A Practical Small-Signal Equivalent Circuit Model for RF-MOSFETs Valid Up to the Cut-Off Frequency

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***Abstract* — The non-quasistatic contribution to the Y-parameters is shown to be much smaller than usually expected. This is especially true for advanced pocket-implant MOSFET technologies being developed for RF devices. Therefore, a simple and practical equivalent-circuit model valid up to the cut-off frequency becomes possible. The small interdependence of the different model elements allows an explicit and sequential extraction of the individual element values.**

I. Introduction

Recently, MOSFET devices are entering into the field of RF applications, but models for circuit simulation are still under intensive development [1]. The largest effort is directed towards the inclusion of the non-quasistatic carrier response, which can in principle be done by solving the continuity equation. However, an explicit model formulation with inclusion of the continuity equation cannot be obtained. The Bessel function formulation has been developed for small signal analysis [2], but requires a high cost of intensive numerical calculations.

Another approach to include the non-quasistatic carrier response is the description by an equivalent circuit. It is generally assumed that a quasistatic equivalent circuit is valid up to 1/10 – 1/3 of the cut-off frequency (f_T) [3]. To extend the validity further, many additional elements such as resistances and inductances are added into the equivalent circuit. This leads to two serious problems.

1. The equivalent circuit becomes complicated.
2. Extraction of element values becomes difficult.

Our aim is to develop a simple equivalent circuit model valid up to f_T for 100nm MOSFET technologies. Unfortunately, there is no clear quantitative analysis of the magnitude of the non-quasistatic effect for such a practical case. For this reason we have extracted the non-quasistatic contribution by comparing the quasistatic equivalent-circuit approach with 2D device simulations solving the continuity equation self-consistently. Based on the result we have developed a simple non-quasistatic equivalent-circuit model and verified its validity for real devices up to measurement limit of 20GHz.

II. Extraction of the Non-Quasistatic Y-Parameter Contribution

Fig. 1 shows the extraction procedure of the non-quasistatic Y-parameter contribution. First, the Y-parameters are calculated with the 2D device simulator MEDICI [4], solving the Poisson equation and the current-density equation together with the continuity equation, simultaneously. This means that the 2D simulation includes the contribution of the non-quasistatic carrier response in a self-consistent way. 2D-simulated cut-off frequencies of n-MOSFET are shown in Fig. 2 as an example for the gate length (L_g) of 0.5μm and 0.13μm. With the simulated Y-parameter results, all capacitances appearing in the quite conventional quasistatic equivalent circuit of Fig. 3 [3] are extracted.

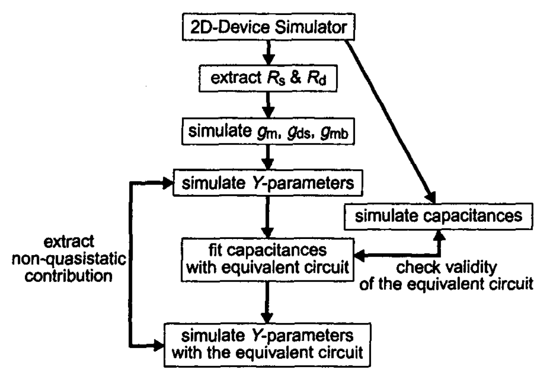

Fig. 1. Flowchart for the extraction of the non-quasistatic Y-parameter contribution.

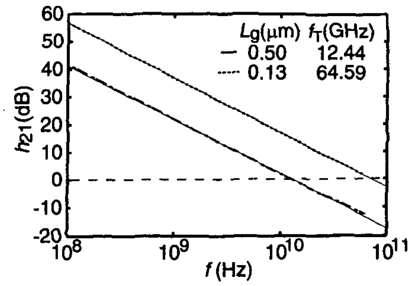

Fig. 2. 2D-simulated cut-off frequencies for n-MOSFETs with L_g equal 0.5μm and 0.13μm at $V_g = g_{m_{max}}$ (giving maximum transconductance) and $V_d = 1.2$V.

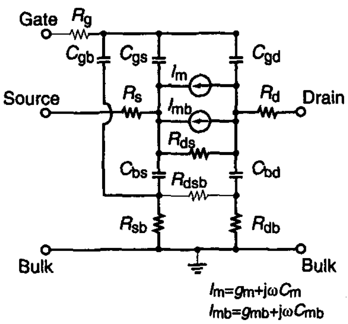

Fig. 3. Quasistatic equivalent circuit.

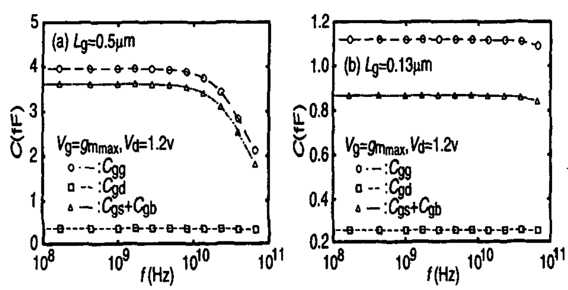

Fig. 4. Comparison of extracted n-MOSFET capacitances (lines) with those calculated by MEDICI independently (symbols) for (a) $L_g = 0.5\mu$m and (b) $L_g = 0.13\mu$m under the same bias condition as given in Fig. 2.

In the input profile, determining device structures for the 2D simulation, an ideal gate contact ($R_g = 0$) is assumed. The purpose is to eliminate the influence of the gate resistance, which is unimportant for extracting the magnitude of the non-quasistatic effect. Only R_{sb}, R_{db} and R_{dsb} are added to describe the coupling with the carrier distribution in the bulk [5]. The extracted capacitances are compared in Fig. 4 with those calculated by MEDICI independently. A very good agreement is seen.

Figs. 5 and 6 show calculated Y-parameter values from the equivalent circuit of Fig. 3 for $L_g = 0.5\mu$m

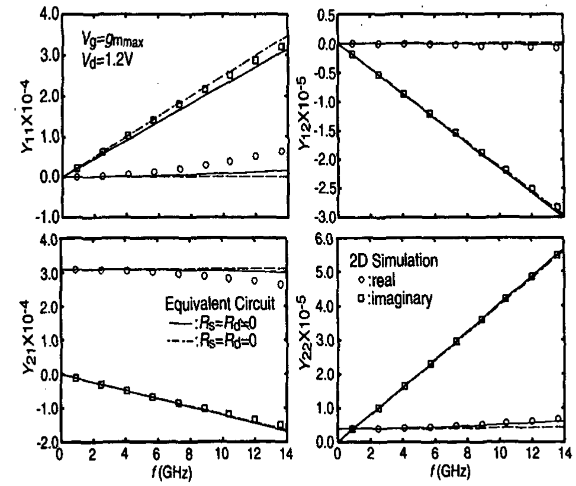

Fig. 5. Calculated n-MOSFET Y-parameter values from the equivalent circuit of Fig. 3 for $L_g = 0.5\mu$m.

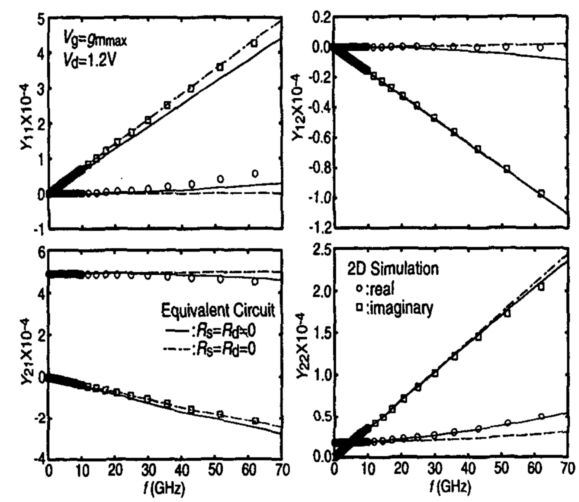

Fig. 6. The same figures as Fig. 5 but for $L_g = 0.13\mu$m.

and 0.13μm, respectively. For the calculation the extracted capacitances (C_{gg}, C_{gd}, C_{gb}, C_{gs}) are used, and other element values in the equivalent circuit, such as the transconductance and the contact resistances are taken from the MEDICI simulation. The three bulk coupling resistances (R_{sb}, R_{db}, R_{dsb}) of the equivalent circuit are fitted to the 2D-simulated Y-parameter values Y_{22}, which have the highest sensitivity. On the other hand, Y_{11} and Y_{21} are mainly influenced by the gate capacitances, which are checked for self-consistency with the 2D-simulation results. Good overall agreement is seen for all calculated Y-parameters. The main reason for this good agreement is attributed to

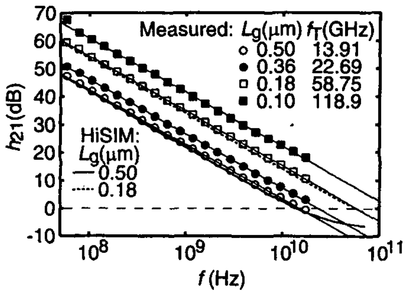

Fig. 7. Measured n-MOSFET cut-off frequencies for the L_g of 0.5μm to 0.1μm. Calculation results with HiSIM are also depicted at $V_g = g_{m_{max}}$ and $V_d = 1.2$V.

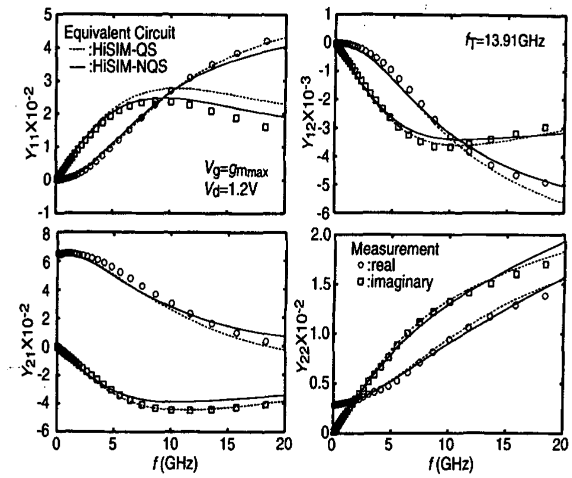

Fig. 8. Comparison of calculated n-MOSFET Y-parameters with measurements for $L_g = 0.5\mu$m.

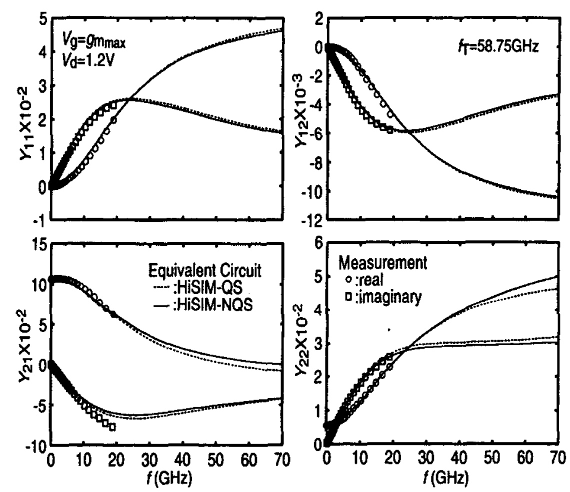

Fig. 9. The same figures as Fig. 8 but for $L_g = 0.18\mu$m.

the accurate determination of the capacitance values (see Fig. 4).

There remains, however, a deviation between the quasistatic equivalent circuit and the 2D simulation, which is largest for Y_{11}. The cause is exactly the quasistatic approximation of the equivalent circuit. It is expected that the contact resistances R_s and R_d sensitively influence the high-frequency response. The Y-parameter results are therefore also depicted for R_s, $R_d = 0$. The deviation is somewhat enhanced, but not so drastic as reported previously [6], for Y_{11} as well as Y_{21}. Therefore, the main insights from Figs. 5 and 6 are that the non-quasistatic contribution (difference between quasistatic equivalent circuit and non-quasistatic 2D simulation) is not so large as expected, and that the Y-values are mostly determined by the capacitances even under high-frequencies.

III. Device Measurements and Model Verification

We have checked the validity of the conclusions, obtained by the simulation study, for real devices. Devices studied here are fabricated by a 100nm technology with the pocket implantation technology. Fig. 7 shows measured cut-off frequencies. The limit of the measurement lies at 20GHz. Figs. 8 and 9 show comparisons of calculated Y-parameters with measurements for $L_g = 0.5\mu$m and 0.18μm, respectively. Unfortunately, the measurable frequency limit was too low for the shortest L_g of 0.1μm. Therefore, we selected these two L_g for intensive study. Again the quasistatic equivalent circuit of Fig. 3 is used. The capacitances and other element values are calculated with HiSIM for which the model parameters of the used MOSFET-technology were extracted. HiSIM is a circuit simulation model based on the drift-diffusion approximation, describing all device characteristics with surface potentials obtained by solving the Poisson equation [7]. All terminal charges are calculated self-consistently, which is a key for accurate calculation of capacitances.

The measured Y-parameter characteristics of Figs. 8 and 9 are quite different from the MEDICI simulations of Figs. 5 and 6, because the nonlinear gate resistance R_g was neglected. R_g (see Fig. 3) is fitted to measurements after approximate estimation with Eq. (1) below [3]:

$$R_g \simeq \frac{\text{measured}\{\text{Re}(Y_{11})\}}{\text{measured}\{|\text{Im}(Y_{11})|^2\}} \qquad (1)$$

The fitted value and the result of Eq. (1) turned out to be nearly equal.

The bulk-coupling resistances R_{sb}, R_{db} and R_{dsb} are again extracted from Y_{22} and shown in Fig. 10. Different from the MEDICI result the non-quasistatic contribution is obvious rather in the imaginary part of Y_{11}. The reason is that R_g itself acts as an inertia for the rapid charge. All other Y-parameter values are nearly perfectly reproduced with the simple quasistatic equivalent circuit.

Fig. 11 shows an equivalent circuit including the Elmore resistances R_{gs} and R_{gd} [8]. The Y-parameter calculation with this equivalent circuit is also depicted in Fig. 8. The values R_{gs} and R_{gd} are fitted to the imaginary part of the measured Y_{11}. Unfortunately, R_g cannot be neglected, as usually done in literature, even by introducing R_{gs} and R_{gd}. This simple improvement is seen to be sufficient up to f_T. The influence of the non-quasistatic contribution is small for $L_g = 0.18\mu m$ as shown in Fig. 9, where the simulated Y-parameter values differ scarcely up to 20GHz. The reason that the simple non-quasistatic equivalent circuit reproduces measurements up to high-frequency is due to large channel conductance g_{ds} caused by the pocket implantation. The inductance, usually included to reproduce the non-quasistatic carrier response ($R_{gs}C_{gs} \simeq L_d g_{ds}$ [3]), is much lower for the pocket-implant technology and can be neglected. The resistances turn out to be much more important for such an advanced technology.

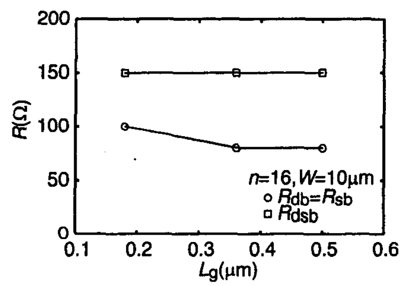

Fig. 10. Extracted three bulk resistances (R_{sb}, R_{db}, R_{dsb}) for n-MOSFETs with 16 fingers, each with $10\mu m$ width.

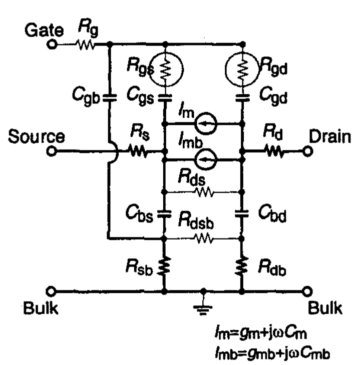

Fig. 11. Equivalent circuit including the Elmore resistances shown by circles.

IV. Conclusion

We have extracted the non-quasistatic contribution to Y-parameters for an advanced pocket-implant MOSFET technology with the help of a 2D device simulator. The result shows that the contribution is not so large as reported previously. More important for accurate Y-parameter simulation is the correct estimation of the capacitances. A quasistatic equivalent circuit with correct capacitances is found already satisfactory up to about $f_T/2$. For a simple non-quasistatic equivalent-circuit model, valid up to the cut-off frequency, the addition of two Elmore resistances in the gate circuitry is sufficient. The important capacitances and Elmore resistances can be determined for MOSFETs with long L_g and therefore low f_T. Since their values do not change or are easily scalable for shorter L_g, it becomes possible to predict Y-parameter values of short-L_g MOSFETs with high cut-off frequencies, for which no measurements are available yet.

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