Accurate Small-Signal Model and Its Parameter Extraction in RF Silicon MOSFETs

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ABSTRACT

An accurate method to extract a small signal equivalent circuit model of RF Silicon MOSFETs is presented. Analytical calculations are used for each intrinsic parameter and accuracy is within 1% for *the entire operational region*. 2-D physical device simulation is used to analyze this methodology. A simple non-quasi static (NQS) model is reported, which offers good accuracy needed for circuit simulation, including simple network representing the coupling between source and drain. Accurate extraction method of extrinsic parameters have been also developed. The compact model and its parameter extraction are verified on Si-MOSFETs through s-parameter measurements.

INTRODUCTION

Standard CMOS technology has become a popular choice for realizing radio frequency (RF) application. A critical issue for RF design is the availability of accurate compact model. Unfortunately the most of the commercially available MOS transistor model is not particularly suited for high frequency. In this report, we propose that the substrate network [4-6] is not necessary because its effect is overshadowed by the coupling between source and drain. Also accurate modeling of NQS effect is discussed, which is closely related to induced gate noise. Through the knowledge of accurate intrinsic characteristic, de-embedding of extrinsic parasitics is developed. The complete small-signal model of the intrinsic device is developed from the physically-based device simulation. The methodology developed through the device simulation is applied to RF Si-MOSFET to verify its robustness.

SMALL SIGNAL EQUIVALENT CIRCUIT MODEL

Design of very high-frequency circuits is often done by using the so-called "y-parameters". Without any assumption except that it has four terminals, general y-parameter model [1] is shown in Fig, 1. Thus by examining the frequency response of y_{gs}, y_{gd}, y_{gb}, y_m, y_{mx}, y_{bd}, y_{bs}, y_m, y_{mb}, and y_{mx} through 2-D device simulation, circuit model is developed.

NQS MODEL

The distributed effect along the channel length is commonly modeled as a bias-dependent RC distributed transmission line as shown in Fig. 2. The most widely used NQS model [7] is the series RC circuit as shown in Fig. 3. However, the characteristic of the parameters, R_{gs} and R_{gd}, are not well known. The corresponding conductance and capacitance can be written as:

$$-y_{gs} = \frac{R_{gs}C_{gs}^2\omega^2}{D_{gs}} + j\omega\frac{C_{gs}}{D_{gs}}, -y_{gd} = \frac{R_{gd}C_{gd}^2\omega^2}{D_{gd}} + j\omega\frac{C_{gd}}{D_{gd}} \quad (1)$$

$$D_{gs} = 1 + (\omega C_{gs}R_{gs})^2, D_{gd} = 1 + (\omega C_{gd}R_{gd})^2$$

The R_{gs} and R_{gd} are bias dependent and $R_{gd} \neq R_{gs}$, except when V_{ds}=0, in contrast to BSIM4 model. Van der Ziel has shown that the admittance to have a real part that grows as the square of frequency [3] as shown in Fig. 4. This frequency dependent admittance comes from the channel resistance coupled through gate capacitance and is the source of the gate induced noise. To extract accurate gate induced noise coefficient, gate resistance (i.e., gate contact resistance and poly sheet resistance) need to be de-embeded properly. The equation (1) accurately represents the behavior of Y_{11} and Y_{22}.

TRANSCONDUCTANCE AND TRANSCAPACITANCE

The $|y_{mb}|$ in Fig. 1 is about 10% to 30% of the $|y_m|$ at low frequency. However as frequency increases, y_{mb} decreases appreciably compared to y_m due to the fact that effective ac voltage drop (V_{bseff}) across source to substrate junction decreases as more voltage drops in the substrate with increasing frequency. The y_{mx} is usually ignored even at low frequency. The simulated y_m, y_{mb}, and y_{mx} are compared in Fig. 5. Therefore y_{mb} and y_{mx} in Fig. 1 can be ignored without hurting the RF characteristics.

COUPLING BETWEEN SOURCE AND DRAIN

The incremental charge method of capacitance calculation is absolutely inapplicable in the case of large conduction current in the device (i.e., between source and drain), which is often the case when the capacitance is negative and strongly frequency dependent (i.e., C_{sd} and C_{ds}) [2] as shown in Fig. 6. This frequency dependence contradicts the most of the commercially available model such as BSIM4. The frequency dependence of y_{sd} can be modeled using the circuit shown in Fig. 3. The C_b, C_j, R_b, and R_{sdi} are model parameters to represent the frequency behavior of G_{sd} and C_{sd}. This coupling between source and drain dominates over substrate on the output characteristic (i.e., $G_{sd} \gg G_{bd}$, and $C_{sd} \gg C_{bd}$) as shown in Fig. 7, which means the substate network is not necessary to represent the output characteristic (i.e., Y_{22}). Thus the y-parameter model in Fig.1 can be simplified as the model in Fig. 3. Note that y_{gb} is lumped with y_{gs} together.

INTRINSIC PARAMETER EXTRACTION

All the parameters in Fig. 3 can be analytically extracted given measured s-parameters. Fig. 8 shows some of the extracted parameters. Device simulations shows that the relative error between simulated and constructed s-parameters is within 1% for the entire operational region confirming the validity of the model. Fig. 9 shows *S*-parameters constructed from extracted model parameters compared with *S*-parameters from measurement. Virtually all agree very well.

EXTRINSIC PARAMETER EXTRACTION

It is crucial to separate extrinsic parasitics to model intrinsic device behavior at the *GHz* frequencies. After standard pad de-embedding procedure (i.e., ISS, SOLT), parasitics such as contact resistance, poly gate resistance, or bond wire connecting the device need to be extracted. The general representation of the extrinsic parasitics are shown in Fig. 10. Through the accurate knowledge of frequency behavior of intrinsic device at RF, the extrinsic parasitics are extracted using non-linear curve fitting at $V_{gs} = \infty$, and $V_{ds} = 0$ as shown in Fig. 11. This method is shown to have error less than 2%.

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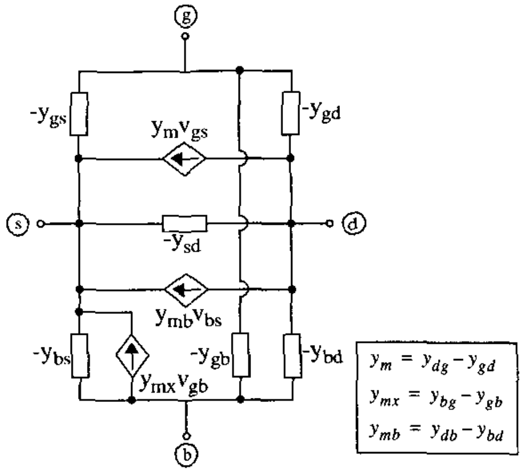

Fig. 1. General y-parameter model for 4 terminal device.

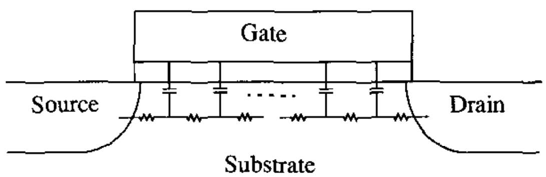

Fig. 2. Commonly used distributed RC network scheme to model NQS effect.

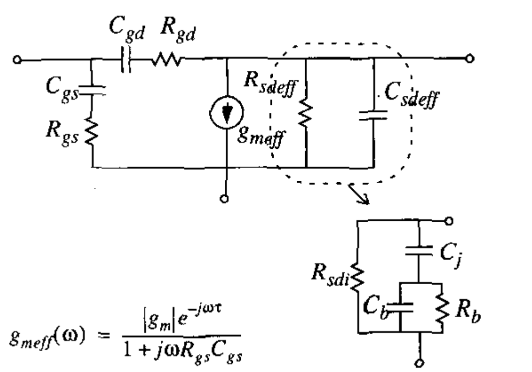

Fig. 3. Proposed RF small-signal model for MOSFET. g_{meff} is frequency dependent and shows decreasing characteristic as frequency increase. R_{sdeff} and C_{sdeff} are also frequency dependent and are represented by non-frequency dependent parameters (R_{sdi}, C_j, C_b, and R_b).

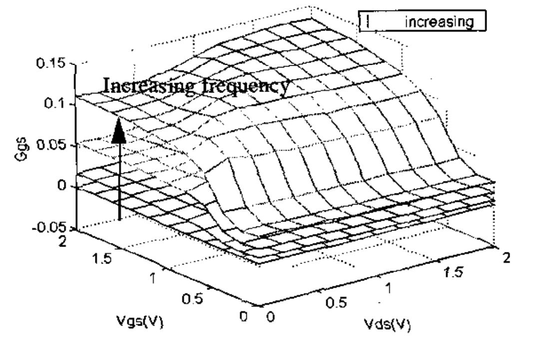

Fig. 4. Frequency response of measured G_{gs} (*W/L* = 30.24 *um* / 0.3 *um*). The frequencies are 1.7 *GHz*, 9.2 *GHz*, 16.7 *GHz*, and 24.2 *GHz*. The box 'increasing' means the absolute parameter value is increasing with increasing frequency. Note that all parameters in this report are normalized by Zo = 50Ω

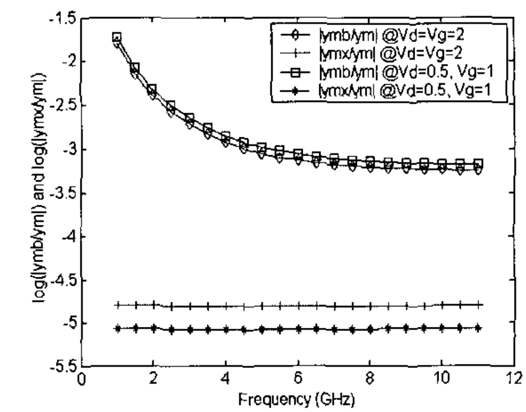

Fig. 5. The frequency response of simulated $|y_m|$, $|y_{mb}|$, and $|y_{mx}|$ from (*W/L* = 30.24 *um* / 0.3 *um*).. The $|y_{mb}|$ becomes less than 0.1% of $|y_m|$ at 0.1 f_T

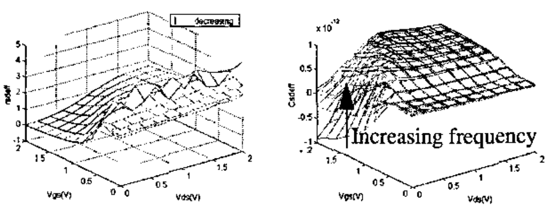

Fig. 6. The extracted R_{sdeff} and C_{sdeff} from S-parameter measurements. C_{sdeff} shows strong frequency dependence in linear region. R_{sdeff} also shows strong frequency dependence in subthreshold region

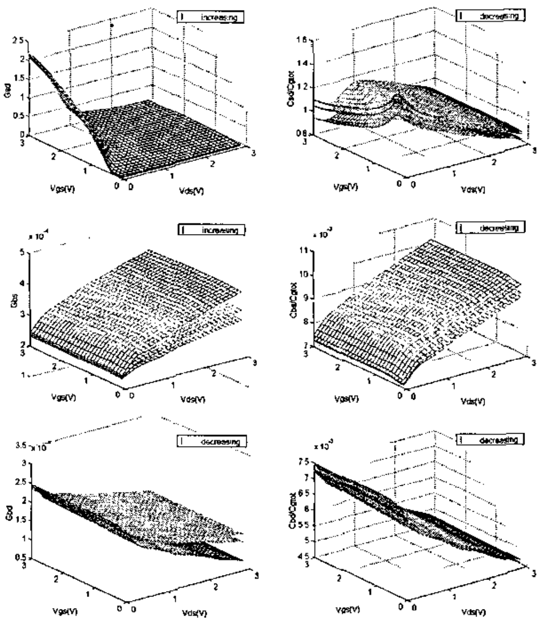

Fig. 7. The simulated frequency response of C_{sd}, C_{bs}, C_{bd}, G_{sd}, G_{bs}, and G_{bd}. The frequencies are 0.1*GHz*, 5 *GHz*, and 10 *GHz*.

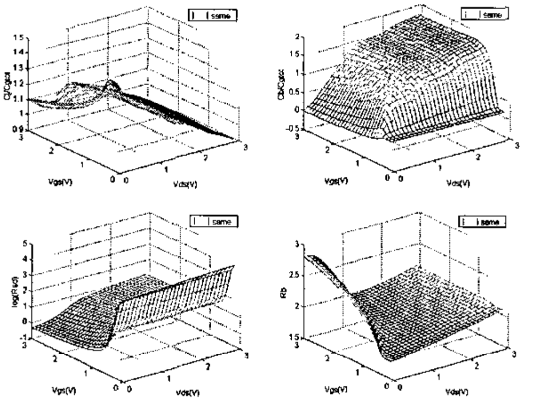

Fig. 8. The extracted parameters (C_b, C_j, R_b, and R_{sdi}). These parameters represent R_{sd} and C_{sd} as in Fig. 8.

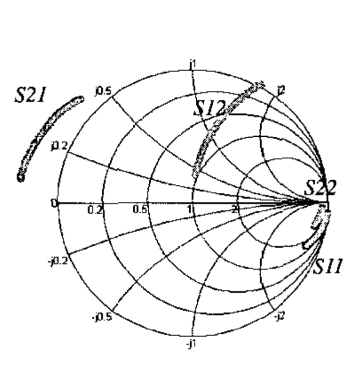

Fig. 9. Measured S-parameter (yellow) compared with model (others) ($V_{ds}=1.8V$, $V_{gs}=2.0V$)

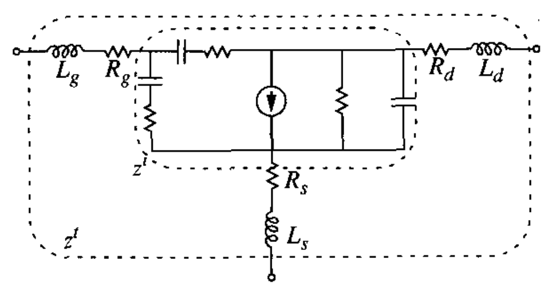

Fig. 10. MOSFET with a generalized extrinsic parasitics.The z^i represents intrinsic device including source and drain. L_g, L_d, L_s, R_g, R_s, and R_d (i.e., contact resistance, bond wires) are extrinsic parasitics.

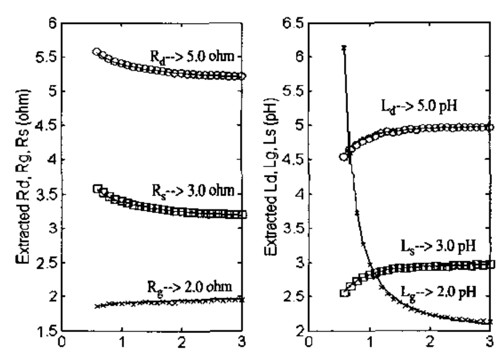

Fig. 11. Non-linear curve fitting (line) of extracted extrinsic parameters (symbol) at $V_{ds} = 0$. The extracted R_d, R_g and R_s converges correct values when V_{gs} approaches infinite.