ANALYSIS AND MODELING OF NQS Effects in MOSFET's

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ABSTRACT

Three issues regarding NQS effect in MOSFET's are investigated: starting point at which NQS effect becomes significant, NQS effect on channel charge partition, and NQS model implementation in advanced MOSFET models (PSP, Hisim2 and Bsim4). The starting point of NQS is found to be consistent with device current unit-gain frequency (ft). It is found that almost no charge is partitioned to drain side in saturation region at very high frequency. Three NQS implementation approaches are compared includinginternal node approach, hidden state approach and Spline correlation approach. It is proved that the intenal node appraoch and hidden states approach are theoretically equivalent.

Keywords: NQS effect, MOSFET, charge partition, compact model, circuit simulation

1 INTRODUCTION

As the development of semiconductor technology and increase of circuit performance, switching speed of MOSFET in integrated circuits is getting faster and faster. Especially in RF application where long channel devices are common in the ciruict, signal rising or falling speed is comparible to the intrinsic response time of the charge redistribution in channel. In this case, quansi-static (QS) models widely used in circuit simulation are not able to capture the right trainsient behavior of MOSFET's, thus cause accuracy problem in circuit simulation. Therefor, many investigations are put on NQS (Non-Quai-Static) effect on MOSFET behavior and different NQS models are developed [1~4].

Despite many of the theoretical investigation and modeling development efforts, there are basically three different approaches of NQS model implementation in popular cormertially available compact models for circuit simulation. That is, the relaxation time based RC network approach in Bsim model [5], the delay based hidden states approach in Hisim model [6] and spline correlation based approach in SP/PSP models [2]. Yet, another more physical based model for circuit simulation is the channel segments based approach proposed in [7]. In this paper, using the channel segments approach given by [7], two important issues in NQS effects are analyzed including the starting point of NQS effect and its scaling characteristics, and the NQS effect on channel charge partition. Then the three approaches used in compact model implementation are compared and their advantages and disadvantages are discussed in detail.

2 MOSFET'S NQS EFFECTS AND MODELING

Usually, people use QS model to model channel charge. QS model assumes that the channel charge is solely determined by terminal biases of the device, no matter how fast the terminal biases are changing. In reality, the change of channel charge always has a delay following the change of termimal biases. This is the cause of NQS effects.

A straightforward approach to model NQS effect in MOSFET is to use channel segments method [7]. In this approach, channel of the MOSFET is divided into multiple parts. Each part is modeled as a short channel MOSFET. Then the delay machanism (NQS effect) is handled by interaction between different parts automatically. Short channel effect, overlap capacitance and serial resistance as well parasitic diodes are removed in the setment short MOSFET, so that the segments can model the intrinsic part of the channel properly. According to the investigation in [7], 10 segments are used in the investigation to ensure the accuracy.

2.1 Starting Point of NQS Effects in MOSFET's

The nature of NQS effect is delay of channel charge distribution following change of terminal biases. This delay is more severe for devices with longer channel. In this section, we will analyze when the NQS effect on device behavior becomes non-negaligible. That is, the dependence of NQS effect on channel length and frequency of the terminal signals.

As shown in figure 1, a simple single MOSFET circuit is used in the investigation. Drain is biased at zero voltage, and gate is biased at strong inversion region. Small signal input is added to drain node, and trainsient simulation, rather than AC simulation is used. One can not use AC analysis in NQS investigation because AC algorithm in spice linearizes the devices at DC biases and then the non-linearity of the device is ignored. Gate current is used as measurement of the channel charge modulation by drain volgate. Using gate current rather than drain/source current can eliminate the influence of DC drain current component

caused by drain biases, so that the charge dynamic behavior can be seperated from DC current.

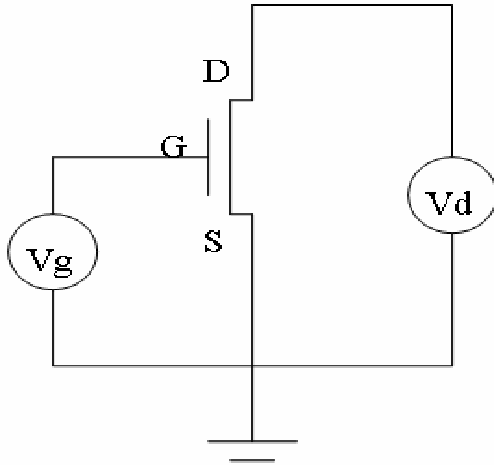

Figure 1: Circuit used in NQS effect investigation.

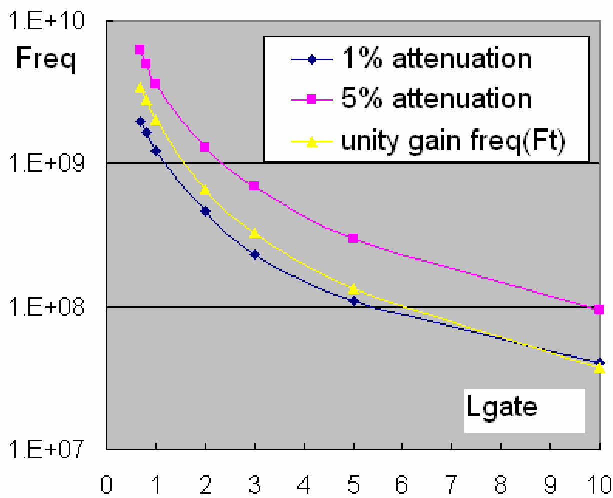

Figure 2: Channel length dependency of frequency point at which gate current is attenuated by 1% and 5% in NQS case compared with QS case. Also plotted is the unity current gain frequency of the devices (ft)

Due to the delay of channel charge distribution following ternimal biases changes, in NQS case (using 10 segments channel) gate current is less than that in QS case. The frequency point at which gate current is attenuated by 1% and 5% as measurement of NQS strength are plotted in figure 2, together with the unity current gain frequency of the same device (ft). Figure 3 gives the results of 1% and 5% attenuation point unified with ft. It can be seen that the 1% attenuation point is in the range of 50% and 100% of ft for the devices with gate length from 0.4um to 10um. And the shorter of the channel length, the lower of the percentage of NQS attenuation with respect to ft. This means using QS approximation is causing only a few percents deviation from NQS model provided that the device works in a lower frequency range than unify current gain frequency. This is consistent with the conclusion got from [8].

The delay of channel charge distribution also causes phase shift in gate current. Figure 4 gives the relative phase shift results (scaled with signal frequency) with respect to frequency for devices with different channel lengths. Figure 5 is the 1% and 5% relative phase shift frequency together with the unity current gain frequency point. Similar conclusion can be drawn from phase shift as that from amplitude attenuation.

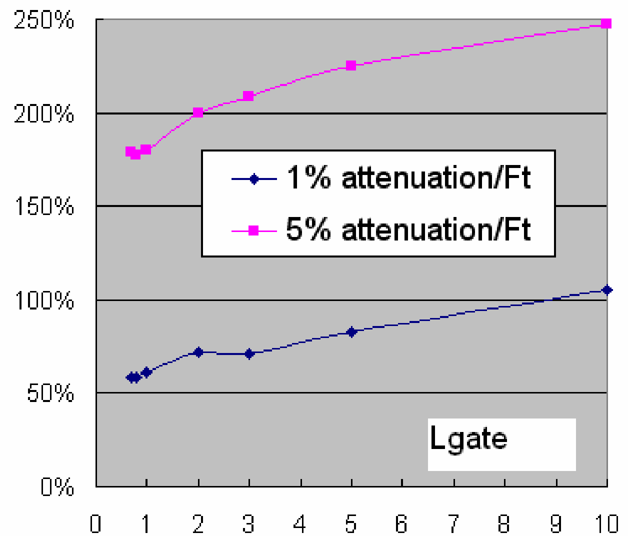

Figure 3: Same results of figure 2 scaled with unity current gain frequency (ft).

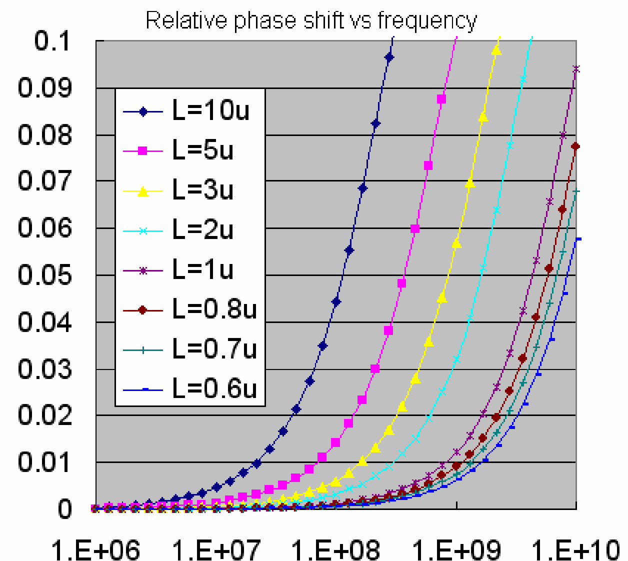

Figure 4: Gate current phase shift due to NQS effect at different frequency for devices with different channel lengths.

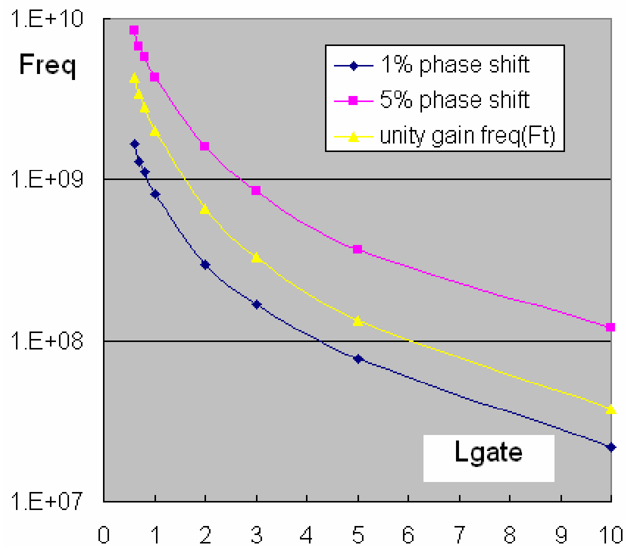

Figure 5: 1% and 5% phase shift frequency point as function of device gate length together with unity current gain frequency (ft).

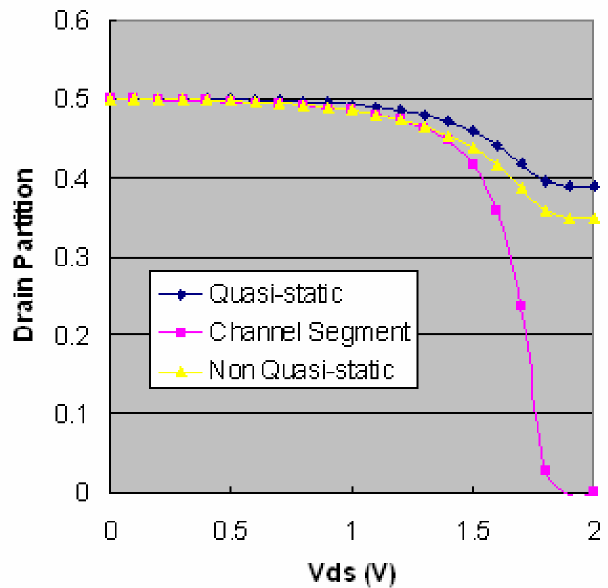

Figure 6: Channel charge partition to drain side as function of drain voltage. Frequency is 1e9Hz, Lgate=10um, Wgate=20um.

2.2 NQS Effects on Channel Charge Partition

In compact models, channel charge has to be partitioned to drain part and source part. Usually people use 40/60 partition, i.e. 40% of the channel charge is partitioned to drain side and 60% of the channel charge is partitioned to source side, which is the most physical scheme. In order to eliminate some unphysical behavior, like huge drain current during switch, 0/100 partition scheme is also used by designer [5]. In this section, the NQS effect on channel charge partition is examined.

Same circuit as shown in figure 1 is used for this investigation. Again, gate is biased to strong inversion region. The small signal is applied to gate and drain voltage is swept from zero to Vdd. Then small signal Is (source current) and Id (drain current) are probed. The charge contribution to the small signal current is got from total small signal current minus the part from DC current contribution. Then $Idac/(Idac+Isac)$ represents the channel charge partition to drain side. As shown in figure 5, QS model gives an estimation of 39% drain partition at saturation region, while the channel segment approach gives the results of around 0%. This means almost no charge is partitioned to drain side in saturation region at very high frequency due to NQS effect, and thus the 0/100 partition method gives correct estimation. Also provided are the results with analytical NQS model simulation, which gives about 35%. Although the analytical NQS model correctly predicts the trend of channel charge partition caused by NQS effect, it is far away from the results using channel segment approach.

2.3 NQS Model Implementation in Compact Models for Circuit Simulation

Although the channel segment approach can be used as a general method for NQS modeling in circuit simulation, its usage is limited due to performance and usability. Use N segments will increase by N times the number of devices which need consider NQS effect. And special handling in device model is needed to use channel segment approach as explained in [7] and in beginning of this section. So, build-in analytical approach for NQS effect is necessary.

Among the popular compact models (Bsim, PSP, Hisim), there are three different approaches to implement NQS effect in compact model for circuit simulation. Bsim3/Bsim4 models are using relaxation based RC network approach [5] for NQS effect, while Hisim model is using delay based hidden state approach [6] to model NQS effect. It will be shown that the two approaches are theoretically equivalent with advantages and disadvantages from either side. The key concept in Bsim NQS model is defit charge defined with [5]:

$$Q_{def}(t) = Q_{cheq}(t) - Q_{ch}(t) \tag{1}$$

Q_{cheq} is the channel charge at eqilibrium and Q_{ch} is the real channel charge at certain time. The deficit charge is controled by:

$$\frac{\partial Q_{def}(t)}{\partial t} = \frac{\partial Q_{cheq}(t)}{\partial t} - \frac{Q_{def}(t)}{\tau} \tag{2}$$

In Bsim models, a RC network is used to get Q_{def} by solving equation (2). It will be shown here that an equivalent implementation can be done by hidden states.

From equation 2, after descritization, we get:

$$\frac{Q_{def}^{j+1}-Q_{def}^{j}}{t_{j+1}-t_{j}}=\frac{Q_{cheq}^{j+1}-Q_{cheq}^{j}}{t_{j+1}-t_{j}}-\frac{Q_{def}^{j+1}+Q_{def}^{j}}{2*\tau} \quad (3)$$

Then once the values of Qdef and Qcheq at last time point were stored (hidden states), we can calculate Qdef at current time point by:

$$Q_{def}^{j+1}=\frac{Q_{cheq}^{j+1}-Q_{cheq}^{j}+Q_{def}^{j}*\left(1-\frac{t_{j+1}-t_{j}}{2*\tau}\right)}{1+\frac{t_{j+1}-t_{j}}{2*\tau}} \quad (4)$$

Hisim models using a similar hidden states approach for its NQS modeling. In nature this approach is equivalent with the RC network approach used in Bsim models. However, they have subtle differences in circuit simulation. Using RC network approach Q_{def} represented by the voltage of the internal node, is solved together with all the other circuits states during the solving the circuit equations. So that the accuracy of Q_{def} is controlled by different integration method and time step control algorithms using in circuit simulator. However, in the hidden states approach, the integration method is fixed, and the interaction between the hidden states with time step control algorithms is ignored. So, generally speaking, RC network approach has better accuracy. Advantage of the hidden states approach is the fact that an extra internal node is not required. So the circuit equation number is reduced and the performance is expected to be better than RC network approach.

PSP/SP models use spline correlation method to model NQS effects. The advantage of this approach is its flexibility of choosing number of the order used in NQS model so that it can potentially provide higher accuracy. It is expected that the speed is lower for higher order model. But the trade-off between accuracy and speed is completely controlled by user through model flag.

3 CONCLUSIONS

Channel segment approach is used to investigate NQS effect on MOSFET's behavior. It is demonstrated that both amplitude attenuation and phase shift of the gate current can be used as indicator of NQS effect strength. For a device with certain channel length, frequency at which NQS effect causes noticeable difference is consistent with the unity current gate frequency (ft) of the device. It is also shown that NQS effect has more profound influences on channel charge partition than that modeled with either QS approximation or analytical NQS approach. Almost no charge is partitioned to drain side by fully taking into consideration of NQS effect at very high frequency. Three approaches of NQS model implementation in compact models: RC network approach, hidden states approach and spline correlation approach are discussed. It is shown that the first two are theoretically equivalent and have their own advantage and disadvantages respectively. Spline correlation method has more capability to modeling higher order NQS effects due to its flexibility, while its performance might not be good if higher order formula is chosen.

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