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Analysis of Non-Quasistatic Contribution to Small-Signal Response for Deep Sub-μm MOSFET Technologies

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Introduction

MOSFET applications for RF regime are no more future tasks but are already under development. To predict carrier response in such high frequency operation, extension of the quasistatic (QS) approximation to the non-quasistatic (NQS) level considering the carrier transit delay in the channel is being intensively investigated, mostly basing on equivalent circuit descriptions. However, due to many approximations applied to realize the simple extension, reliability of the NQS evaluation is doubtful. On the contrary, 2D numerical simulation derives accurate carrier response for the NQS effect. However, it is hard to estimate the NQS contribution separately from the QS phenomenon. The purpose of this work is to develop a method to estimate the NQS contribution accurately by solving the continuity equation explicitly together with the current equation. Since the design of RF circuits is usually done with the Y-parameters, we concentrate on modeling the Y-parameters. The correct estimation of the NQS effect is important for correct description of carrier response under around the cut-off frequency, as well as for the appropriate RF-device design.

Investigation Method

To consider the NQS effect the current density equation has to be solved together with the continuity equation. Final equations for Y-parameter components have been written by series of polynomial functions of frequency (f) under the drift approximation. For advanced MOSFET applications with reduced bias condition, inclusion of the diffusion term in the current density equation is necessary. Basing on the drift-diffusion approximation, all device characteristics are described with surface potentials, obtained by solving the Poisson equation iteratively. Thus each term of the series consists of coefficients determined by the surface potentials in stead of applied biases, different from the conventional drift approximation [1]. Under the QS approximation only the first term of the polynomial function is considered, whereas up to 19 terms are required to calculate the NQS condition correctly. Our calculation procedure is linked with the circuit simulation model HiSIM [2], providing the surface potential values as well as device parameter values required for the Y-parameter calculation.

Results

Figs. 1 and 2 compare calculated intrinsic $Y_{\rm gg}$ and $Y_{\rm dg}$ for MOSFET with the gate length ($L_{\rm g}$) of 0.5μm and 0.18μm by the NQS and QS models, respectively, excluding the extrinsic resistances and capacitances. Though the imaginary part calculated by the NQS model almost coincides with that calculated by the QS model, deviation starts around the cut-off frequency ($f_{\rm T}$). This deviation is attributed to the capacitance reduction due to the delay of the carrier response at high frequency operation as shown in Fig. 3a. On the other hand, the real part of $Y_{\rm gg}$ calculated by the NQS model deviates from zero predicted by the QS model already beyond $f_{\rm T}/3$. This deviation is caused by the capacitance reduction as the imaginary part and the carrier transit delay (τ) in the channel as shown in Fig. 3b, which is historically described by the Elmore capacitance [3]. In the literature, it has been reported that the NQS contribution occurs already beyond $f_{\rm T}/10$ [4].

Fig. 4 depicts the NQS contribution to Y-parameters at f = 5GHz normalized by Im$\{Y(\text{NQS}, \text{5GHz})\}$ ($|Y(\text{NQS}) - Y(\text{QS})|/\text{Im}\{Y(\text{NQS}, \text{5GHz})\}$) as a function of $L_{\rm g}$. It can be seen that the NQS contribution is surprisingly small for f = 5GHz. It reaches about 20% for $L_{\rm g} = 1\mu$m at $f = f_{\rm T}$.

It is known that the gate resistance plays an important role for the Y-parameter response in real devices. Figs. 5 and 6 compare measured $Y_{\rm gg}$ and $Y_{\rm dg}$ with the QS and NQS model including the gate resistance ($R_{\rm g}$) for $L_{\rm g} = 0.5\mu$m and 0.18μm. $R_{\rm g}$ is fitted to the measurement results and the extracted value is 300Ω and 350Ω for $L_{\rm g} = 0.5\mu$m and 0.18μm, respectively. Though the measured frequency regime is not sufficient for $L_{\rm g} = 0.18\mu$m, deviations between the measurements and the model results are obvious for both $L_{\rm g}$ lengths. The reason is attributed to the different test structures used for the Y-parameter measurements and the parameter extraction with HiSIM. Different from the results shown in Figs. 1 and 2 excluding the gate resistance, inclusion of $R_{\rm g}$ results in enhanced deviations between the NQS and QS approximations in the imaginary parts, and the deviations in the real parts is almost diminished. The $R_{\rm g}$ contributes to increase the real part of $Y_{\rm gg}$ and causes enhanced delay of the phase. However, the phase delay, the delay of carrier response, saturates after a certain phase delay and the NQS and QS results become the same. The same discussion is valid for $Y_{\rm dg}$.

Conclusion

We have calculated the NQS contribution to Y-parameters for deep sub-μm technology MOSFETs by solving the current density equation and the continuity equation simultaneously. Our result shows that the NQS contribution is much smaller than previously predicted. The magnitude of the NQS contribution is larger in the real part of the intrinsic Y-parameter values. However, the inclusion of the gate resistance diminishes the contribution to the real part and that to the imaginary part becomes larger, which is attributed to the saturating characteristics of the phase shift.

References

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[5] MEDICI User's Manual, Avant!.

[1] present add.: Matsushita Communication Industrial Co. Ltd.
[2] present add.: Semiconductor Technology Academic Research Center

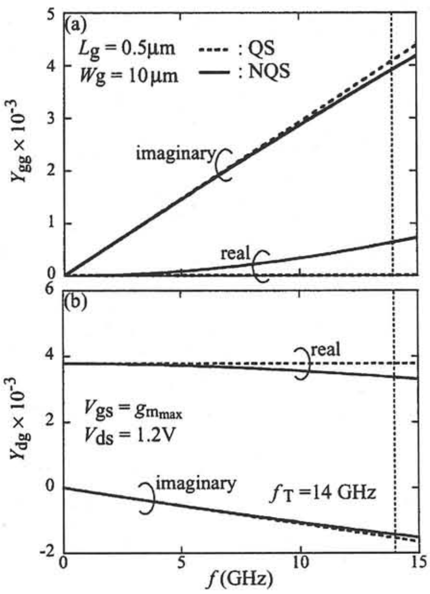

Fig. 1: Calculated Y-parameters ((a): Y_{gg}, (b): Y_{dg}) in the intrinsic part of 0.5μm-MOSFET with the NQS model (solid curves) and the QS model (dashed curves). The vertical dashed line indicates the cut-off frequency f_T.

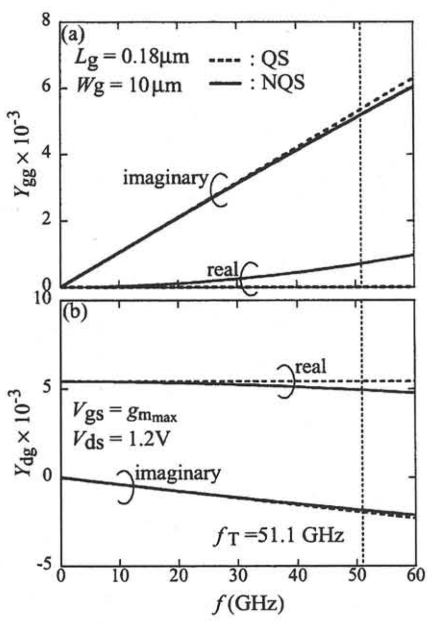

Fig. 2: The same figures as Fig. 1 but for $L_g = 0.18\mu$m.

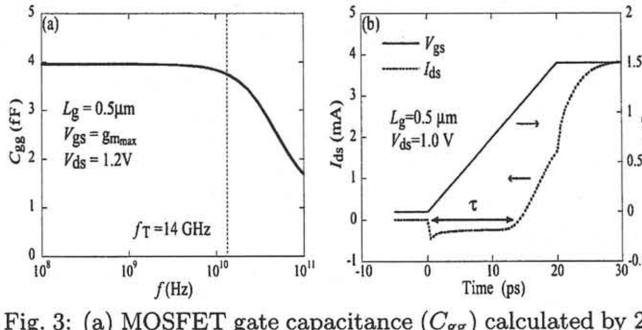

Fig. 3: (a) MOSFET gate capacitance (C_{gg}) calculated by 2D device simulator MEDICI [5] as a function of f. (b) Transient drain current calculated by MEDICI. τ is the transit time of carriers from source and drain.

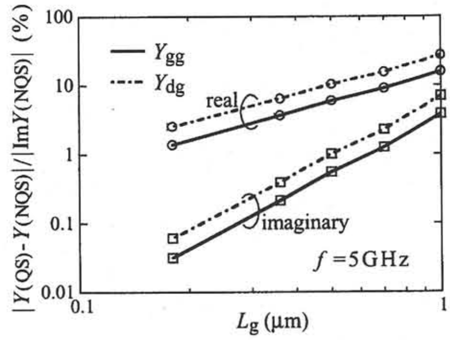

Fig. 4: Calculated NQS contribution $|Y(\mathrm{NQS}) - Y(\mathrm{QS})|/\mathrm{Im}\{Y(\mathrm{NQS})\}$ at $f = 5$GHz as a function of L_g.

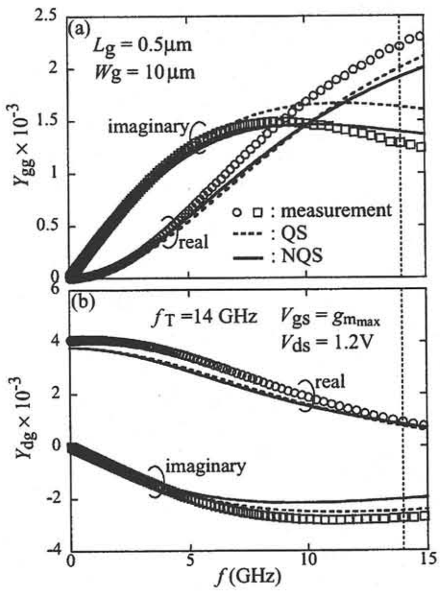

Fig. 5: Measured (open symbols) and calculated Y-parameters with the NQS model (solid curves) and the QS model (dashed curves) for $L_g = 0.5\mu$m.

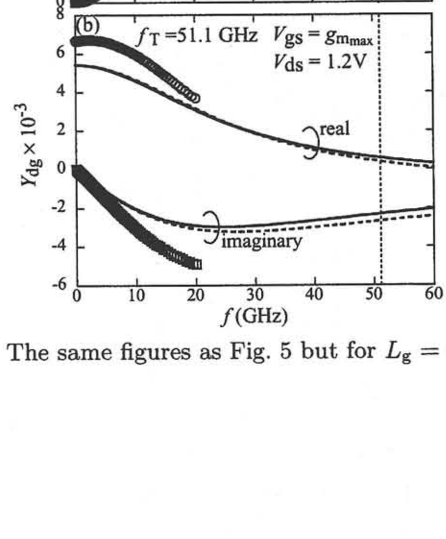

Fig. 6: The same figures as Fig. 5 but for $L_g = 0.18\mu$m.