A Carrier Transit Time Delay-Based Non-Quasi-Static MOSFET Model for Circuit-Simulation

Dondee Navarro, Noriaki Nakayama*, Youichi Takeda, Mitiko Miura-Mattausch,
Hans Jurgen Mattausch, T. Ohguro*, T. Iizuka*, M. Taguchi* and S. Miyamoto*
Graduate School of Advanced Sciences of Matter, Hiroshima University, 739-8530, Japan
Semiconductor Technology Academic Research Center
Phone: +81-82-424-7637, Fax: +81-82-424-7638, E-mail: navarro@hiroshima-u.ac.jp

1. Introduction

With recent developments of integrating scaled-down MOSFETs in RF technology, the accuracy of MOSFET models for circuit-simulation becomes a primary issue [1]. Quasi-static (QS) approximation based models are shown to fail in predicting device behavior at very fast switching. Fig. 1 shows the erroneous calculation of HiSIM-QS [2] in comparison with a 2D device simulator result. Non-quasi-static (NQS) effects are evident due to the fact that the basic assumption of QS at RF switching fails. QS approximation assumes that channel equilibrium is instantaneously achieved and that steady-state solutions can be successively applied to predict transient behavior.

The model developed here is an extension to HiSIM-QS, which incorporates delay mechanisms caused by drift and diffusion of carriers. The model correctly calculates terminal currents at very fast switching. Using the model, calculated harmonic distortion at cut-off frequency operation shows a shift of harmonic curves from that predicted by QS-based models.

2. Model Formulation

Carriers in the channel take time to build-up as opposed to the QS approximation. Fig. 2 shows the carrier density calculated by MEDICI for QS and NQS cases. In HiSIM-NQS, the carrier formation is modeled with the transit delay τ as

$$q(t_i) = q(t_{i-1}) + \frac{t_i - t_{i-1}}{\tau}\left[Q(t_i) - q(t_{i-1})\right] \qquad (1)$$

where $q(t_i)$ and $Q(t_i)$ represent the transient carrier density and the quasi-static carrier density at time t_i, respectively. t_{i-1} indicates the value of quantities at previous time step. Equation 1 implies that the formation of carriers in the NQS is always delayed by τ with respect to the QS one, which is the origin of the NQS effect. This is the basic idea of the model. τ involves delay mechanisms caused by diffusion and drift of carriers as the channel is being formed. These delay mechanisms are combined using the Matthiessen rule. Delay mechanisms at saturation and at a rise time input of 20ps is shown in Fig. 3.

The total drain/source terminal current is derived from the superposition of the transport current I_0 and the charging current [3]. For the drain current,

$$I(t) = I_0(t) + \frac{dq_D}{dt} \qquad (2)$$

where I_0 is a function of the instantaneous terminal voltages and is given by the steady-state solution. The source and drain charging currents are the time derivatives of the associated charges in the terminals, q_S and q_D, respectively. In HiSIM-NQS, these charges are replaced by the NQS carrier formation described above.

3. Results and Discussion

A good reproduction of the drain current for a rise time and fall time of 80ps is validated. Calculation results for a faster switching time are shown in Figs. 4a and b. The artifacts associated with conventional QS modeling, which increase for faster switching as depicted by the circles, are successfully eliminated.

Fig. 5 shows that HD for a 1KHz input is correctly modeled with HiSIM-QS. For our calculation, only measured I-V characteristics are fitted, and no extra fitting parameters are required even for higher-order distortion calculation. This validates the accuracy of our model at low frequency operation. Since the harmonic frequency is low enough, NQS effects are not observed.

At 5GHz, a shift of the calculated NQS HD curves is obvious especially at low gate bias region as shown in Fig. 6. In this region, the cut-off frequency is comparable with the fundamental harmonic frequency ω_0. The shift originates from the delay of the current flow, which is itself the NQS effect as shown in Fig. 7. The difference at higher gate bias region is not observed since the MOSFET cutoff frequency increases with gate bias. In this region, the QS calculation is still valid. This is summarized in Fig. 8. At low gate voltage, the harmonic frequency is greater than or comparable with the operating cutoff frequency, the NQS effect is observable and thus, the QS calculation fails. At high gate voltage, the operating cutoff frequency increases and the QS calculation remains valid.

4. Conclusion

HiSIM-NQS, a non-quasi-static (NQS) model, is developed based on time-delay of the carrier response. The model calculates correct transient current at very fast switching as well as harmonic distortion characteristics. Using the developed model, changes in the calculated harmonic distortion characteristics near the device cut-off region are observed. The model secures correct simulation of MOSFET device performance for RF circuit-simulation.

References

1. Y. P. Tsividis, et.al, IEEE J. of Solid-State Circuits, Vol. 29, pp. 210-216, 1994.
2. http://www.starc.or.jp/kaihatu/pdgr/hisim/index.html
3. S.Y. Oh, et al, IEEE J. of Solid-State Circuits, Vol. SC-15, No. 4, Aug 1988.
4. MEDICI User Manual, Synopsys, 2002.

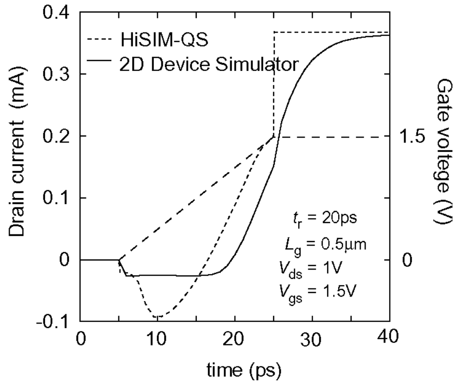

Fig. 1. Erroneous calculation of QS-based models at high frequency switching.

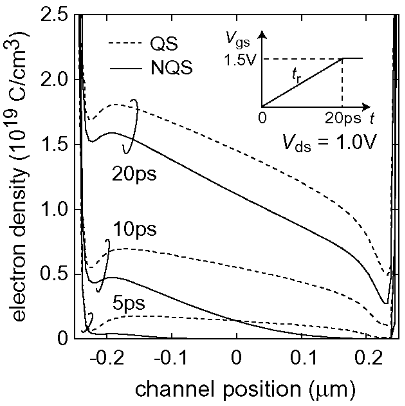

Fig. 2. Carrier density calculated by MEDICI.

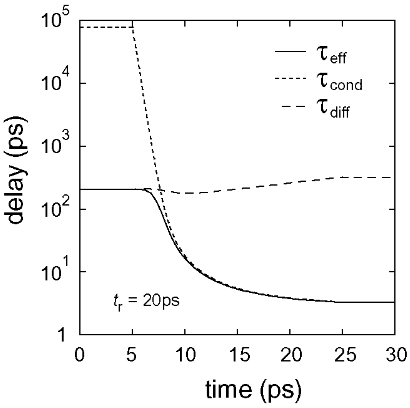

Fig. 3. Time-delay mechanisms employed in HiSIM-NQS.

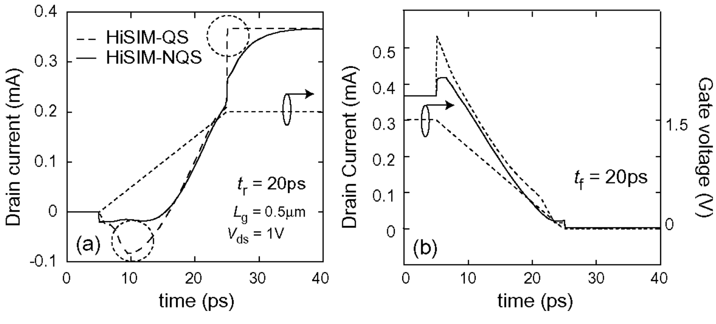

Fig. 4. Calculated NQS current in comparison with HiSIM-QS.

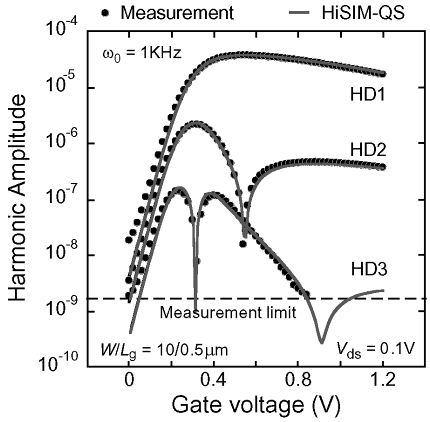

Fig. 5. Calculated HD characteristics of HiSIM-QS in comparison with measurements.

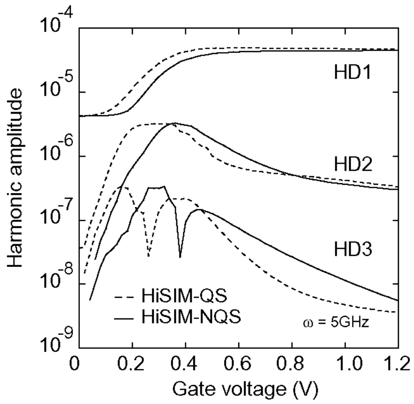

Fig. 6. HD characteristics at 5GHz switching.

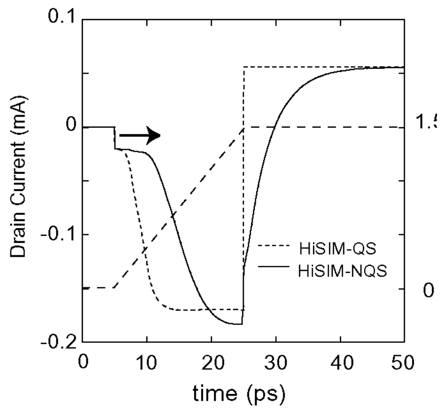

Fig. 7. Delay of drain current which causes the shift in HD characteristics.

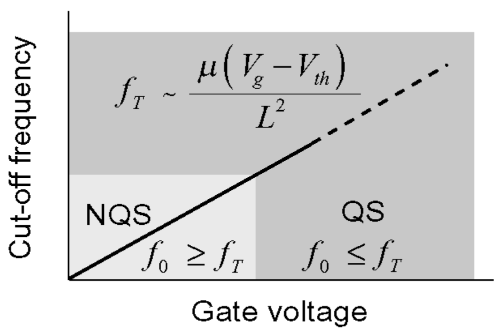

Fig. 8. Region of validity in using QS-based models.

A Carrier Transit Time Delay-Based
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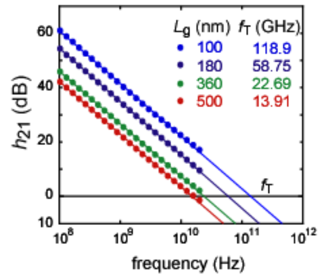
[1]Hiroshima University, [2]STARC

Scaled-Down MOSFET Characteristics

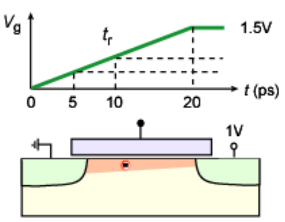


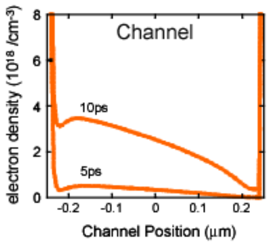
- Improved cut-off frequency as gate length is decreased

Desirable for RF applications

MOSFET Models for Circuit Simulation

Quasi-Static (QS) Approximation

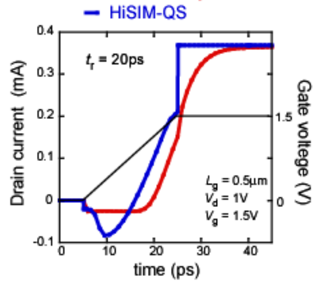




- Channel equilibrium is instantaneously achieved.

Can QS-based models correctly predict device behavior at RF switching?

QS-based model at RF switching



- Non-quasi-static (NQS) effects become evident.

Incorrect prediction of device behavior.

NQS model is necessary.

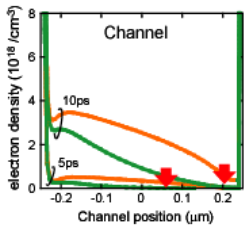
Objectives

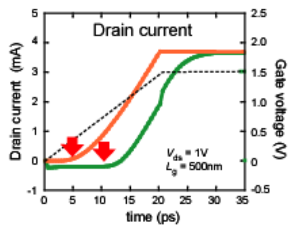
- To develop a non-quasi-static model as extension to quasi-static models
- To investigate high-frequency-related phenomena in devices using the developed model

Non-Quasi-Static Analysis

2D Numerical Device Simulation Results

QS : DC simulation
NQS : Transient simulation





- Channel formation is delayed in NQS.

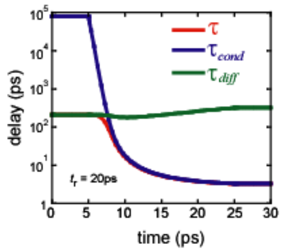
Channel Formation

NQS charges are delayed with respect to QS ones.

$$q(t_i) = q(t_{i-1}) + \frac{t_i - t_{i-1}}{\tau}\left[Q(V(t_i)) - q(t_{i-1})\right]$$

q : NQS carriers Q : QS carriers τ : Delay mechanisms

Delay Mechanisms



Effective delay

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{diff}} + \frac{1}{\tau_{cond}}$$

Model Verification

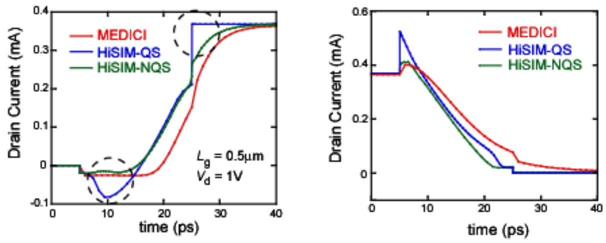
- Drain current
- Harmonic distortion

Results of the model are verified using
MEDICI: 2D Numerical Device Simulator

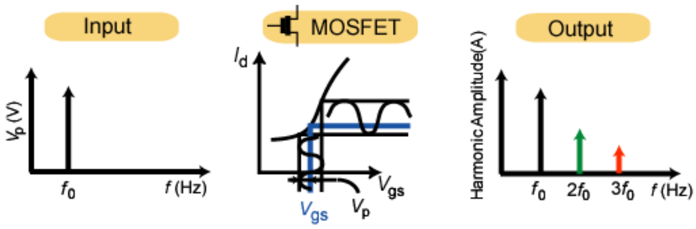
Poisson equation
Continuity equation
Current density equation

Drain Current

V_{gs}=1.5V rise/fall time = 20ps

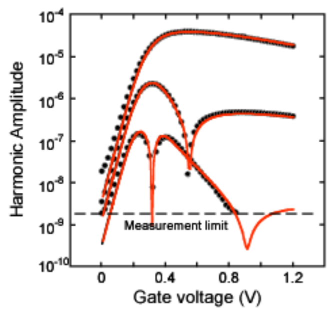


Harmonic Distortion



- Illustrates the nonlinear behavior of MOSFETs.

Harmonic Distortion at Low Frequency



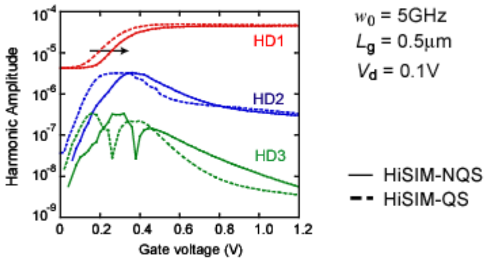
w_0 = 1KHz
L_g = 0.5µm
V_d = 0.1V

• Measurement
HiSIM-QS

- NQS effect is not yet significant.

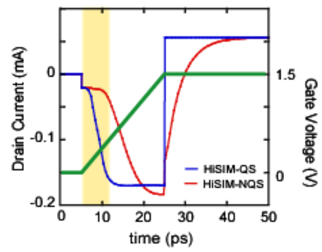
Harmonic Distortion at High Frequency (1)

NQS effect : Shift of harmonic curves

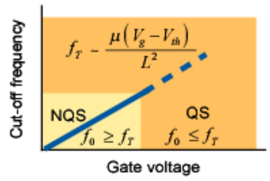


- Effect is more significant at low gate bias.

Harmonic Distortion at High Frequency (2)



- At low gate bias, the harmonic frequency is greater than the cut-off frequency.



At low gate bias, the harmonic frequency f_0 is comparable with the cut-off frequency.

QS calculations become inapplicable.

Summary

- A non-quasi-static model based on diffusion and conduction delays is developed.
- The model correctly calculates drain current and predicts harmonic distortion characteristics.
- NQS effects on harmonic distortion are found to be a shift of harmonic curves.