_ox \]

\[ dV_C \]

\[ dQ'_i \]

\[ dQ'_B \]

\[ \Rightarrow \begin{cases} 
C'_i = -\frac{dQ'_i}{d\phi_s} \equiv -\frac{Q'_i}{\phi_t} \\
 dQ'_i = C'_i (dV_C - d\phi_s) 
\end{cases} 
\]

\[ dV_C = d\phi_s - \frac{\phi_t}{Q'_i} dQ'_i \]

Drain current (including both drift and diffusion transport mechanisms)

\[ I_D = \mu W Q'_i \frac{dV_C}{dy} = -\mu W Q'_i \frac{d\phi_s}{dy} + \mu W \phi_t \frac{dQ'_i}{dy} \]
The ACM model - Fundamentals

\[ Q'_i = -C'_\text{ox} (V_{GB} - V_{FB} - \phi_s) - Q'_B \]

Expanding in power series around \( \phi_{sa} = \phi_s \bigg|_{Q'_i=0} \) for \( V_G \) constant

\[ Q'_i = nC'_\text{ox} (\phi_s - \phi_{sa}) \Rightarrow dQ'_i = nC'_\text{ox} d\phi_s \]

\[ V_G - V_{FB} = \phi_{sa} - \gamma \cdot \text{sign}(\phi_{sa})(\phi_{sa} + \phi_t(e^{-\phi_{sa}/\phi_t} - 1))^{0.5} \]
The ACM model 2 - Drain current

Drain current

\[ I_D = -\mu W Q'_I \frac{d\phi_s}{dy} + \mu W \phi_t \frac{dQ'_I}{dy} \]

\[ \Downarrow \quad dQ'_I = nC'_ox d\phi_s \]

\[ I_D = \frac{\mu W L}{Q'_IS^2 - Q'_{ID}^2} - \phi_t(Q'_IS - Q'_{ID}) \]

Small-signal output conductance

\[ g_d = \frac{\partial I_D}{\partial V_D} = \frac{\mu W}{L} \left[ -\frac{Q'_{ID}}{nC'_ox} + \phi_t \right] \frac{dQ'_{ID}}{dV_D} = -\frac{W}{L} \mu Q'_I(V_D, V_G) \]
The ACM model 3 - Charge evaluation

\[ dQ'_{ID} \left( \frac{1}{nC'_{ox}} - \frac{\phi_t}{Q'_{ID}} \right) = dV_D \]

\[ \downarrow \]

\[ \frac{V_P - V_{S(D)}}{\phi_t} = \frac{Q'_{IP} - Q'_{IS(D)}}{nC'_{ox}\phi_t} + \ln \left( \frac{Q'_{IS(D)}}{Q'_{IP}} \right) \]

\[ \times 10^{-9} \]

Error = \frac{(V_P - V_{S(D)})/\phi_t - (Q'_{IP} - Q'_{IS(D)})/nC'_{ox}\phi_t}{\ln(Q'_{IS(D)}/Q'_{IP})}

Error (V)

Error (V)

Error (V)

\[ V_G (V) \]

Conclusions
### The ACM model 4 - Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>U0</td>
<td>Carrier mobility</td>
<td>m²/Vs</td>
</tr>
<tr>
<td>TOX</td>
<td>Gate oxide thickness</td>
<td>m</td>
</tr>
<tr>
<td>VT0</td>
<td>Threshold voltage</td>
<td>V</td>
</tr>
<tr>
<td>NA</td>
<td>Acceptor densities</td>
<td>cm⁻³</td>
</tr>
<tr>
<td>VFB</td>
<td>Flat-band voltage</td>
<td>V</td>
</tr>
<tr>
<td>GAMMA</td>
<td>Body effect factor</td>
<td>√V</td>
</tr>
<tr>
<td>LAMBDA</td>
<td>Channel length modulation factor</td>
<td>-</td>
</tr>
<tr>
<td>THETA</td>
<td>Mobility reduction factor</td>
<td>1/V</td>
</tr>
<tr>
<td>M</td>
<td>Temperature factor</td>
<td>-</td>
</tr>
<tr>
<td>VMAX</td>
<td>Velocity saturation</td>
<td>m/s</td>
</tr>
<tr>
<td>XJ</td>
<td>Junction depth</td>
<td>m</td>
</tr>
<tr>
<td>SIGMA</td>
<td>Drain-induced barrier lowering factor</td>
<td>m²</td>
</tr>
</tbody>
</table>
Using the User Definable Model (UDM) tool.

Algorithm used for the numerical calculation of the inversion charge in the UCCM obtains relative errors of less than $10^{-7}V$.

Algorithm used for the numerical calculation of $\phi_{sa}$ obtains relative errors of less than $10^{-7}V$.

The model code was written in C.

It was implemented in ELDO version 6.6, release 2005.3.
Gummel symmetry test - ACM
Gummel symmetry test - HiSIM
Gummel symmetry test - PSP

\[ dI_D/dV_X \]

\[ d^2I_D/d^2V_X \]
MOSFET binary current divider

I_{REF} 

Current Mirror (1:1) 

\[ \frac{V_{DD}}{V_{DD}} \]

\[ \frac{I_{M2}}{I_{REF}} = \frac{I_{M4}}{2} = \frac{I_{M6}}{4} = \frac{I_{M8}}{8} = \frac{I_{M10}}{8} \]
MOSFET binary current divider - ACM

\[ I_{M2} \]
\[ I_{M4} \]
\[ I_{M6} \]
\[ I_{M8} = I_{M10} \]
MOSFET binary current divider - HiSIM

$I_{M8} = I_{M10}$

$I_{M2}$

$I_{M4}$

$I_{M6}$

$I_NORM$ vs $I_{REF}$ (A)

$10^{-7}$ to $10^{-4}$
MOSFET binary current divider - PSP

\[ I_{M8} = I_{M10} \]

\[ I_{M6} \]

\[ I_{M4} \]

\[ I_{M2} \]

\[ I_{\text{NORMALIZED}} \]

\[ I_{\text{REF}} (A) \]

\[ I_{\text{NORMALIZED}} = I_{M10} \]

\[ I_{\text{REF}} (A) \]

Simulation times

Conclusions

Benchmark tests

Computer Implementation

Advanced Compact MOSFET Model

Capacitive model of the field-effect

Pao-Sah model

Advanced Compact MOSFET Model

Conclusions

Simulation times

Benchmark tests
## Simulation times

<table>
<thead>
<tr>
<th>Circuit</th>
<th>ACM&lt;sub&gt;cap&lt;/sub&gt;</th>
<th>ACM</th>
<th>EKV</th>
<th>MM11</th>
<th>HiSIM</th>
<th>PSP</th>
<th>BSIM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>schmitfast</td>
<td>1s580ms</td>
<td>1.02</td>
<td>0.84</td>
<td>2.14</td>
<td>1.63</td>
<td>1.87</td>
<td>1.16</td>
</tr>
<tr>
<td>schmitslow</td>
<td>2s430ms</td>
<td>1.00</td>
<td>0.70</td>
<td>1.75</td>
<td>1.60</td>
<td>1.93</td>
<td>1.28</td>
</tr>
<tr>
<td>g1310</td>
<td>640ms</td>
<td>0.98</td>
<td>0.92</td>
<td>1.28</td>
<td>1.23</td>
<td>1.31</td>
<td>1.19</td>
</tr>
<tr>
<td>hussamp</td>
<td>3s020ms</td>
<td>1.07</td>
<td>1.11</td>
<td>1.02</td>
<td>1.06</td>
<td>1.11</td>
<td>1.06</td>
</tr>
<tr>
<td>ab_ac</td>
<td>1s400ms</td>
<td>1.03</td>
<td>1.02</td>
<td>2.35</td>
<td>1.63</td>
<td>1.86</td>
<td>1.25</td>
</tr>
<tr>
<td>ab_integer</td>
<td>1s370ms</td>
<td>1.00</td>
<td>0.98</td>
<td>1.09</td>
<td>1.01</td>
<td>1.13</td>
<td>0.98</td>
</tr>
</tbody>
</table>
ACM is a powerful and useful tool for simulation and design because it consists of simple, accurate and single equations (valid in all regions (including accumulation)) together with a small number of physical parameters.
Main references


