Modeling CMOS Non-Quasi-Static Effects in a Quasi-Static Simulation Engine

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Abstract: -This paper gives an overview on the difficulties in developing a non-quasi-static MOSFET model for circuit simulation. Some approximate solutions to capture the device behavior and their deficiencies are discussed. The physically correct approach to handle non-quasi-static effects and the limitation imposed by device simulation engine is also explained.

Introduction

Most MOSFET models available in circuit simulators are Quasi-Static (QS). That is, we assume all charges and currents are dependent only on the terminal voltages $V_x(t)$ alone and without explicit dependent on time. It is because most circuit simulation engine are based on solving a system of linear equations in a matrix format, and the construction of linear circuit systems does not include an explicit variable that involve time. The accuracy of the QS approach has been questioned with increasing circuit switching speed, and there is a demand for a model that can predict a switching even using a Non-Quasi-Static (NQS) methodology. However, due to the limitation of simulation platform, most existing NQS models are only partial solutions to the problem.

NQS Effect in Large Signal Transient Simulation

The most significant problem in QS model when handling fast switching circuits is shown in Fig. 1. Considering a MOSFET switching from off-to-on, the QS model decomposed the current into a transport current and a charging current. The drain current of a MOSFET is thus given by

$$i_D(t) = I_D\left(V_{D,S,G,B}(t)\right) + \frac{dQ_D\left(V_{D,S,G,B}(t)\right)}{dt} \quad (1)$$

The transport and charging current components are shown in Fig. 1(a), and their superposition is shown in Fig. 1(b). However, correct response which is also shown in Fig. 1(b), indicating the deficiency of the QS model. To understand the NQS behavior without going through the complex mathematics, the channel charge evolution during fast turn-on is shown in Fig. 2, indicating the total current is not dependent on the external voltage alone. Thus, the correct equation used should be

$$i_D(t) = i_{DT}\left(v_{D,S,G,B}(t), t\right) + \frac{dq_D\left(v_{D,S,G,B}(t), t\right)}{dt} \quad (2)$$

That is, the transport current is not equal to the DC current. In addition, the evaluation of channel charging current from source and drain requires a dynamic charge partition model, which depends on the switching speed as shown in Fig. 3. Calculating both current components accurately has been shown to be extremely difficult.

Most reported NQS models [1][2] use some approximation, which is based on the concept of breaking a long transistors into a number of smaller ones or introducing a distributed RC network as shown in Fig. 4(a). Some approximate models are shown in Fig. 4(b). The models give a more accurate estimate of the switching delay. However, the calculation of channel charge remains incorrect and the problem of dynamic charge partition are not addressed. The results of the distributed RC approach is the negative current at the beginning of the turn on as shown in Fig. 5.

The exact description of NQS effect can be formulated by the continuity equation apply to the a small region in the channel, which is given by:

$$\frac{\partial i(y,t)}{\partial y} = W\frac{\partial q_i(y,t)}{\partial t} \quad (3)$$

Relating charge and current to channel voltage, we have

$$q_i(y,t) = -C_{ox}\left(v_{GB}(t) - V_{FB} - \phi_0 - v_{CB}(y,t) - \gamma\sqrt{\phi_0 + v_{CB}(y,t)}\right) \quad (4)$$

and

$$i(y,t) = -\mu W q_i(y,t)\frac{\partial v_{CB}(y,t)}{\partial y} \quad (5)$$

Equations (3)-(5) are the governing equation for NQS effects with 3 unknowns, which theoretically can be solved. In practice, these equations are extremely difficult, if not impossible, to be included explicitly existing simulation platform. NQS effects modeling in large signal transient remains as an interesting research topics.

NQS Effect in Frequency Domain Simulation

NQS AC models have been proposed by a number of researchers [3]. However, strictly speaking, NQS effect does not exist in AC or frequency domain simulation. NQS effects arise from the approximation of terminal charges and currents at terminal voltages $v_{D,S,G,B}(t)$ and time t with that at the same voltage but at $t=\infty$. That is, the DC equilibrium value is used to approximate a transient result. However, in small signal AC simulation, all charges have achieved DC equilibrium as shown in Fig. 6, and the bias current is given by that in equation (1). The result of a distributed RC approach is shown in Fig. 7 indicating the accuracy increases with number of transistor segments. Frequency domain simulation, is thus not limited by the simulation engine and easier to tackle than the transient large signal case. Due to the different assumptions used, converting transient to frequency response with Fourier transform gives different result from direct AC simulation if NQS effect is considered.

Conclusion

NQS effects are due to non-equilibrium condition during transient and explicit time dependent of terminal charge and current is necessary to correctly model it. It is often confused with high frequency effects, which is really not NQS effects. While there is no simple solution to accurately model NQS effects in transient due to the QS nature of the simulator, AC behavior can be modeled by a simple equivalent RC network.

Acknowledgement

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References

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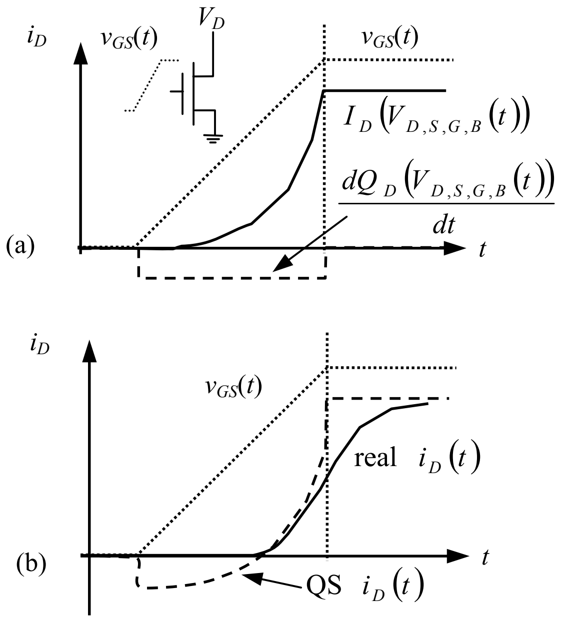

Fig. 1: Qualitative sketch of turn on characteristics of a MOSFET (a) showing individual transport and charging components of the drain current and (b) the total drain current from QS model and exact solution

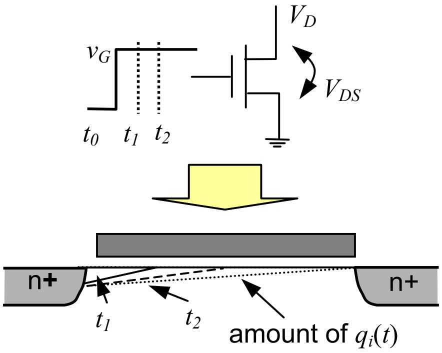

Fig. 2: Illustration of the channel charge under a fast input voltage at 2 different time with the same terminal voltages but different amount of channel charge

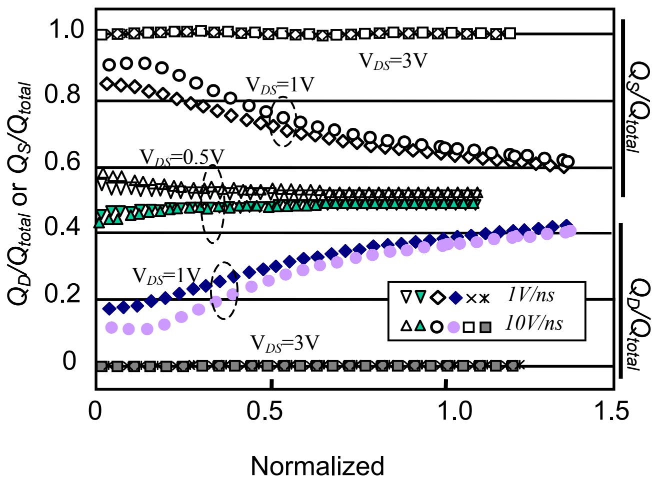

Fig. 3: Charge partition ratio during MOSFET turn-on at different drain voltage with different ramp rate. At high V_D, the charge partition ratio is close to 0/100 instead of the popular 40/60 calculated with geometry consideration

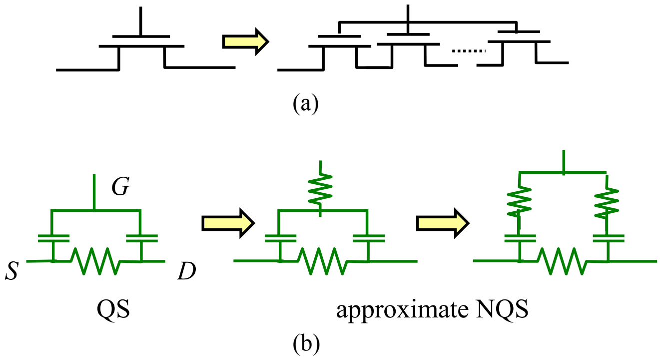

Fig. 4: (a) the concept of dividing a long channel MOSFETs to a number of shorter MOSFETs in series to take care of the RC distributed network in the channel and (b) the approximate model for (a) using a lumped RC circuit to approximate the distribute network

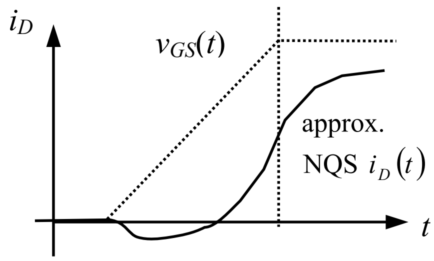

Fig. 5: Transient response of the approximate NQS model given in Fig. 4, which still shows a negative current at the beginning of turn-on that does not exist in the exact solution in Fig. 1(b)

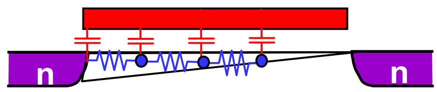

Fig. 6: Equilibrium RC network used in AC simulation. The channel charge has already achieved equilibrium and simple constant values for R's and C's calculated from the DC equilibrium condition is sufficient to predict the AC performance

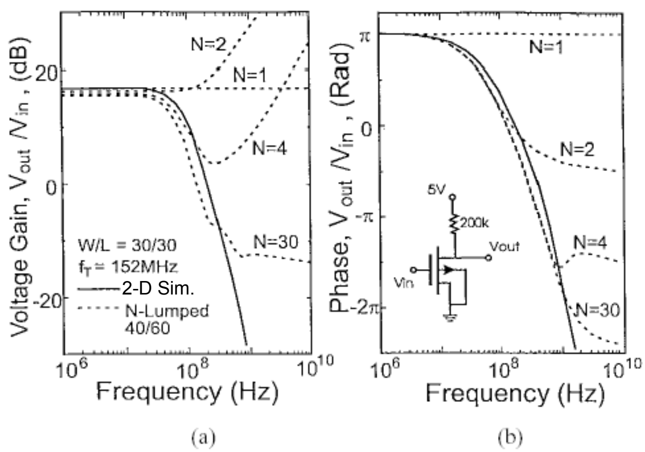

Fig. 7: Frequency response of a resistive load NMOSFFET common source amplifier using the distributed model by breaking down a long device into N shorter ones. The accuracy increase with the number of division