Abstract

Two basic capacitance effects can be distinguished: the space-charge capacitances and the one of the overlap regions. These effects have a substantial influence on the total capacitance behaviour of the transistor if the channel is shorter than $0.25\ \mu m$. A model has been developed and incorporated into the existing BSIM3v3.1 compact model for circuit simulation.

1. Introduction

With decreasing channel length the capacitances of the drain and source regions become a substantial factor to the total C(V)-behaviour of short channel LDD-MOSFETs. In this paper we report therefore about the modelling of the non-linear space charge and overlap capacitances of those regions. The validity of the model is compared with device simulations and measurements.

In order to describe the interesting effects a typical LDD-MOSFET (fig. 1) with its doping and surface potential is used for demonstration. Depending on the gate voltage different surface potential $\psi_S$ exist. Accordingly the overlap region ($n^-$) is able to collect electrons and holes as the device simulations (fig. 2) indicates. Those charges represent the non-linear overlap capacitance $C_{ov}(V)$. The other capacitance is the one of the space charge layer $C_{SC}(V)$. The charge distribution is depict in fig. 3. The C(V)-behaviour of the inner MOS-transistor (fig. 1) is used unchanged as defined in the BSIM3v3.1 [1] description as well as the fringing effect represented by $C_{fr}$.

Figure 2. Electron and hole distributions in the overlap region resulting from a device simulation
2. Theory

To describe these effects accurately the 2-dimensional Poisson’s equations has to be solved. To simplify the description the 2D-problem has been splitted into two 1D-problems: First Poisson’s equations for the non-gated diodes source-bulk and drain-bulk has been solved using the depletion approximation. Using this solution of the 1D-Poisson’s equation as boundary condition for the vertical problem the charge distribution can be determined (Appendix A).

3. Simulation and Discussion

The doping profile is approximated by a step function profile. This simplifies the solution of Poisson’s equation. In this case a Gaussian profile with just two parameters was used and for each step the potential $\psi$, the body effect coefficient $\gamma$, the flat band voltage $V_{FB}$ and the fermi level $\phi_f$ determined. These individual results are used to derive the surface potential $\psi_S$ and the charge for each doping step and location respectively.

The results for negative gate voltages are shown in fig. 4 for the drain side. Applying a negative gate voltage the overlap region is depleted. The positive ions $N_D^+$ result in a positive depletion charge $Ov_D$ belonging to the drain charge. Enhancing the negative gate voltages holes flow from the bulk into the overlap region and build an inversion layer. Its charge $\sigma_{OV}(Bulk)$ can be considered to be a bulk charge. In the space charge regions holes are accumulated resulting in a bulk charge $\sigma_{SC}(Bulk)$ also. In fig. 4 the charge distributions $\sigma_{OV}(Drain)$ and $\sigma_{OV}(Bulk)$ are also shown. Fig. 5 shows the case for positive gate voltages. The charge distributions are $\sigma_{SC}(Drain)$ and $\sigma_{SC}(Bulk)$ analogous to $\sigma_{OV}(Bulk)$ and $\sigma_{OV}(Drain)$ as shown in fig. 4.
However, in circuit simulators only the total charges are interesting. In fig. 6 the total charges are shown versus the gate voltage and compared with the one of the inner transistor \( Q_{MOS(Bulk)} \) and \( Q_{MOS(Drain)} \) respectively. This comparison was performed with the circuit simulator SABER on a device with a channel length of \( 0.25 \mu m \). Fig. 6 demonstrates the importance of modelling the source and drain charges in comparison to the one of the inner transistor modelled by the existing BSIM3v3.1 C(V)-description.

The capacitances can be calculated by

\[
C_{SG} = \frac{\partial Q_S}{\partial V_G}, \quad C_{DG} = \frac{\partial Q_D}{\partial V_G}, \quad C_{BG} = \frac{\partial Q_B}{\partial V_G}, \quad C_{GG} = \frac{\partial Q_G}{\partial V_G}
\]
with

\[
Q_S = Q_{MOS(Source)} + Q_{SC(Source)} + Q_{Ov(Source)} + Q_{fr}
\]
\[
Q_D = Q_{MOS(Drain)} + Q_{SC(Drain)} + Q_{Ov(Drain)} + Q_{fr}
\]
\[
Q_S = Q_{MOS(Bulk)} + Q_{SC(Bulk)} + Q_{Ov(Bulk)}
\]
\[
Q_G = -(Q_S + Q_D + Q_B)
\]

\[
U_{GD} \leq U_{FB}:
Q_{Ov(Drain)} = \int C_{ox}' (\gamma \sqrt{-\psi_s - V_1}) \, dx
\]
\[
Q_{Ov(Bulk)} = \int -C_{ox}' (U_{GD} - U_{FB} - \psi_s) \, dx
\]
\[
U_{GD} > U_{FB}:
Q_{Ov(Drain)} = -\int C_{ox}' (U_{GD} - U_{FB}) \, dx
Q_{Ov(Bulk)} = 0
\]

\[
\psi_S = \frac{\psi_w}{1 + \frac{1}{f_3(-\psi_S^w)} \ln [1 + \exp (f_3(\psi_S^w - \psi_w^w))]};
\]

with

\[
\psi_w^w = -\frac{1}{4} \left( \frac{\gamma V}{\gamma} \right)^2
\]
\[
\psi_S^{st} = 2\phi_F + U_{BD} - \psi - m\phi_I
\]
\[
m = f(U_G, U_D, U_B) \approx 6.
\]
\[
V = -\gamma^2 + 2\sqrt{\gamma^2 - 4(U_{GD} - \psi - U_{FB})}
\]
\[
V_{1(2)} = \frac{\sqrt{2\phi_I}}{\gamma + \sqrt{2\phi_I}} \ln \left(1 + f_1(2)(U_{GD} - \psi - U_{FB}) \right)
\]
\[
f_1 = -2 \frac{\gamma + \sqrt{2\phi_I}}{\gamma^2 + 2\phi_I} + f_2
\]
\[
f_2 = \frac{2}{3} \frac{\gamma}{\sqrt{2\phi_I(\gamma + 2\phi_I)^2}}
\]

\(f_3\) is a factor for a smooth transition of the surface potential \(\psi_S\) from depletion to inversion.

The charges of the space charge regions can be determined analogously.

The work was sponsored by DFG Ho-1325/2-2

[1] BSIM3v3 manual, University of California, Berkeley, CA 94720, ftp site rely.eecs.berkeley.edu