CHAPTER 5: Non-Quasi Static Model

5.1 Background Information

As the MOS transistor becomes more performance-driven, the need to accurately predict circuit performance operating near device cut-off frequency becomes more essential as well. However, most device models available in circuit simulators such as SPICE fall short this need. They include models which are formulated upon Quasi-Static (QS) assumptions. In other words, the finite charging time for the inversion layer is ignored. When these models are used with the common 40/60 charge partitioning option, unrealistically large drain current spikes frequently occur [31]. In addition, the inability of these models to accurately simulate channel charge re-distribution causes problems in fast switched-capacitor type circuits. Many Non-Quasi-Static (NQS) models have been published, but these models have two shortcomings: 1) they assume, unrealistically, no velocity saturation, and 2) They are complex in their formulations; intuitive insights into NQS effects and solutions are lost. In addition, these models increase circuit simulation times by 4 to 5 times.

5.2 The NQS Model in BSIM3v3

BSIM3v3 includes a physical NQS transient model which alleviates the above problems. Although it is a physical model that takes in account velocity saturation effects, it is conceptually simple to understand because its formulation is based on familiar channel relaxation principles.

5.3 Model Formulation

The channel of a MOSFET is analogous to a bias dependent RC distributed transmission line (Figure 5-1a). In the Quasi-Static (QS) approach, the gate capacitor node is lumped with both the external source and drain nodes (Figure 5-1b). This ignores the finite time for the channel charge to build-up. One Non-Quasi-Static (NQS) solution is to represent the channel as *n* transistors in series (Figure 5-1c). This model, although accurate, comes at the expense of simulation time. BSIM3v3 uses a more efficient approach formulated from the circuit of Figure 5-1d. This Elmore equivalent circuit models channel charge build-up accurately because it retains the lowest frequency pole of the original RC network (Figure 5-1a). To accommodate this new NQS model, two new parameters are introduced (See Table 5-1).

Name	Function	Default	Unit
NQSMOD	Flag for the NQS model	0	(False)
ELM	Elmore constant of the channel	5	none

Table 5-1. New NQS model parameters.

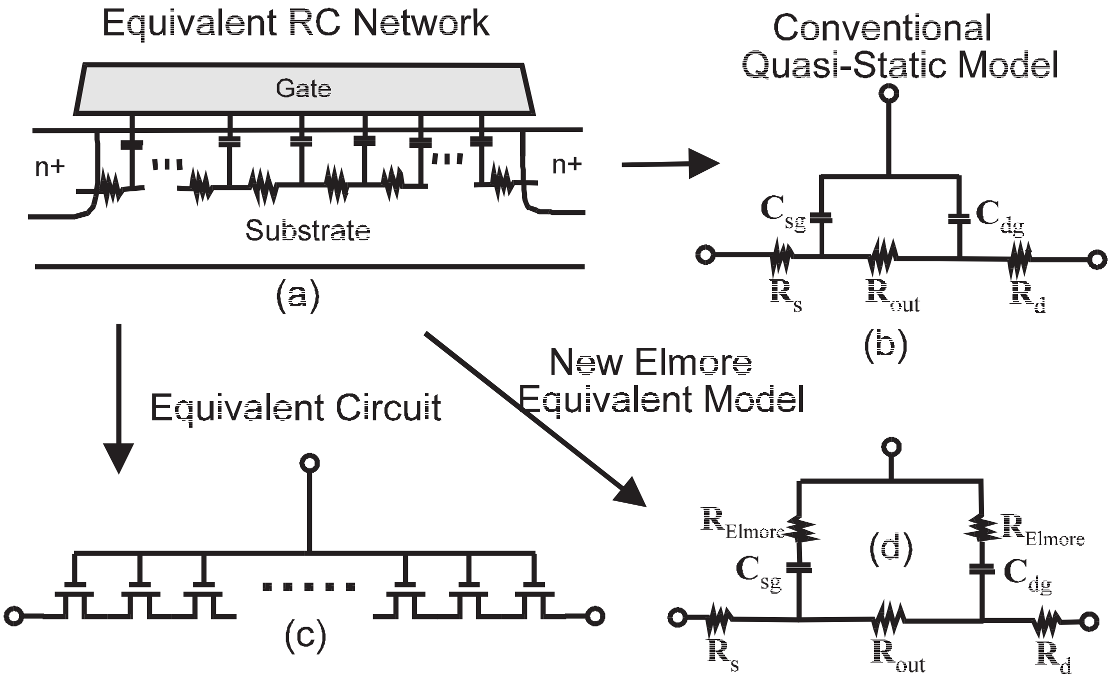

Figure 5-1. Quasi-Static and Non-Quasi-Static models for SPICE transient analysis.

The NQS model also includes the use of the model parameter Xpart (usually associated with the A.C. model) to control charge partition to the source/drain. In BSIM3v3, the Elmore resistance, R_{Elmore}, is calculated from the channel resistance under strong inversion as:

(5.2.1)

$$R_{Elmore} = \frac{L_{eff}^2}{\varepsilon\mu_{eff} Q_{ch}} \approx \frac{L_{eff}^2}{\varepsilon\mu_{eff} Q_{cheq}}$$

where ε is the Elmore constant of the RC network in the channel with a theoretical value close to 5. Q_{ch} is the actual channel charge in the channel and Q_{cheq} represents the quasi-static equilibrium channel charge. The value $R_{Elmore}C_{Channel}$ is the relaxation time constant for charging and discharging the channel. Under strong inversion, the conduction is mainly due to drift current. As such, the relaxation time constant due to drift current is given by:

$$\tau_{drift} \approx R_{Elmore} C_{ox} W_{eff} L_{eff} \approx \frac{C_{ox} W_{eff} L_{eff}{}^{3}}{\varepsilon \mu_{eff} Q_{cheq}} \tag{5.2.2}$$

Under weak inversion, conduction is mainly due to diffusion current. The relaxation time constant can be approximated by:

$$\tau_{diff} \approx \frac{q(L_{eff}\ /\ 4)^{3}}{\mu_{eff}\, kT} \tag{5.2.3}$$

The overall relaxation time for channel charging and discharging is given by the combination of both the diffusion and the drift terms:

$$\frac{1}{\tau} = \frac{1}{\tau_{diff}} + \frac{1}{\tau_{drift}} \tag{5.2.4}$$

Using this relaxation time concept, the NQS transient effect in BSIM3v3 is implemented with the subcircuit given in Figure 5-2. The parameters X_d and X_s are the charge partition allocated to the drain and source and are assigned values of 0.4 and 0.6, respectively.

The state variable, Q_{def}, is an additional node created to keep track of the amount of deficit (or surplus) channel charge necessary to achieve equilibrium . Q_{def} will decay exponentially into the channel with a bias dependent NQS relaxation time τ. The derivative of Q_{def} with respect to time is the gate charging current. This gate current is partitioned into separate drain and source current components. A complete list of all NQS model equations is provided in the Appendix.

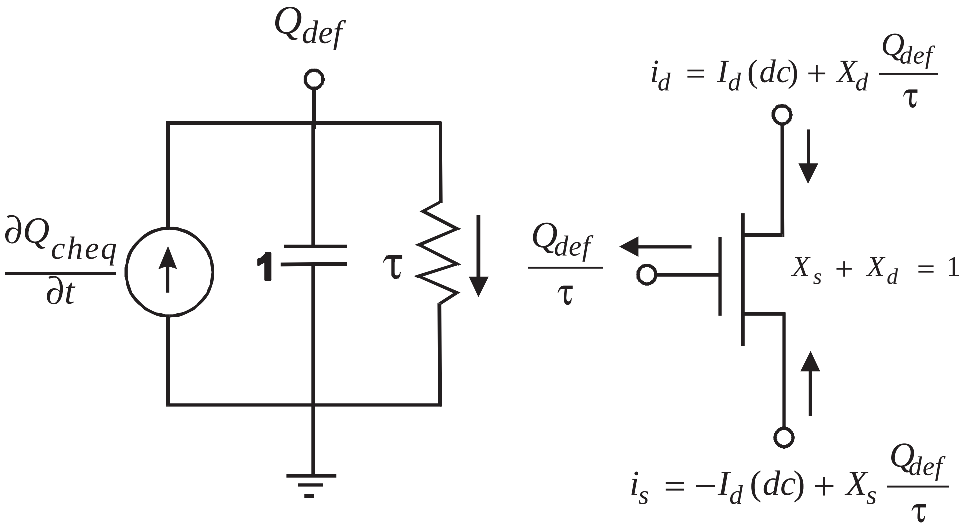

Figure 5-2. NQS subcircuit implementation in BSIM3v3.