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A Large-Signal MOSFET Model Based on Transient Carrier Response for RF Circuits

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1. Introduction

Aggressive shrinking of gate length of MOSFET has made it possible to use CMOS in RF domain. Recently, a one-chip full CMOS wireless circuit is demonstrated [1]. To facilitate RF CMOS circuit design, RF circuit simulators and tools should give an accurate behavior of MOSFETs in RF domain to designers. Specially, large-signal behaviors of MOSFET are important to simulate the RF circuits.

In the past studies [2-5], the large-signal model of MOSFET has already been developed. However these models have some problems in terms of accuracy, simulation time and complexity when implementing them into SPICE model.

In this paper, to overcome these problems, we propose a large-signal MOSFET model based on transient carrier density response. To calculate the transient carrier density response at certain time, a new device-physics-based calculation method is developed. The problem in accuracy does not occur in our model. Additionally, the problems in simulation time and implementing complexity have been also overcome. The details are described in section 3.

The accuracy of the developed model is compared with the device simulation results. The developed model can capture the device characteristics in RF domain accurately, and model description is very compact.

2. Non-Quasi Static and Quasi-Static Model

General circuit simulators are based on the quasi-static (QS) approximation. This approximation causes enormous error in simulation results with fast time varying. In QS approximation, the carriers are supposed to be able to respond to the fast time variation without any delay time. However the carriers cannot respond instantaneously in real devices. This behavior is, in general, called as non-quasi static (NQS) effect. The limitation of QS approximation is demonstrated in **Fig.1**. The dashed line and open square symbols show the result simulated under QS approximation by a general model and by a device simulator, respectively.

The past models [2-5] have been applying the Elmore resistance [2] and/or segment model [3] to overcome the limitation of QS approximation (schematic image is shown in **Fig.2**). However, these models have the problems in accuracy and complexity when implementing them into SPICE model. The recent models [4-5] calculate a carrier position and its density at a certain time. This approach requires not only much simulation time but also a special numerical method such as Runge-Kutta method.

3. Developed Model Description

We developed an advanced model to overcome these problems. Node current is described as following equation.

$$I_{node}(t) = I_{node,0} - \left.\frac{\partial Q_k(t)}{\partial t}\right|_{k=G,S,D,B} \qquad (1)$$

Where, $I_{node,0}$ is a static current. The second term shows the transient current generated by time-varying node charge. Each node charge can respond to the voltage variation in finite time. This finite time is called as the carrier relaxation time (CRT). This CRT value is directly linked to the carrier mobility in a channel. When calculating the transient drain current at a certain time, carrier position is not important, since no information about carrier position is included in equation (1). However, it is important to predict the carrier density in the node at a certain time for calculating the node current. Thus, we developed the following equation as a predictor of the carrier density at a certain time.

$$S_{carr}(t,V_D) = \frac{\alpha_{low} - \alpha_{high}}{1.0 + \left(\frac{t}{\tau_{cond}}\right)^p} + \alpha_{high} \qquad (2)$$

The coefficient of the carrier density α_{low} and α_{high} are determined by a bias condition. For example, when we calculate a transient drain current, these values are calculated by the following equations.

$$\alpha_{high} = \frac{Q_d(V_G, V_D)}{Q_d(V_{G,high}, V_D = 0.0)} - 0.5 \qquad (3)$$

$$\alpha_{low} = Q_{d0}\left[\beta(V_{D,high} - V_D)\right] + Q_{doff} \qquad (4)$$

Where, β is the inverted thermal voltage. The Q_d is physically determined at a certain gate voltage V_G and drain voltage V_D. $V_{G,high}$ and $V_{D,high}$ is the maximum voltage of gate and drain terminals, respectively. Q_{d0} and Q_{doff} are uniquely determined if a substrate concentration of MOSFET had been given. And, CRT τ_{cond} and the power coefficient *p* in equation (2) are determined by a carrier response to the fast voltage variation. Their behaviors are shown in **Fig.3** and **Fig.4**, respectively, and the equations to lead them are described in each figure. The power coefficient *p* saturates at high drain voltage region due to the velocity saturation of carriers.

4. Results and Discussion

The calculated drain charge density using the developed predictor $S_{carr}(t,V_D)$ at V_D=1.3 [V] and V_D=0.4 [V] are shown in **Fig.5** and **Fig.6**, respectively. The carrier density is normalized by the source charge density. The developed model can predict the carrier density at a certain time, and has the scalability to the drain voltage. We simulated a transient current. The results including the parasitic capacitance response are shown in **Fig.7** (V_D=1.3 [V]) and **Fig.8** (V_D=0.4 [V]). The results fit the simulated results of a device simulator well. The mean square error of the results is 5.06 %. We summarize the comparison results with the past studies [2-4] in accuracy and the number of calculation step from initializing to final drain current in table-1. Finally, we show transient currents of all the terminals (drain, source and gate) in **Fig.9** and **Fig.10** in the case of ramp-up and ramp-down, respectively. Our model can capture all current components precisely.

3. Conclusions

In this paper, a large-signal NQS model using a predictor for RF CMOS circuit simulation has proposed. This model can give an accurate current and transient carrier density response. Also, this model does not have the problems in accuracy and calculation time. Consequently, the developed model is very effective for RF CMOS circuit design.

4, Reference

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[2] M. Chan, *et al*, IEEE Trans., ED-**45** (1998) 834
[3] A. J. Scholten *et al*, IEDM Tech. Dig., (1999)
[4] W. Liu, *et al*, IEDM Tech. Dig., (1996)
[5] H. Wang, *et al*, IEEE Trans., ED-**50** (2003) 2262

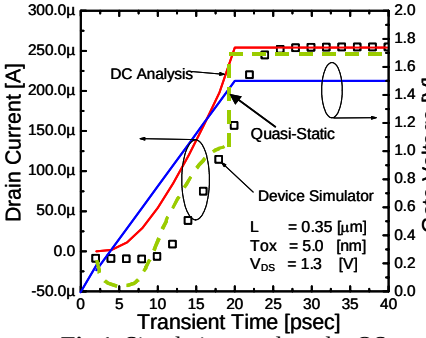

Fig.1, Simulation result under QS approximation. Enormous error is observed in result.

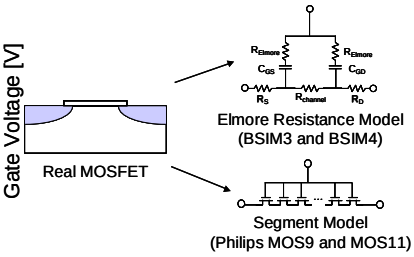

Fig.2, A concept of the past models on NQS approximation

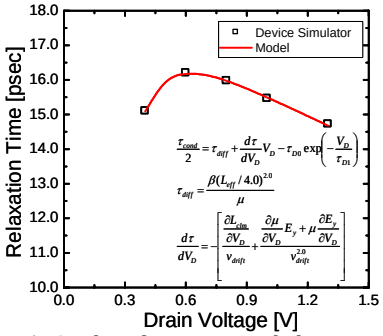

Fig.3, The relaxation time behavior at certain drain voltage, and model equation. The model fits the extracted data well.

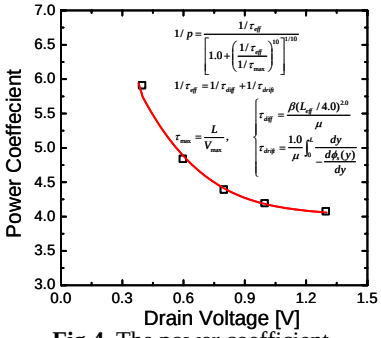

Fig.4, The power coefficient behavior at certain drain voltage, and model equation.

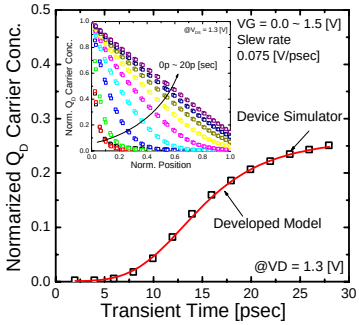

Fig.5, The integrated carrier density at high-field. The model can depict the transient carrier response.

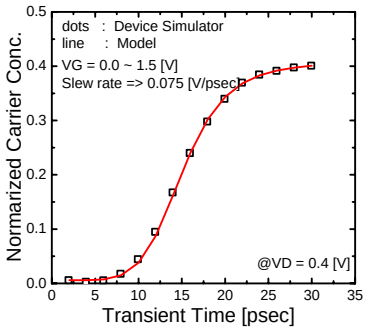

Fig.6, The integrated carrier density at low-field. The model can depict the transient carrier response.

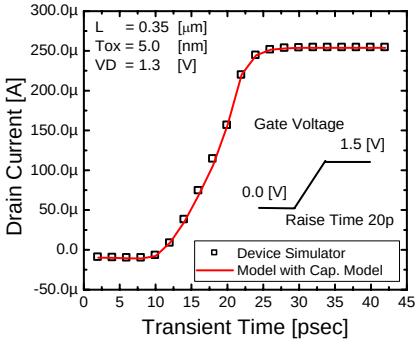

Fig.7, The simulated transient drain current with capacitances response at high-field.

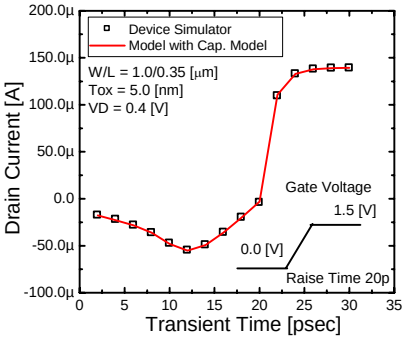

Fig.8, The simulated transient drain current with capacitances response at low-field.

Table-1, The summary about the mean square error and calculation steps from initializing to final current.

	Error [%] (Drain Current)	Number of Step
Our Model	5.06	5 (Predictor)
Ref. [2]	138	3 (Elmore)
Ref. [3]	<3	>11 (Segment)
Ref. [4]	12	7 (Runge-Kutta)

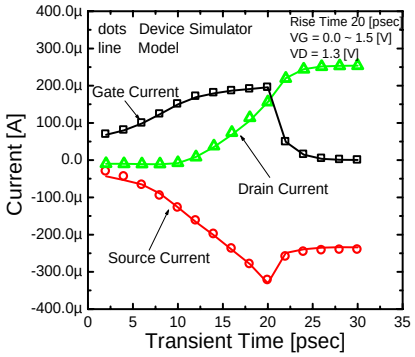

Fig.9, The simulated all transient currents in the case of ramp-up.

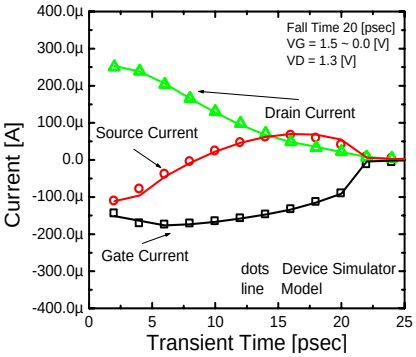

Fig.10, The simulated all transient currents in the case of ramp-down.