A New Continuous Model for Deep Submicron MOSFETs


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ABSTRACT
A 1-D model is developed to account for mobile charges in the Source/Drain junction regions of a MOSFET. 2-D effects such as Threshold Roll-off and Drain Induced Barrier Lowering are accounted for with an empirical function \( G \) constructed by fitting our equations to measured data. The model is scalable, and only one round of fitting to measured data is needed for each process technology. The resulting drain current is continuous over the entire operating range of the transistor.

INTRODUCTION
Solution of the potential and inversion charge distributions of a wide n-MOSFET is inherently a two-dimensional problem. However, in order to yield a closed-form solution, the gradual channel approximation (GCA) is employed to calculate the mobile charge

\[
Q_l = Q_G - Q_B
\]

where \( Q_G \) and \( Q_B \) are the gate and bulk charges (per unit area), respectively. With the charge sheet assumption [1], equation (1) can be rewritten in terms of the surface potential \( \phi_s \) as

\[
Q_l(y) = -C_{ox}[V_G - V_{FB} - \phi_s(y)] - Q_G(y) = -C_{ox}[V_G - V_{FB} - \phi_s(y)] - \gamma \phi_s(y)
\]

where \( C_{ox} \) is the oxide capacitance, \( V_{FB} \) is the flat-band voltage, and \( \gamma \) is the body factor. Using equation (2), one can obtain the drain current in terms of the surface potential values at the Source and Drain ends of the channel, as given by

\[
I_D = \frac{W}{L_{eff}} \left[ \int_{-Q_l}^{Q_l} (-Q_l) d\phi_s + \frac{kT}{q} \int_{Q_l}^{Q_l} dQ_l \right]
\]

where \( W \) is the width of the transistor and \( \mu_n \) is the average channel electron mobility. The effective channel length \( L_{eff} \) in equation (3) is assumed to be bias-independent, which is valid for long-channel devices. Under this approximation, the currents inside the Source/Drain junction space-charge regions are not accounted for. As the channel length becomes shorter, these space-charge regions constitute a sizable portion of the physical channel length \( L \) (from Source junction to Drain junction). The major difficulty in calculating \( I_D \) correctly is that we cannot use equation (2) to calculate the mobile charge inside these space-charge regions where GCA is no longer valid. In the next section, we present a methodology whereby the mobile charge inside each of the junction space-charge regions is accounted for. In so doing, short-channel effects are automatically included in our calculation of the drain current.

METHODOLOGY
As shown in Figure 1, we divide the physical channel into Gate, Source, and Drain controlled regions. The substrate is chosen as the reference node, so that Source and Drain are interchangeable. We will first discuss how to model the channel current in each region and then impose the current continuity condition to obtain a self-consistent solution.

Gate Controlled Region
The current inside this region is similar to the long-channel drain current given by equation (3) because GCA is assumed to be valid here. However, to capture the short-channel effects, a modification has to be made. From Figure 1, this region lies within \( x_s \leq y \leq L - x_d \). We replace \( L_{eff} \) in equation (3) by \( L - \Delta L \), with \( \Delta L = x_s + x_d \). Since \( x_s \) and \( x_d \) are junction space-charge region widths, they increase approximately as functions of \( V_{SB}^{1/2} \) and \( V_{DB}^{1/2} \), respectively, and the channel length under the Gate controlled region is shortened as \( V_{DB} \) and/or \( V_{SB} \) increase. Thus the effect of Channel Length Modulation (CLM) is incorporated, at least to the first order. It has been pointed out [2] that the 1-D solution with square-root dependence on voltage overestimates the current. We will now show how
the inclusion of 2-D effects from the junction space-charge regions in our model will correct this problem.

The effective mobility is calculated by averaging the mobility over the entire channel as follows.

\[
\mu_{\text{eff}} = \frac{1}{L} \int_{0}^{L} \frac{1}{\mu} \ dy.
\]  

(4)

Using existing degradation model\[3\], the field-dependent mobility can be expressed as

\[
\mu = \mu_{0} \left( \frac{E_{\text{eff}}}{E_{0}} \right)^{\frac{1}{n}} \left( E_{\text{eff}} - E_{0} \right) - \mu_{1} \left( E_{\text{eff}} - E_{0} \right)^{2},
\]  

(5)

where \( \frac{\mu_{s}}{E_{\text{eff}}^{2}} \) takes on its value at the source.

Substituting equation (5) into (4) and assuming that \( E_{\text{eff}} \) is independent of \( y \), the effective mobility can be calculated as

\[
\mu_{\text{eff}} = \mu_{s} \left( \frac{E_{\text{eff}}}{E_{0}} \right)^{\frac{1}{n}} \left( E_{\text{eff}} - E_{0} \right) - \mu_{1} \left( E_{\text{eff}} - E_{0} \right)^{2},
\]  

(6)

where \( \mu_{s} = \frac{\mu_{0}}{1 + \frac{Q_{s}}{2E_{\text{eff}}}} \) takes on its value at the source.

Junction Controlled Regions

The use of \( \Delta L \) as defined above only captures the voltage dependencies, but fails to predict the effect of CLM accurately. In general the source/drain junctions are dominated by the lateral electric field. We assume that \( Q_{i} \) extends from the edge of the gate-controlled region and that the quasi-Fermi potential varies linearly in these regions. A y-independent relationship can be devised as follows.

\[
Q_{i}(S,D) \cup \sim \text{Cos}[VGB - VFB - \phi(S,D) - \gamma \sqrt{\phi(S,D)}]
\]  

(7)

The drain current can then be computed iteratively using the following equations.

\[
I_{D} = \frac{V_{D} - V_{S}}{R_{S}} = \frac{V_{D} - V_{S}}{R_{D}} = \frac{W\mu_{\text{eff}}}{L - x_{S} - x_{j}} \phi_{i}^{(L-x_{j})} \left[ -Q_{j} + kL \phi_{j}^{(L-x_{j})} - \frac{q}{L} \phi_{j}^{(L-x_{j})} \right] \phi_{j}^{(x_{j})} Q_{j}^{(x_{j})}
\]  

(8)

where \( R_{S} = \frac{x_{S}}{W\mu_{\text{eff}}} \), \( R_{D} = \frac{x_{D}}{W\mu_{\text{eff}}} \).

We note that \( R_{S} \) and \( R_{D} \) are physically part of the channel resistance. They are independent of the Source/Drain series resistances of the MOSFET. In a long-channel MOSFET, where GCA is valid, the surface potential is derived from solution of the 1-D Poisson equation for the MOS capacitor. However, in short-channel MOSFETs, the lateral fields from Source and Drain junctions introduce considerable 2-D effects, making our use of the long-channel surface potential expression \[1\] for the Gate controlled region seemingly impractical. This shortcoming is partially offset in our model by the inclusion of the junction space-charge regions. Further, instead of solving the 2-D Poisson equation to obtain a new surface potential expression, we define a fitting function \( \Gamma \) to take into account the 2-D effects such as Threshold Roll-off and Drain Induced Barrier Lowering. The only change is to replace \( V_{FB} \) everywhere by \( (V_{FB} + \Gamma) \) in equations (2) and (7), where \( \Gamma \) is a bias-dependent fitting function. Poly-depletion effect is modeled using an additional gate voltage drop \[3\] in the surface potential calculation.

RESULTS

The function \( \Gamma \) is constructed empirically by fitting the drain current computed using equation (6) to measured data. The function itself is then fitted to polynomials of gate voltage, drain voltage, and channel length. Comparison of \( I_{D}-V_{D} \) and \( I_{D}-V_{G} \) results from our model and measured data is given in Figure 2 and Figure 3.

![Figure 2: Drain current-drain voltage characteristics and drain conductance for the 0.35 μm MOSFET. Solid lines are results from our model, while points are measured data. Process parameters: L_mask = 0.4 μm, tox = 70 Å, x_j = 0.15 μm, and N_A = 3×10^{17} cm^{-3}.](image-url)
The main advantage of our approach is that only one set of fitting parameters, namely the function \( G(V_D, V_G) \), needs to be extracted compared to dozens of electrical parameters in existing short-channel compact models [4]. In addition, our model is continuous over all regions of operation, making it attractive for low-power circuit and analog circuit simulations [5]. To demonstrate the continuous behavior of our model, we have plotted the normalized transconductance versus drain current characteristics obtained from our model, as shown in Figure 4.

**CONCLUSION**

We have demonstrated the utility of a semi-empirical short-channel MOSFET model that requires only one fitting function \( \Gamma \), and is continuous over the entire operating bias range. Further, we separate the physical parameters from the fitting parameters, while the polynomial function provides sufficient flexibility for benchmarking our model against existing process technologies. The extraction of \( \Gamma \) is performed only once for each process technology. The model, with the extracted \( \Gamma \), can then be incorporated into a circuit simulator. As in other modeling schemes, our model accounts for 2-D and short-channel effects without solving the 2-D Poisson equation.

**REFERENCES**


