Accurate Four-Terminal RF MOSFET Model Accounting for the Short-Channel Effect in the Source-to-Drain Capacitance

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Abstract—**A four-terminal RF MOSFET model to accurately describe the three-port network characteristics is presented. It has been found that the short-channel effect in the source-to-drain capacitance plays a critical role in predicting behavior of the MOSFET in the common-gate/body configuration. Performance of the developed model was verified with the device simulation results.**

Keywords-CMOS RF modeling; Parameter extraction; Three-port modeling; Four-terminal modeling; Non-quasi-static effect; Substrate signal coupling; Short-channel effect

I. INTRODUCTION

The MOSFET is a four-terminal device and requires three-port network parameters to describe its small-signal behaviors completely [1]. In spite of this fact, the MOSFET has been modeled as a three-terminal device in the RF range in many works [2] to simplify the modeling procedure. It has been claimed that the MOSFET can be handled as a three-terminal device when its source and body terminals are tied together as in many applications. However, it is not true because, even for this configuration, the potential of the intrinsic body node is neither the same as the extrinsic body terminal nor as the source [1]. Although some recent works [3] have introduced the four-terminal models for RF MOSFETs, it has not been shown that the models can describe the three-port characteristics successfully.

In this work, an accurate four-terminal RF MOSFET model is presented, of which the parameters can be completely extracted from the two-port *Y*-parameter data. Extraction from the two-port data is very important because there is no established measurement technique to perform an on-wafer three-port *S*-parameter measurement valid up to several tens of *GHz*. The constructed model was shown to accurately predict not only the two-port but also the three-port characteristics with considering the short-channel effect in C_{sd}.

II. FOUR-TERMINAL MODELING WITH ACCURATE C_{sd}

Fig. 1 shows the equivalent circuit model used in this paper, which is valid in all regions of device operation. It includes the series parasitic resistances (R_g, R_s, R_d), extrinsic gate capacitances (C_{gs0}, C_{gd0}, C_{gb0}), and junction capacitances (C_{js}, C_{jd}). R_{dsb}, R_{sb}, and R_{db} represents the bulk spreading resistances for describing the substrate-signal-coupling (SSC) effect [3]. The intrinsic *y*-parameters are given by the first-order approximation of the non-quasi-static (NQS) model [4]. They were simplified to have only two time constants: τ for the charging delay and τ_m for the transport delay.

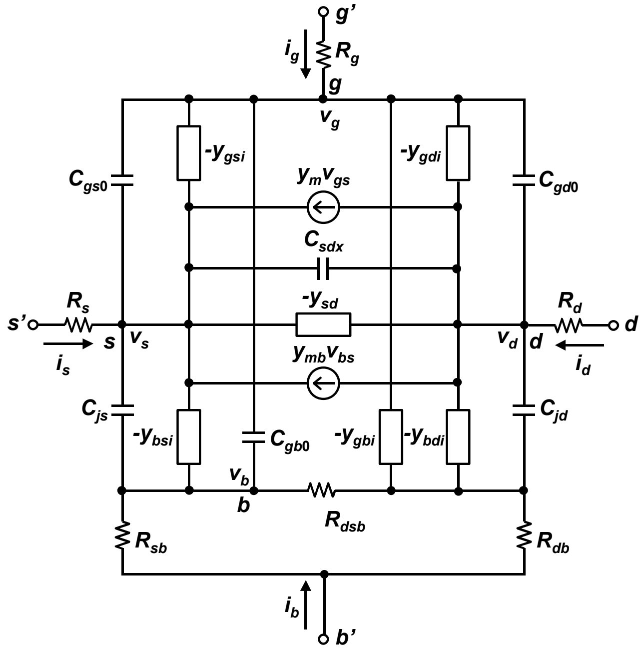

Figure 1. Small-signal equivalent circuit model of RF MOSFETs improved with C_{sdx}.

The conventional four-terminal NQS models don't have the component C_{sdx} shown in Fig. 1, which was included for considering the short-channel effect in C_{sd}. C_{sd} is negative in non-saturation and becomes zero in saturation for long-channel devices [4]. However, a modern short-channel device can have a positive C_{sd} due to the DIBL effect [5]. Without C_{sdx}, C_{sd} in our model is given by $-\tau_m g_{sd}$, where g_{sd} is a drain conductance, and always has a negative or zero quantity. As a result, modification is required for enabling C_{sd} to be positive and an additional component C_{sdx} was used. With C_{sdx}, C_{sd} is given by $C_{sdx}-\tau_m g_{sd}$. Fig. 2 shows the C_{sd} versus voltage characteristics

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This work was supported by the National Program for Tera-level Nano Devices in 2003 through MOST.

obtained from the device simulation of a 0.3-μm-long n-MOSFET. As expected, C_{sd} increases with V_{DS} at fixed V_{GS}, while C_{sd} has a maximum value near threshold voltage (0.5 V for this device) and decreases with V_{GS} over the threshold at fixed V_{DS}. The imaginary part of Y_{sd} defined by

$$Y_{sd} = i_s / v_d \big|_{v_g=v_s=v_b=0} \qquad (1)$$

is very sensitive to C_{sd} and hence, varies with V_{DS} significantly as shown in Fig. 3. By analyzing the circuit shown in Fig. 1, Im(Y_{sd}) in the low-frequency range is obtained as

$$\mathrm{Im}(Y_{sd}) = -\omega(C_{sd} + g_{mb}R_{sub}C_{bd}) \qquad (2)$$

and as C_{sd} increases to the positive, the slope of Im(Y_{sd}) in the low-frequency range becomes more negative. The value of C_{sd} can be obtained by fitting Im(Y_{sd}).

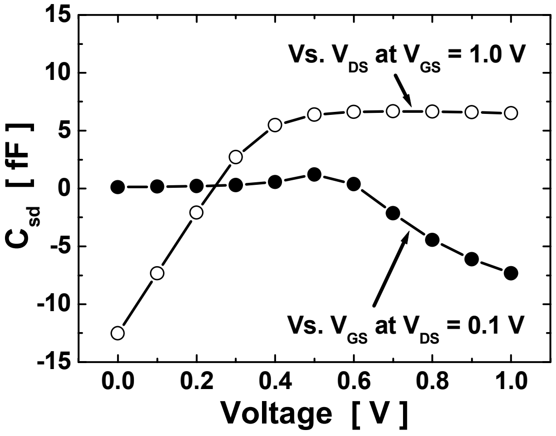


Figure 2. C_{sd} vs. V_{GS} at V_{DS} = 0.1 V and C_{sd} vs. V_{DS} at V_{GS} = 1 V.

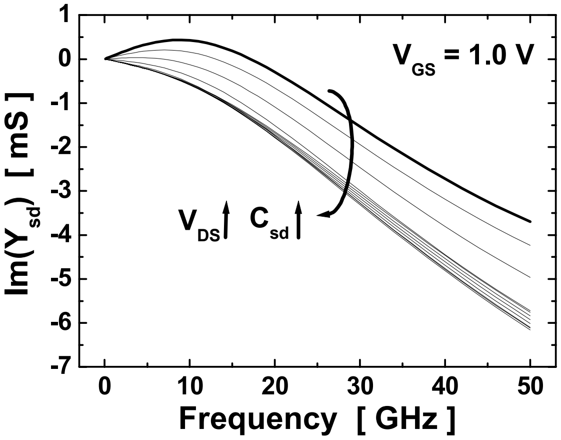
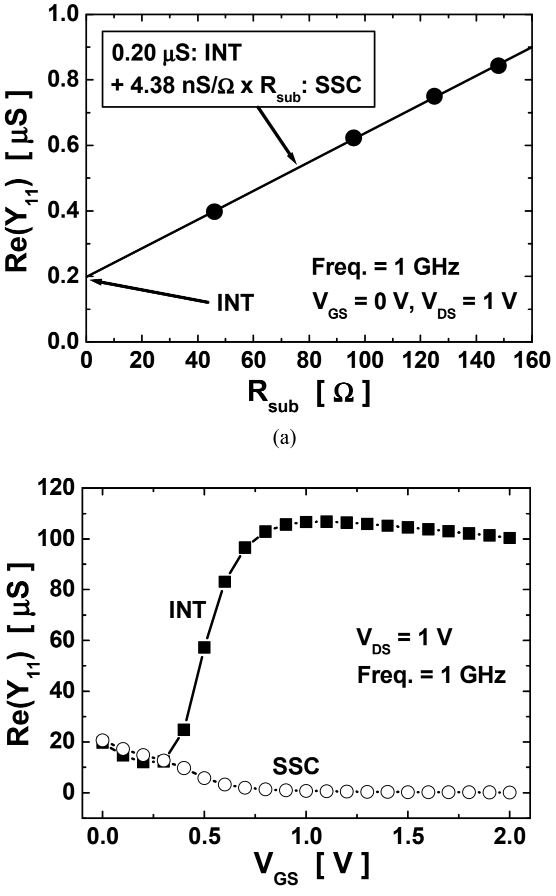


Figure 3. Im(Y_{sd}) vs. frequency curves with varying V_{DS} at V_{GS} = 1 V.

III. RESULTS AND DISCUSSIONS

Four 0.3-μm-long n-MOSFETs with different substrate resistance values and identical intrinsic characteristics were simulated to decompose each Y-parameter into the intrinsic component and the SSC component. Decomposition was performed assuming that the three substrate resistances in Fig. 1 can be approximated as a single substrate resistance at low frequencies. This decomposition technique enables the complete extraction of the four-terminal parameters from the two-port data measured in the common-source/body configuration and the detailed procedure will be reported as a separate paper.



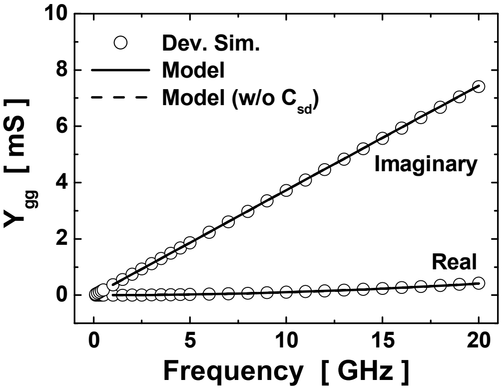
(a)

(b)

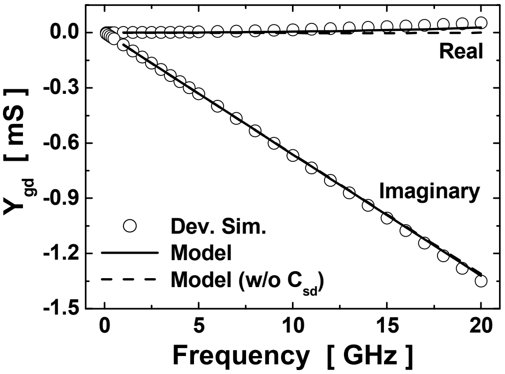
Figure 4. Decomposition example of Re(Y_{11}): (a) decomposition process, (b) decomposition results.

Decomposition example for Re(Y_{11}) is shown in Fig. 4. Re(Y_{11}) was fitted to a linear function of substrate resistance as shown in Fig. 4(a) and the results are shown in Fig. 4(b). The intrinsic term of Re(Y_{11}) include (C_{gs}+C_{gd}) and shows its corresponding gate bias dependence while the SSC term of Re(Y_{11}) decreases with V_{GS} due to C_{gb}. Note that, from the data simulated at V_{DS} = 0 V with varying V_{GS}, R_g, R_s, and R_d were extracted and removed [6] before decomposition. The value of C_{sdx} was extracted from Im(Y_{sd}). Y_{sd} can be obtained for the real devices from the two-port S-parameter measurement made in common-gate/body configuration. At V_{GS} = V_{DS} = 1 V and V_{BS} = 0 V, C_{sdx} was 8.9 fF, which resulted in 6.5 fF of C_{sd}.

Fig. 5 shows the three-port results from the model compared with the device simulation data. Assigning the body terminal as a reference node, the network parameters were obtained for the three-ports: gate, source, and drain. A total of nine parameters – Y_{gg}, Y_{gd}, Y_{gs}, Y_{dg}, Y_{dd}, Y_{ds}, Y_{sg}, Y_{sd}, and Y_{ss} – determine the three-port network characteristics. An excellent accuracy of the developed model was verified up to 20 *GHz*, while the model without C_{sdx} failed to describe Im(Y_{sd}) accurately.



(a)



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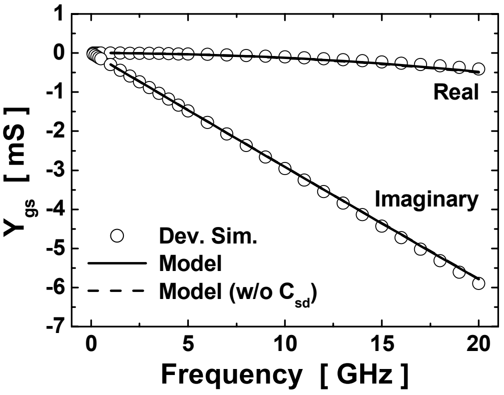

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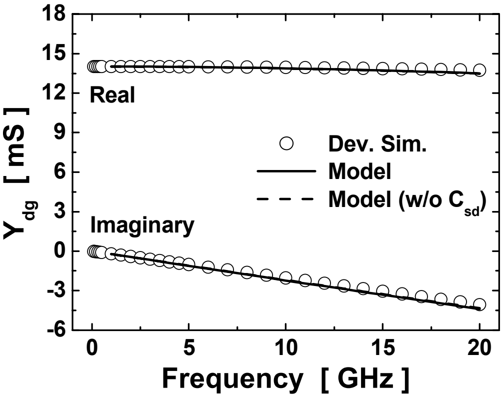

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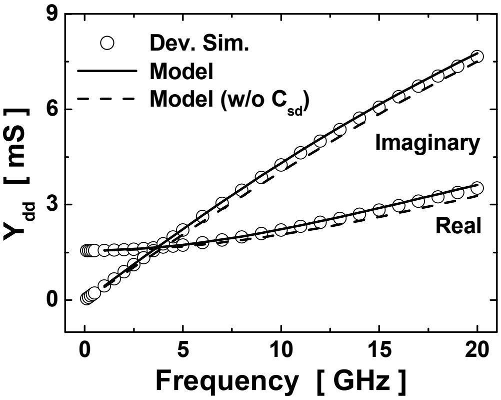

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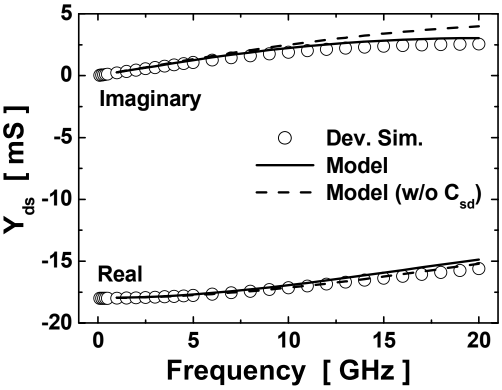

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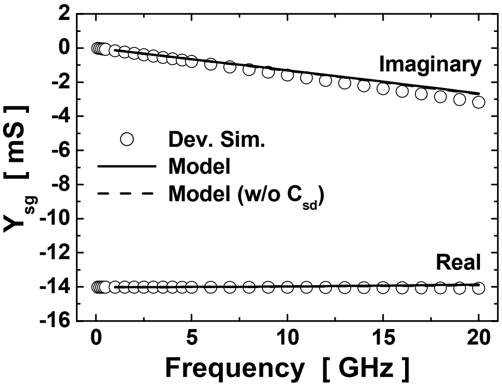

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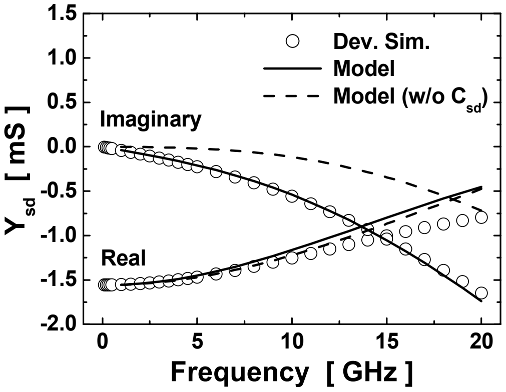

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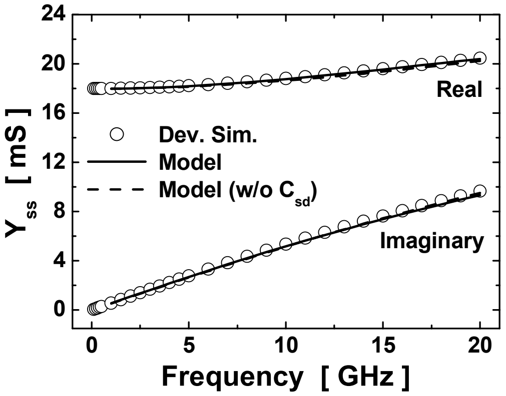

(i)

Figure 5. Three-port *Y*-parameters from the model and the device simulation at $V_{GS} = V_{DS} = 1$ *V*: (a) Y_{gg}, (b) Y_{gd}, (c) Y_{gs}, (d) Y_{dg}, (e) Y_{dd}, (f) Y_{ds}, (g) Y_{sg}, (h) Y_{sd}, (i) Y_{ss}.

IV. CONCLUSIONS

An accurate four-terminal RF MOSFET model has been presented with its parameter extraction scheme. An additional component was used in the equivalent circuit model to consider the short-channel effect in C_{sd} and excellent accuracy in predicting the three-port device characteristics was verified up to 20 *GHz* with the device simulation results.

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