Closed Form Expression MOS Transistor Model for Analog Circuit Simulation

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Summary

The MOS transistor model for circuit design and simulation presented here is valid in all operating regions, and in particular in weak and moderate inversion. Its main features are: closed form expressions providing continuous transitions between the operating regions, accurate modeling of small-signal characteristics, simple physical description of the ideal transistor with modular extensions to include nonidealities such as short and narrow channel, nonuniform doping and impact ionization effects.

Introduction

The MOS transistor models in the commercially available SPICE-like simulators have to be adapted to the requirements for improved accuracy in analog designs. It is important to have good models in all operating regions for the low- and high-frequency small-signal characteristics and for the noise. The increased number of analog applications which require low-voltage operation and low current consumption led to the development of special micropower techniques [1]; they take advantage of the weak inversion operation performance such as the maximum transconductance-to-current ratio, the minimum noise for a given current and the very low saturation voltage. Often the trade-off between the weak and strong inversion performance result in designs in the transition region called moderate inversion [2][3]. An adequate characterization of the weak and moderate inversion regions, with emphasis on the small-signal behavior are the main issues addressed by the model presented here.

Model description

The proposed model is based on the analytical solution of the semiconductor physics equations for the ideal MOS structure (long and large channel, uniform doping, constant mobility, etc.) for which a closed form approximation is obtained as in [4]. Then, these equations are adapted to include the extensions for the effects neglected in the ideal case, nevertheless maintaining their original form.

Closed form analytical expressions of the ideal MOS can be obtained only for the weak and strong inversion asymptotic regions. Nevertheless, both are functions of the same V_{GB} dependent pinch-off voltage V_P which is related to the weak inversion surface potential and corresponds to the cut-off of the channel charge in its strong inversion approximation; therefore a continuous moderate inversion transition can be obtained with a mathematically defined interpolation function, which for the DC current is:

$$I_{DS} = 2 \cdot n \cdot \mu \cdot C_{ox} \cdot \frac{W}{L} \cdot \left(\frac{k \cdot T}{q}\right)^2 \cdot \left\{ ln^2\left[1 + exp\left(\frac{V_P - V_{SB}}{2 \cdot k \cdot T/q}\right)\right] - ln^2\left[1 + exp\left(\frac{V_P - V_{DB}}{2 \cdot k \cdot T/q}\right)\right]\right\}$$

where *n* is the weak inversion slope. Notice that the current is expressed as the difference between two symmetrically defined forward and reverse components, as for the bipolar transistor; the saturation is reached asymptotically when the reverse current is much smaller than the forward current. Compared to the direct linking of the weak and strong inversion regions in SPICE level 2 and 3 models, or to the addition of a weak and a strong components in the BSIM model [5], the proposed interpolation function gives a much better moderate inversion transconductance to current ratio as shown in the Fig. 1.

Similar interpolation, as proposed by Enz [6], is used for the five internal capacitance model from [2] and for an improved thermal noise model; the flicker noise, expressed as in [1], is not bias dependent.

The model has been extended to include: mobility reduction for the transversal and longitudinal fields, threshold voltage modulation considering nonuniform doping and drain induced barrier lowering, short and narrow channel effects on a few selected parameters (body effect, zero bias threshold and vertical field mobility reduction), drain saturation voltage reduction due to velocity saturation, weak inversion slope adjustment for fast surface states and nonuniform doping, channel length modulation saturation current increase adapted to the output conductance model considering nonlinear drain voltage dependence and high current reduction, and, finally, the impact ionization substrate current. The linear to saturation transition continuity has been obtained defining, with an interpolation function, an effective drain voltage which is limited at its saturation value; it is used to limit the reverse current and to smoothen the channel length modulation and the velocity saturation effects. Temperature effects, junction current and capacitances, continuous extrapolations for the unphysical bias conditions which might occur during iterations, etc. have also been considered. The modular structure of the model allows for optional descriptions of the considered effects and of the mathematical interpolations. The model has been implemented in the ELDO® simulator from ANACAD using its UDM user definable model interface and has been successfully tested.

References

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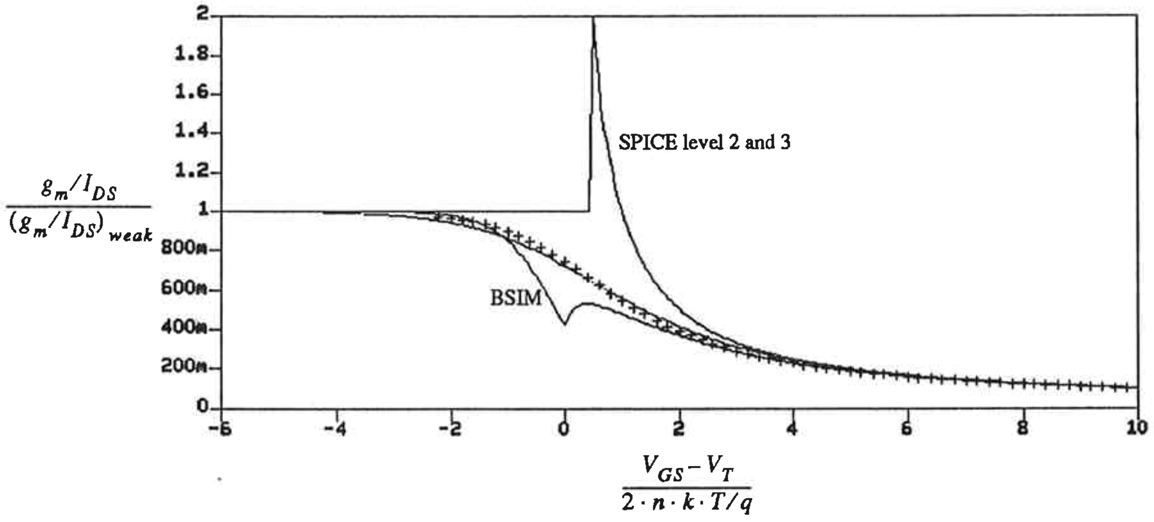

Fig. 1 Normalized transconductance-to-current ratio compared with measurements (+++) and with other models (BSIM and SPICE level 2 and 3)