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Evaluation of the Impact of Non-Quasi-Static Effects in RF Applications

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1. Introduction

The high demand of integrated RF systems has driven the use of CMOS circuits in high frequency operations. The most popular small signal AC simulation methodologies used in SPICE based on Quasi-Static (QS) approximation that the channel charge of the MOS transistor can achieve equilibrium instantaneously once input varies [1]. However these models cannot predict the circuit behavior correctly in high frequency simulation, such as RF circuits, due to the Non-Quasi-Static (NQS) effects [2]. Many reports have already illustrated the problem of ignoring the NQS effect in high frequency simulation [2], [3]. A number of NQS models have been proposed [4] these models are usually very complicated that significantly slower. Therefore these models should be avoided unless the operating frequency of device really entered the NQS regime. It is thus important to provide a guideline on the boundary between QS and NQS operation for effective and efficient circuit simulation.

In this paper, we have investigated the NQS effects of a MOSFET under small signal operation by 2-D device simulator. By directly comparing the actual amount of charge in the channel and the amount of charge predicted by the QS assumption at different frequency, the degree of NQS behavior can be evaluated. A guideline on the frequency range that the QS model is applicable will be given based on the tolerant of a circuit to the NQS effect. It is found that the QS models are sufficient for most of the practical circuits.

2. Methodology

To evaluate the seriousness of the NQS effect, a MOSFET as shown in Fig. 1 is constructed for 2-D simulation. With the same channel doping concentration and gate oxide thickness, MOSFETs with different channel lengths are studied. To evaluate the small signal response, a DC bias is first applied to the gate of the MOSFET to ensure it is in strong inversion condition. On top of the DC bias, a small time varying AC signal is applied to the gate. The total amount of inversion charge in the channel due to the AC signal (DC value subtracted) as a function of time $Q_{inv}(\omega t)$ is measured. At very low frequency, $Q_{inv}(\omega t)$ follows the AC signal (QS prediction). As the frequency is increased, we expect the amplitude and phase of $Q_{inv}(\omega t)$ to deviate from the QS condition. The difference in the instantaneous inversion charge $Q_{inv}(\omega t)$ and the time-normalized inversion charge $Q_{inv0}(\omega t/\omega_0)$ at low frequency (ω_0) gives the degree of NQS effect under a given operation condition.

3. Simulation Results

Fig. 2 shows the variation of inversion charge with normalized time in responds to AC signal with different frequency for a 5μm MOSFET. The amplitude and phase of $Q_{inv}(\omega t)$ varies with frequency indicating the inversion charge cannot follow the applied signal (NQS condition). The QS approximation is valid at the frequencies that $Q_{inv}(\omega t)$ only deviate slightly from $Q_{inv0}(\omega t/\omega_0)$.

Defining R as the ratios of the amplitudes between the instantaneous inversion charge and the inversion charge at low frequency and ϕ as the phase delay of the instantaneous inversion charge $Q_{inv}(\omega t)$ to the applied signal. The dependence of R and ϕ with frequency for devices (in linear region) with different channel lengths is shown in Fig. 3. Similar plots for devices working in saturation region are shown in Fig. 4. The onset of NQS effect can be observed from the point that R drops from unity and the onset frequency can be approximated by

$$f_{NQS} = n\mu_{eff}\left(V_G - V_T\right)/L_{eff}^{\ 2} \tag{1}$$

where n is a fitting parameter depends on the tolerant of the simulation to an NQS event. For very accurate simulation R must be very close to 1 and ϕ cannot be more than a few degrees, the QS approximation is only valid up to a relatively low frequency. However, if the value of R and ϕ can be relaxed, the QS model can be applied to a much higher frequency. Fig. 5 summaries the simulation results relating device sizes and operating frequencies that satisfy a certain R and ϕ requirement. For example, to simulate the transistor behavior of a 5μm device with an accuracy of $R > 99\%$ and $\phi < 1^\circ$, the QS assumption only valids up to 34MHz. This corresponds a n value of 0.005 in equation (1).

The unity gain frequency f_T of the MOSFET as a function of channel length is also plotted in Fig. 5 (a) for comparison. As shown in the figure, f_{NQS} has a good agreement with f_T in which $R = 99\%$. Thus f_{NQS} can also be a measure of maximum useful frequency when MOSFET is used in amplifier circuit. We can see that when R and ϕ can be relaxed, QS model can do a good job in predicting high frequency device performance.

4. Conclusion

The onset frequency of NQS effect in MOSFET is determined using transient analysis. The NQS effect reveals the variation of channel inversion charge and phase delay in respond to the input signal at high frequency operation. A guideline on the frequency range that the QS model is applicable has been setup based on the tolerant of a circuit to the NQS effect. The onset frequency of NQS effect is found to be very close to f_T and the QS model is sufficient for most of the practical applications.

Acknowledgements

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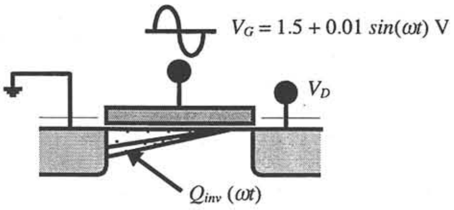

Fig. 1 MOSFET structure used in the simulation. The drain-gate and source-gate overlaps are minimized to eliminate the effect of source-gate and drain-gate overlap capacitance.

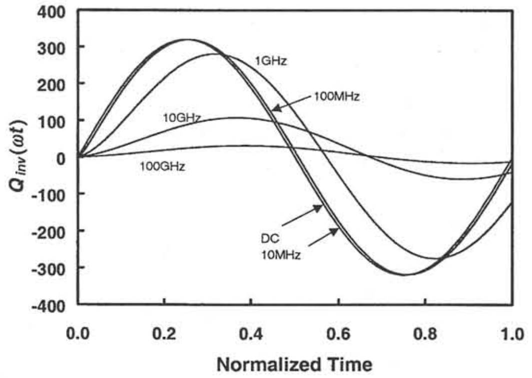

Fig. 2 The transient channel charge variation curves as a function of normalized time for 5 μm MOSFET with different signal frequencies.

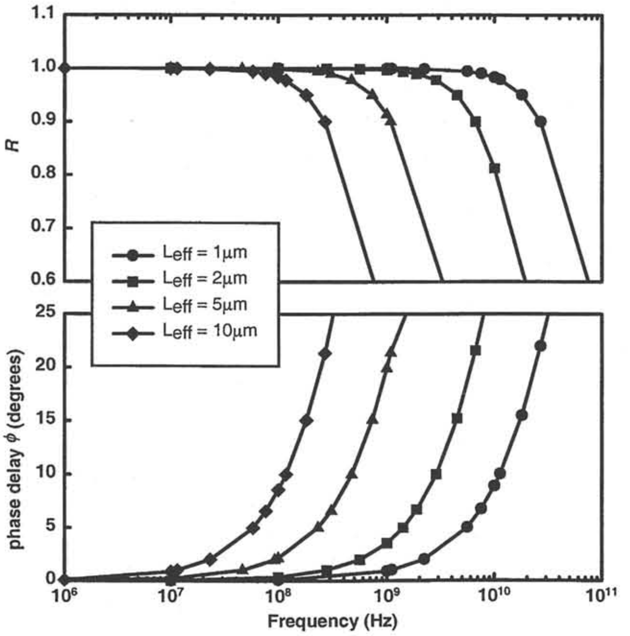

Fig. 3 The normalized R and phase delay ϕ is plotted as a function of input signal frequency in linear region.

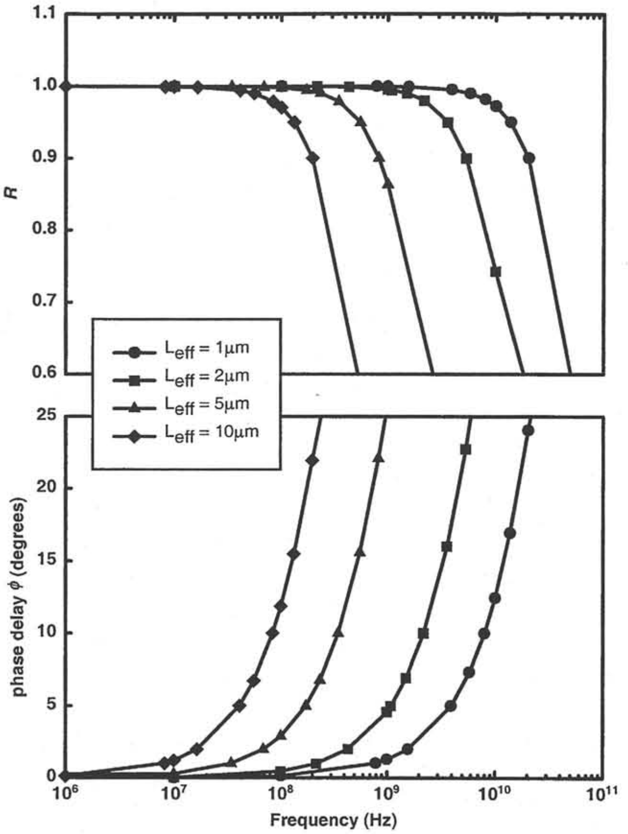

Fig. 4 The normalized R and phase delay ϕ is plotted as a function of input signal frequency in saturation region.

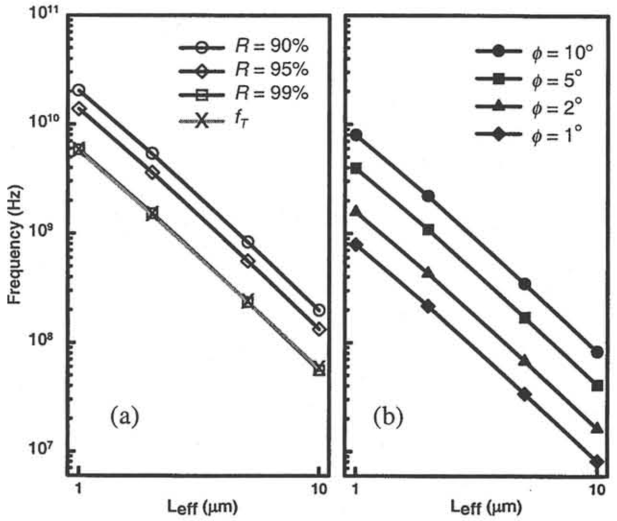

Fig. 5 The tolerant of operating frequency in terms of R and ϕ is plotted as a function of device size respectively.