

On the Large-Signal CMOS Modeling and Parameter Extraction for RF Applications

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Abstract – A small-signal equivalent circuit of an RF MOSFET not only fully compatible with 4 terminal large-signal quasi-static I-V and Q-V models but suitable for 3 terminal two-port S-parameter measurement, is proposed along with very simple and accurate parameter extraction method. This model includes the intrinsic and extrinsic elements important for AC simulation at RF. The validity and accuracy of our approach is verified from 0.18 μm RF NMOS results.

I. INTRODUCTION

The construction of proper small-signal models and the extraction of their parameters which are fully compatible with 4 terminal quasi-static large signal I-V and Q-V models, is very important not only for device and circuit characterization but for the circuit design. Recently, many suggestions have been made to improve the prediction of high-frequency properties by simple modification to the conventional MOSFET equivalent circuits developed for low-to-medium frequencies. Several methods of extracting small-signal equivalent circuit parameters from the S-parameter measurement data have been reported [1]-[4]. But they require complex curve fitting and optimization steps, or are not accurate enough to be used for RF IC simulation, nor compatible with large-signal models. In this paper, we propose a simple four-terminal small-signal model valid in strong inversion region, which is not only compatible with 4 terminal large signal model, but also with 3 terminal s-parameter measurement. Using the proposed method, model parameters can be extracted very efficiently through the linear regression and the simple analytical process. Accuracy of the proposed model was verified with the measured data and inaccuracy in capacitance of the conventional model and the typical macro-model was addressed. Also, we investigate the bias dependence of small-signal parameters extracted using the proposed method.

II. CONSTRUCTION OF 4 TERMINAL SMALL-SIGNAL EQUIVALENT CIRCUIT AND ITS PARAMETER EXTRACTION METHOD

We have proposed a simple and accurate parameter extraction method for a 3 terminal small-signal MOSFET model including the substrate-related parameters and important non-reciprocal capacitors C_{gd} and C_{dg} [5]. This work uses a physical small-signal equivalent circuit of the RF MOSFET and proposes an accurate parameter extraction approach by Y-parameter analysis from measured S-parameters.

The quasi-4 terminal small-signal equivalent circuit of a RF MOSFET operating in strong inversion region suitable for 3 terminal s-parameter measurement is shown in Fig. 1 (a) and (b), respectively. The source and body terminals are connected to ground for 3 terminal two-port S-parameter measurement and Y-parameter analysis. Non-reciprocal capacitances important for accurate AC simulation and substrate-related parameters are included in the model. The non-reciprocal capacitances C_{gd} and C_{dg} are required for the simulation accuracy as well as efficiency as will be explained later. For simple circuit representation, the overlap capacitances are included in the correspondent intrinsic capacitances. The capacitive effect of the drain on the gate is represented by C_{gd} , and the capacitive effect of the gate on the drain is represented by C_{dg} . $C_m = C_{dg} - C_{gd}$ is a transcapacitance taking care of the different effect of the gate and the drain on each other in terms of charging currents [6]. This model describes the signal coupling through the substrate using a single-lumped resistance R_{sub} connected to the common end of two junction capacitances C_{js} and C_{jd} , allowing us to use any conventional intrinsic large signal I-V and Q-V models. The signal coupling through the substrate RC network significantly affects the output characteristics of RF MOSFETs [7].

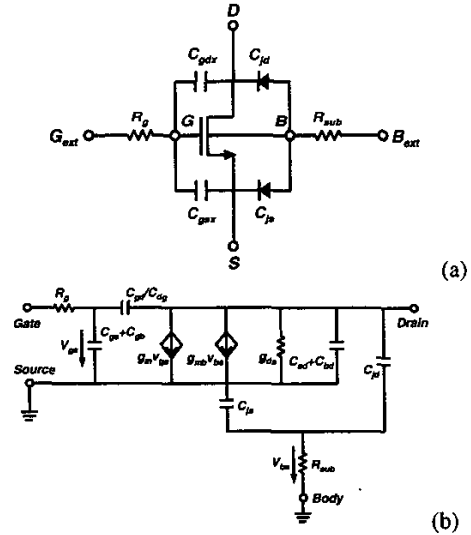


Figure 1: (a) 4 terminal large signal MOS model and (b) its approximated 3 terminal small-signal equivalent circuit for s-parameter measurement and characterization.

Direct extraction is performed by Y -parameter analysis on the equivalent circuit of the MOSFET for high frequency operation. In our approach, an optimization process, which may have uncertainties in obtaining physical parameters, is not required. For operation frequency up to 10 GHz, by using the assumption that $\omega^2 (C_{gs} + C_{gd})^2 R_g^2 \ll 1$, the small-signal equivalent circuit shown in Fig. 1 can be analyzed in terms of Y -parameters [5], [7]. The validity of the assumption will be checked after each parameter is extracted.

All the components of the equivalent circuit are extracted by the Y -parameter analysis. g_m is obtained from the y -intercept of $\text{Re}(Y_{21})$ versus ω^2 and g_{ds} is extracted from the y -intercept of $\text{Re}(Y_{22})$ versus ω^2 , at the low frequency range. R_g , C_{gd} , C_{gs} and C_{dg} can be obtained by (1)–(4) [5].

$$R_g = \text{Re}(Y_{11}) / (\text{Im}(Y_{11}))^2 \quad (1)$$

$$C_{gd} = -\text{Im}(Y_{12}) / \omega \quad (2)$$

$$C_{gs} + C_{gb} = (\text{Im}(Y_{11}) + \text{Im}(Y_{12})) / \omega \quad (3)$$

$$C_{dg} = -\text{Im}(Y_{21}) / \omega - g_m R_g (C_{gs} + C_{gd}) \quad (4)$$

For the extraction of substrate components C_{jd} and R_{sub} , we use the data measured at $V_{gs} = 0$ V and the following relations (5)–(6) [7].

$$C_{jd} = (\text{Im}(Y_{22}) + \text{Im}(Y_{12})) / \omega \quad (5)$$

$$R_{sub} = \text{Re}(Y_{22}) / (\omega^2 C_{jd}^2) \quad (6)$$

C_{js} can be extracted by applying (5) once more to the data measured at $V_{gs} = V_{ds} = 0$ V. If the number of source islands is different from that of drain islands, the additional source-drain reversed structure can be used to obtain more accurate value. The extraction of the substrate parameters gives quite proper values, because they have a very weak gate bias dependence as verified in [7].

With the parameters extracted so far, g_{mb} and C_{sd} can be solved analytically as follow.

$$g_{mb} = \left[\frac{\text{Re}(Y_{22}) - g_{ds}}{\omega^2} - R_g C_{gd} C_{dg} - R_{sub} C_{jd}^2 - g_m R_g^2 C_{gd} (C_{gs} + C_{gd}) \right] / R_{sub}^2 C_{jd} (C_{js} + C_{jd}) \quad (7)$$

$$C_{sd} = \frac{\text{Im}(Y_{22})}{\omega} - C_{gd} - C_{jd} - g_m R_g C_{gd} - g_{mb} R_{sub} C_{jd} + \omega^2 [R_g^2 C_{gd} C_{dg} (C_{gs} + C_{gd}) + R_{sub}^2 C_{jd}^2 (C_{js} + C_{jd})] \quad (8)$$

III. MODEL VERIFICATION

The proposed direct extraction method was applied to determine parameters of the test device, which is a multi-fingered n-MOSFET fabricated by 0.18 μm technology. S -parameters were measured in the common source-substrate configuration using on-wafer RF probes and a HP 8510C vector network analyzer. To remove on-wafer pad parasitics, two-step deembedding process was carried out by using the open and short deembedding structures [8]. The parameters were extracted for n-MOSFETs with 100- and 40- μm width having forty and ten gate fingers, respectively.

The extraction results of the 100- μm wide device at $V_{gs} = V_{ds} = 1$ V were summarized in Table 1. Due to the non-

reciprocity, C_{dg} is larger than C_{gd} as it should be. For the extracted parameter values, $\omega^2 (C_{gs} + C_{gd})^2 R_g^2$ is calculated to be 0.065 and even at 10 GHz, which is much smaller than one. This confirms the validity of the assumption used for deriving (1)–(8).

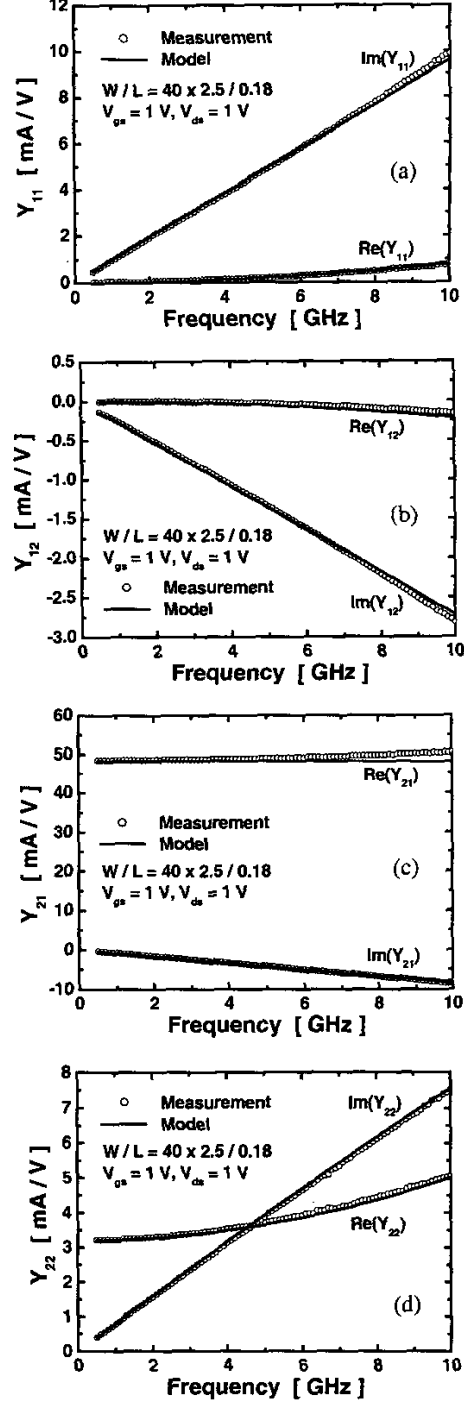


Figure 2: Modeled Y -parameters vs. measured Y -parameters: (a) Y_{11} , (b) Y_{12} , (c) Y_{21} , (d) Y_{22} .

In Fig. 2, the Y -parameters calculated with extracted parameters are compared with the measured data for $V_{gs} = V_{ds} = 1$ V. It shows that the simulation result well matches the measurement without any optimization after direct extraction. The non-reciprocal capacitances C_{gd} and C_{dg} contribute to the imaginary parts of Y_{12} and Y_{21} . Excluding transcapacitance could result in a significant error on the imaginary part of Y_{21} at high frequencies. The substrate coupling significantly contributes to the output admittance Y_{22} at high frequencies. The total root-mean-square error between measured and modeled Y -parameters is only 1.8 %.

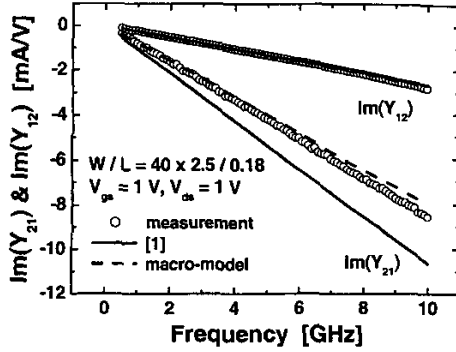


Figure 3: $\text{Im}(Y_{12})$ and $\text{Im}(Y_{21})$ from the models (a model of [1] and a macro-model) and the measurement.

In Fig. 3, we compared the $\text{Im}(Y_{12})$ and $\text{Im}(Y_{21})$ from the conventional small-signal model [1] and the macro-model (Fig. 4) with the measured ones. The model parameters for these models were carefully extracted to best fit the measurement data. The small-signal model in [1] is very simple and doesn't have non-reciprocal capacitances, which results in large discrepancy in $\text{Im}(Y_{21})$. We used the RF macro-model in Fig. 4. External C_{gsx} and C_{gd} are added to describe the bias dependence of the overlap capacitance. These external capacitances also allow one to correct the inaccuracies of the intrinsic capacitances appearing for short-channel devices. However, with the reciprocal capacitance C_{gd} , we cannot simultaneously correct C_{gd} and C_{dg} (and thus, $\text{Im}(Y_{12})$ and $\text{Im}(Y_{21})$) as shown in Fig. 3. It also means that we cannot simultaneously fit both the feedforward gate-to-drain and feedback drain-to-gate capacitances, which are very important for RF circuit design. Inaccuracy in capacitance can significantly affect the matching condition, gain, stability, noise figure, oscillation frequency, and so on. Fig. 2 demonstrates that the model with non-reciprocal capacitances can accurately fit both $\text{Im}(Y_{12})$ and $\text{Im}(Y_{21})$.

IV. BIAS DEPENDENCE OF THE EXTRACTED AC PARAMETERS

Fig. 4 shows the bias dependence of the R_g and R_{sub} , which shows negligible gate bias dependence. Similar independence is obtained for the drain bias. Fig. 5 shows bias dependence of capacitances extracted from the KAIST

small-signal model (KSSM); (a) for the gate bias dependence and (b) for the drain bias dependence. The results from the macro-model including BSIM3 core are also shown for comparison. Note that the C - V behavior is what we expect from MOSFET device physics and specifically that C_{dg} is larger than C_{gd} , demonstrating the necessity of considering transcapacitance of C_m . This consideration of charge conservation is important for the accurate AC simulation as shown before. The capacitance vs. gate bias characteristics obtained from the KSSM is much smoother than that from the macro-model with BSIM3 core. The smooth transition between operation regions is typical for short-channel MOSFETs.

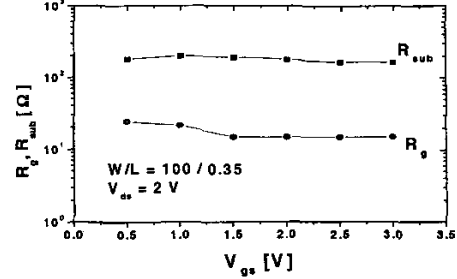


Figure 4: Gate bias dependence of R_g and R_{sub}

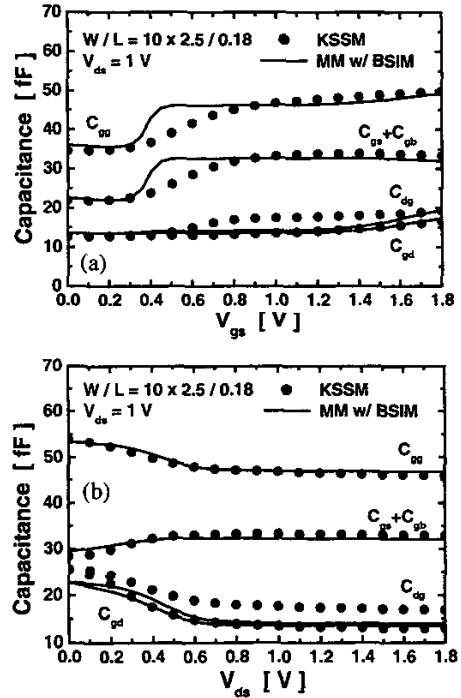


Figure 5: Bias dependence of capacitances: (a) gate bias dependence, (b) drain bias dependence.

The extracted g_{ds} values at $V_{gs} = 0.8, 1$ and 1.2 V were plotted as a function of V_{ds} in Fig. 6(a) with the result from DC measurement while Fig. 6(b) shows I_d - V_{ds} curves generated by integrating the extracted g_{ds} and the curves

from DC measurement. Similar results were obtained for g_m vs. V_{gs} and I_d vs. V_{gs} . The results from S -parameter measurement at high frequencies agree well with those from DC measurement. Therefore, one large-signal I - V model is enough to be used for DC, low-frequency analog, as well as RF circuit simulation.

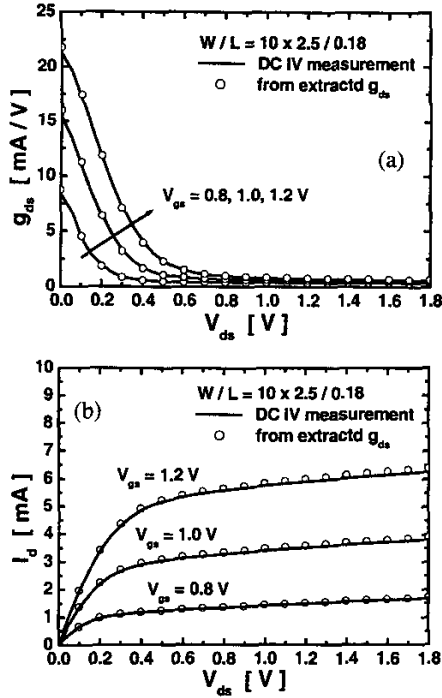


Figure 6: DC measurement vs. extracted results from S -parameters: (a) g_{ds} vs. V_{ds} , (b) I_d vs. V_{ds} .

In Fig. 7, C_{jd} and R_{sub} are presented as a function of drain voltage. As the drain bias increases, C_{jd} and R_{sub} decrease as expected. Also, R_{sub} was extracted for devices with different geometries as shown in Fig. 8. Four devices with various widths of body contacts were measured. The body contacts were placed as vertical strips along the both sides of the device. Fig. 8 shows that extracted R_{sub} is inversely proportional to the width of body contacts W_b as we expected, which indicates that R_{sub} values extracted using the proposed method offer the scalable results.

V. CONCLUSIONS

An approximated 3 terminal small-signal equivalent circuit fully compatible with 4 terminal quasi-static I - V and Q - V model is proposed for two-port s -parameter measurement with very simple and accurate parameter extraction method. The parameters can be extracted directly from the real and imaginary parts of Y -parameters. Without any complex fitting or optimization step, the total root-mean-square error between the modeled and measured Y -parameters is only 1.8%. Especially, the necessity of non-reciprocal capacitances is emphasized for accuracy in AC

circuit simulation. We investigated the bias dependence of small-signal parameters extracted using the proposed method such as intrinsic capacitances and conductances, and substrate parameters. It is found that one accurate large-signal I - V model is enough to be used for DC, low-frequency analog, as well as RF circuit simulation. We also found the R_{sub} shows scalable behavior, demonstrating the accuracy of the proposed model.

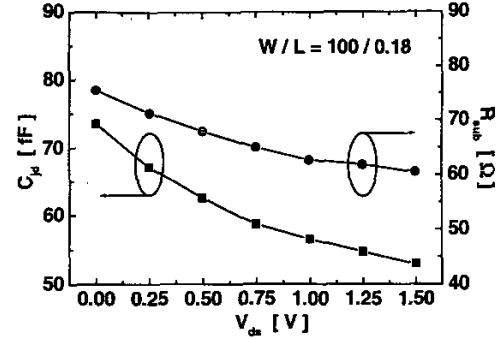


Figure 7: C_{jd} and R_{sub} as a function of V_{ds} .

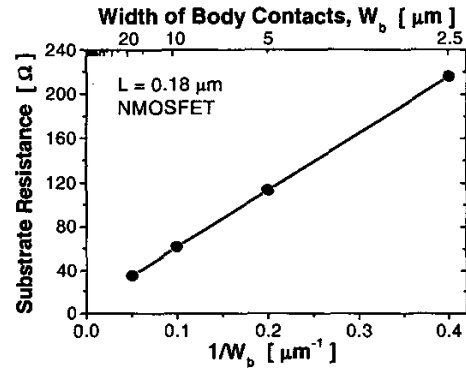


Figure 8: C_{jd} and R_{sub} as a function of width of body contacts, W_b .

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