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P2-13

A Self-Consistent Non-Quasi Static MOSFET Model for Circuit Simulation Based on Transient Carrier Response

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1. Introduction

Circuit simulations are usually performed under the quasistatic (QS) approximation, ignoring the carrier transit time along the channel. According to the increase of the operating speed, the QS approximation causes enormous error in simulation results as shown in Fig. 1.

The mostly applied non-Quasi Static (NQS) model is to separate the channel into n segments to include the carrier transit time in the channel [1]. However, this description requires enhanced calculation time due to the increase of the number of transistors to be considered. Additionally it is not clear whether the ensemble of the segmented transistors preserves the same characteristics as that of the original transistor. The other model approximates the channel charge response with the relaxation time, which is solved with an equivalent circuit [2]. However, the model cannot describe the charge deficit caused by the NQS effect. We present here a new NQS model for circuit simulation including the carrier transit time explicitly in a self-consistent way.

2. New Model Description

To include the NQS effect, the current equation has to be solved together with the continuity equation. The continuity equation considers the carrier position in the channel explicitly. Thus the transit delay τ of injected carriers from the source reaching the drain contact is included in the current as schematically demonstrated in Fig. 2. Final current equations are:

$$I_D(t) = \frac{W}{L}\mu\int_{\psi_{s0}}^{\psi_{sL}} Q_i(y,t)\,d\psi - \frac{W}{L}\int_0^L\int_y^L \frac{Q_i(y',t)}{dt}dy'\,dy \quad (1)$$

$$I_S(t) = \frac{W}{L}\mu\int_{\psi_{s0}}^{\psi_{sL}} Q_i(y,t)\,d\psi - \frac{W}{L}\int_0^L\int_0^y \frac{Q_i(y',t)}{dt}dy'\,dy \quad (2)$$

Both equations consist of the conductive current (the 1. term of RHS) and the displacement current (the 2. term).

The model development is reduced to derive a closed form of the carrier density $Q_i(y,t)$, which is usually done with a series of a trigonometric function [3]. Fig. 3 shows a 2D simulation result of $Q_i(y,t)$ by fixing the drain voltage (V_{ds}=1V) and switching on the gate voltage (V_{gs}) with the rise time of 20ps. We developed the description with the carrier transit time τ (see Fig. 2), which is calculated from the averaged carrier velocity in the channel, and is a function of the potential distribution. Here we approximate that the potential distribution in the channel reacts to the V_{gs} change immediately. The validity of this approximation is proved in Fig. 4 with a 2D simulation result. We model $Q_i(y,t)$ for two conditions separately: carriers are not yet reaching the drain contact ($t \leq \tau$) and after reaching ($\tau < t$). The final $Q_i(y,t)$ descriptions are:

i) $t \leq \tau$: $Q_i(0,t)$ follows the V_{gs} change immediately, and $Q_i(y,t)$ is linearly decreasing from $Q_i(0,t)$ to zero at

$$y = {}^{t}\!/_{\tau} \cdot L$$

in the channel, where L is the cahnnel length.

ii) $\tau < t$: Carrier delay between time step t_n and t_{n+1} at the drain contact is described

$$Q_i(L,t_{n+1}) = \left\{Q_i(L,t_{n+1,QS}) - Q_i(L,t_n)\right\}\cdot \left\{1-\exp\left(-\left(\frac{t_{n+1}-t_n}{\tau_{n+1}}\right)\right)\right\} + Q_i(L,t_n) \quad (3)$$

where $Q_i(L,t_{QS})$ is under the QS approximation.

For the $Q_i(y,t)$ calculation τ, $Q_i(0,t)$, and $Q_i(L,t_{QS})$ are required. The circuit simulation model HiSIM [4], based on the surface potential description, is used. Thus the consistency in the model description is preserved through the surface potential. Calculated τ is shown in Fig. 5, and $Q_i(y,t)$ with the developed description is depicted also in Fig. 3 for comparison. At the initial stage of the switching on the calculated $Q_i(y,t)$ distribution deviates from the 2D simulation result remarkably. At this stage a small current difference between the model calculation and the 2D simulation results in a huge difference in $Q_i(y,t)$. After entering the strong inversion condition the discrepancy disappears.

3. Results

Calculated drain current with our NQS model is also depicted in Fig. 1. Inclusion of the carrier transit delay in the channel describes the NQS phenomena satisfactory as can be seen from the smooth increase of the drain current and the asymptotic approach to the steady-state current.

Fig. 6 compares calculated conductive currents under the NQS and QS conditions (see Eqs. 1&2). Our results demonstrate obvious discrepancy between the NQS and QS conditions. Thus the widely accepted steady-state assumption for the conductive current even under the NQS approximation results in inconsistent estimation of $Q_i(y,t)$, disturbing consistent calculation of capacitances. This simulates incorrect circuit response even though the current response is correctly simulated.

4. Conclusions

We have developed a model for describing the carrier density distribution along the channel with the transit delay. The calculated transient current characteristics with the model describe the non-Quasi Static phenomena in a consistent way, allowing consistent capacitance descriptions at the same time.

Acknowledgments

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References

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[3] C. Turchetti, P. Mancini, and G. Masetti, IEEE J. Solid-State Circuit, SC21, 827, 1986.
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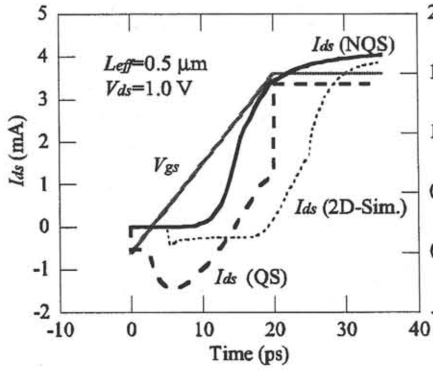

Fig. 1. Drain current *I*ds response for switching on the gate voltage V_{gs} calculated under the Quasi Static and non-Quasi Static approximations. For comparison a 2D simulation result is depicted together. The NQS wave form agrees well with the simulation result, though the simulation result includes extrinsic contributions such as contact resistances, which cause delay of the response.

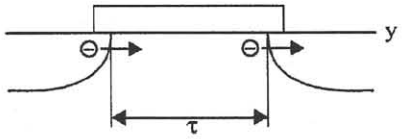

Fig. 2. Schematic for the origin of the non-Quasi Static effect. τ is the carrier transit time from source to drain.

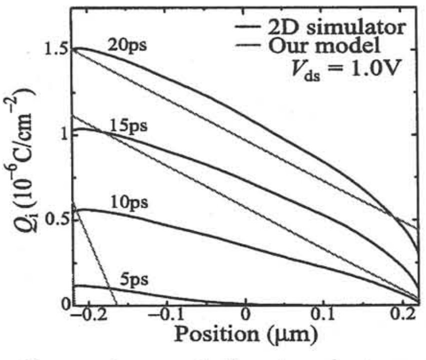

Fig. 3. Comparison of the transient carrier density distribution along the channel with a 2D simulator and our analytical model.

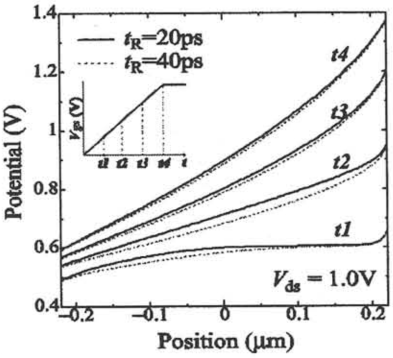

Fig. 4. Comparison of the potential response during switching on V_{gs} with two different switching speeds. Nearly the same response for the two different speeds proves the validity of the approximation of the immediate potential reaction to the V_{gs} change.

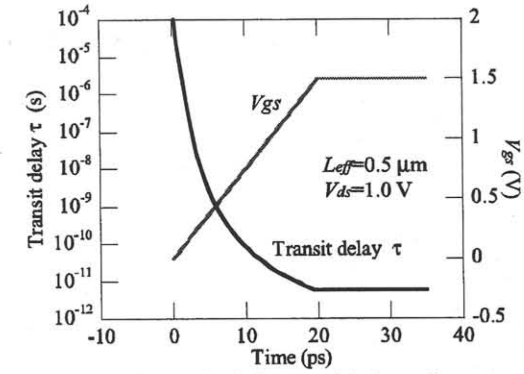

Fig. 5. Calculated transit delay τ of injected carriers from the source to the drain.

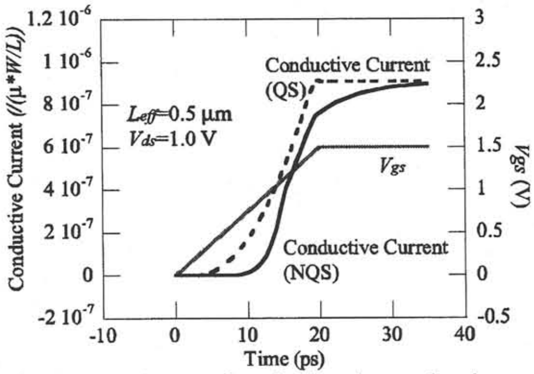

Fig. 6. Comparison of calculated conductive current under the Quasi Static and non-Quasi Static approximations.