Unified 2D Short Channel Effects Model for Bulk CMOS FETs

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Abstract

Analytical models for 2D potential distribution in bulk MOSFETs are presented. From the 2D potential distribution, short channel effects (SCE) models describing \( V_T \) rolloff and subthreshold slope rollup are derived. The models are unified - i.e. they can be applied to a variety of bulk FETs (like retro-grade doped FET, buried channel FET, etc.). All models are exhaustively verified with 2D numerical device simulations. The SCE models along with physically based I-V models show that accumulation FETs are better suited for ultra-low power applications than the normal inversion FET\(^1\).

1. Introduction

Bulk MOSFETs can be of various types depending on their channel and poly doping - the normal surface channel inversion (SCI) FET, the retrograde SCI (RDSCI) FET, the surface channel accumulation (SCA) FET or the buried channel accumulation (BCA) FET. Accumulation FETs are useful for a number of reasons including use of a single poly process and metal gate FETs. To identify the right FET for a given application, one would normally use different device models and compare the short channel effects (SCE). But a unified SCE model results in uniformity of the model accuracy over different FETs and thus device comparison is more reliable. Also, device identification and optimization (for a given application) can be automated.

The general device structure is shown in Fig. 1. The implant doping is denoted by \( N_T \), the substrate doping by \( N_W \), the implant depth by \( y_i \) and the junction depth by \( y_j \). Depending on the poly and implant doping, the bulk NFET can be of the various types shown in Table (1). \( V_T \) control of the SCI FET is done by varying the channel doping, Fig. 2. SCA FET and BCA FET \( V_T \) control is done by varying the doping of the n-type implant. It can be seen that for very low implant doping, the device is a SCA FET whereas for very high concentration implants, the device is a BCA FET.

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Table 1. Bulk NFET classification (all the FETs have a p-type $N_\text{W}$)

<table>
<thead>
<tr>
<th>FET</th>
<th>poly</th>
<th>$N_\text{T}$</th>
</tr>
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<tbody>
<tr>
<td>SCI</td>
<td>n+</td>
<td>p(=$N_\text{W}$)</td>
</tr>
<tr>
<td>RDSCI</td>
<td>n+</td>
<td>p-type</td>
</tr>
<tr>
<td>SCA</td>
<td>p+</td>
<td>n-type</td>
</tr>
<tr>
<td>BCA</td>
<td>p+</td>
<td>n-type</td>
</tr>
</tbody>
</table>

![Figure 3. Surface potential verification for BCA FET for $V_d=0$ and $1V$](image)

the 2D potential as:

$$
\psi(x, y) = u(y) + \phi(x, y)
$$

(1)

where $\phi(x, y)$ is given by,

$$
\sum_{n=1}^{n=\infty} \left( \frac{\lambda_n}{K_n} \exp(\lambda_n (x-L)) + \frac{\lambda_n}{K_n} \exp(-\lambda_n L) \right) F_n(y)
$$

with,

$$
F_n(y) = \frac{C_{ox}}{\lambda_n \varepsilon_s} \sin(\lambda_n y) + \cos(\lambda_n y)
$$

$$
K_n = \frac{1}{2} \left( 1 + \frac{n-1}{d} \left( 1 + \frac{\lambda_n^2 \varepsilon_s^2}{C_{ox}} \right) \right)
$$

$$
\lambda_n : \tan(\lambda_n d) = \frac{C_{ox}}{\lambda_n \varepsilon_s}, \quad \frac{\pi(n-1)}{d} < \lambda \leq \frac{\pi(n-1)}{d} + \frac{\pi}{2d}
$$

$u(y)$ is the long-channel (1D) Poisson solution in the middle of the channel. $\chi_{Dn}$ and $\chi_{Cn}$ are Laplace solutions and are given in detail in [1](downloadable from http://www.ece.gatech.edu/research/labs/gsigroup/publications.htm).

The 2D potential model is verified against 2D numerical simulations (using device simulator MEDICI[2]), Figs. 3-6.

3. $V_T$ Rolloff Model

To evaluate short-channel $V_T$ we need to calculate $\psi_{m}$ at which $\psi(x_m, y_c) = 2\phi_T - V_T$ (for the SCI and RDSCI FETs) or $\psi(x_m, y_c) = \phi_T - V_T$ (for the SCA and BCA FETs), where $(x_m, y_c)$ is the point of minimum potential. $\phi(x, y)$ can be approximated with a single term solution and the rolloff is then given by:

$$
\Delta V_T = \frac{-[\chi_{D1} + \chi_{C1}]\exp(-\lambda_1 L/2)F_1(y_c)}{K_1(1 + \exp(-\lambda_1 L)) - 2\exp(-\lambda_1 L/2)F_1(y_c)}
$$

(2)

where, $y_c = 0$ for SCI, RDSCI and SCI FETs; for the BCA FET,

$$
y_c = \left( 1 + \frac{N_\text{W}}{N_\text{T}} \right) y - \frac{N_\text{W}}{N_\text{T}} d
$$

Verification of the rolloff model for channel lengths down to 50nm is shown in Figs. 7-10. In the Figs., $V_T$ is defined as $V_\text{g}$ required to give $I_d = 1\mu A/\mu m$.

4. Subthreshold Slope Rollup Model

$I_{\text{OFF}}$ estimation becomes very important as channel lengths are scaled, both because of the widespread use of portable computing and heat dissipation problems. A critical component in correct $I_{\text{OFF}}$ estimation is the short channel subthreshold slope ($S_\text{S}$). The 2D potential model...
can be used to find the subthreshold slope factor ($\eta_S$):

$$\eta_S = \left( \frac{\partial \psi(x_m, y_c)}{\partial \phi_0} \right)_{V_A - V_T}^{-1}$$

The resultant expression for $\eta_S$ is:

$$\eta_S^{-1} = u'(y_{ch}) - \left( \frac{\lambda_{D1} + \lambda_{C1}}{K_1} \right) F_1(y_{ch}) \exp \left( -\frac{\lambda_1 L}{2} \right) \left\{ \frac{K_1}{K_1} \right\}$$

$$+ \frac{\lambda_1 L}{2} \left( \frac{\lambda_{D1} + \lambda_{C1}}{\lambda_{D1} + \lambda_{C1}} \right) F_1(y_{ch})$$

where the primes indicate the derivatives of the respective terms. Verification of the rollup model is given in Table (2), which indicates the maximum error in $S_S(= (kT/q)\ln(10)\eta_S)$ for each type of FET, compared to 2D numerical simulation results[2], over channel lengths (eff.) from 300nm down to 50nm.

5. I-V Modeling

The SCE models can be easily applied to $I_d - V_G$ modeling. Velocity overshoot effects are taken care of by modifying $\mu_{eff}$; poly depletion and inversion layer quantization effects are included by modifying $t_{ox}$. Oxide tunneling is modeled separately from first principles. The complete I-V models and verification with simulated and measured data is given in [1]. All regions of operation are modeled by maintaining continuity across regional boundaries and including lateral and vertical high field effects. The I-V models too are entirely physically based.

$I_{ON} - I_{OFF}$ curves generated from the I-V and SCE models are shown in Fig. 11, for BCA and SCI FETs. $V_{DD}$ varies along the x-axis while the threshold voltage is kept constant. There exists a crossover in the BCA and SCI FET curves, which indicates that there exists a region of operation where the BCA FET is better than the SCI device - this is the low $I_{ON}$ region, where $I_{ON} < 10\mu A/\mu m$. The reason for the better performance is that as the implant doping in an accumulation FET is decreased (to increase $V_T$ so as to achieve a low $I_{OFF}$), the conducting channel moves towards the semiconductor-oxide interface and thus the subthreshold slope reduces - this is as opposed to an inversion FET where the channel doping needs to be increased (to increase $V_T$) which results in a decrease in depletion depth and thus an increase in subthreshold slope. Thus the BCA FET should perform better than the SCI FET in applications requiring moderate speed and ultra-low power.

6. Conclusion

Compact 2D models for bulk FETs are presented. The models are entirely analytical and avoid any parameter fitting, thus making them suitable for predicting future technology over the next decade. The unified nature of the models makes them useful for device optimization and performance comparison. 2D potential, $V_T$ rolloff and subthreshold slope rollup have been verified with 2D numerical simulations. The models can be readily used with I-V models to predict power-delay performance. The SCE models along with I-V models indicate that the BCA FET is more suitable than the SCI FET for ultra-low power applications.


Figure 9. $V_T$ rolloff verification for SCA FET

Figure 10. $V_T$ rolloff verification for BCA FET

Figure 11. $I_{ON} - I_{OFF}$ for BCA and SCI FETs

Table 2. Subthreshold slope rollup - model verification (max. error over L from 300nm to 50nm) with 2D numerical simulation data

<table>
<thead>
<tr>
<th>FET</th>
<th>error(%)</th>
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<tbody>
<tr>
<td>SCI</td>
<td>5.4</td>
</tr>
<tr>
<td>RDSCI</td>
<td>6.1</td>
</tr>
<tr>
<td>SCA</td>
<td>4.5</td>
</tr>
<tr>
<td>BCA</td>
<td>7.2</td>
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