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Large-Signal Output Equivalent Circuit Modeling for RF MOSFET IC Simulation

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***Abstract*—An accurate large-signal BSIM4 macro model including new empirical bias-dependent equations of the drain-source capacitance and channel resistance constructed from bias-dependent data extracted from S-parameters of RF MOSFETs is developed to reduce S_{22}-parameter error of a conventional BSIM4 model. Its accuracy is validated by finding the much better agreement up to 40 GHz between the measured and modeled S_{22}-parameter than the conventional one in the wide bias range.**

***Index Terms*—CMOS, MOSFET, RF, modeling, drain-source capacitance, channel resistance, SPICE, parameter extraction, BSIM**

I. INTRODUCTION

Recently, owing to the rapid growth of wireless communication markets, the demand for RF transceivers is increasing. Silicon integrated circuits (ICs) with excellent price competitiveness have been widely used. For the design of RF CMOS IC, the development of accurate RF large-signal MOSFET model to simulate its high-frequency characteristics is essential.

BSIM4 [1] (Berkeley Short-Channel IGFET Model 4) macro model including external resistances, capacitances or diodes [2-5] has been widely used for SPICE RF IC large-signal simulation. However, an inadequacy to simulate output characteristics such as S_{22}-parameter in various bias points has been well known. In particular, accurate large-signal output admittance modeling is very important to simulate output impedance matching circuits in designing RF ICs.

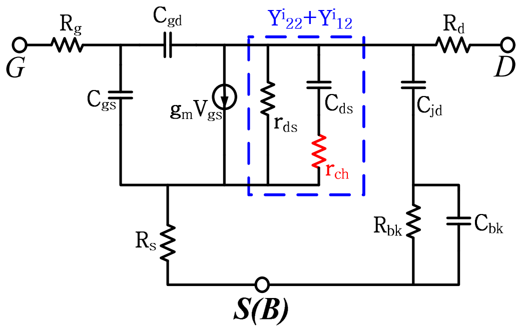

Fig. 1. A small-signal MOSFET equivalent circuit model

Recently, it has physically been verified that the drain-source capacitance C_{ds} should be connected in series with the channel resistance r_{ch} in the intrinsic output of a small-signal MOSFET equivalent circuit in Fig. 1 [6]. It has also been observed that C_{ds} and r_{ch} has strong bias-dependence.

However, in the conventional BSIM4 model, r_{ch} is not considered and C_{ds} is bias-independent. Thus, the conventional model is not appropriate for simulating high-frequency S_{22}-parameter in various bias points.

Therefore, in this paper, we propose a new large-signal BSIM4 macro model including the empirical bias-dependent equations of C_{ds} and r_{ch} constructed from measured S-parameter sets of RF MOSFETs in various bias range.

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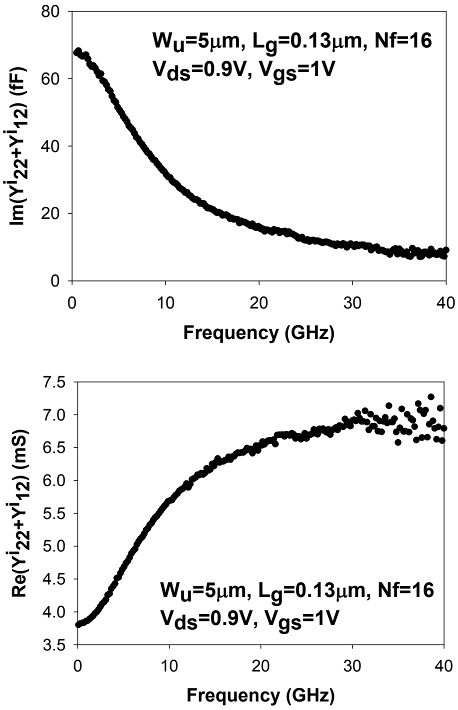

Fig. 2. $(1/\omega)\mathrm{Im}(Y^i_{22}+Y^i_{12})$ and $\mathrm{Re}(Y^i_{22}+Y^i_{12})$ versus frequency

II. PARAMETER EXTRACTION

S-parameters are measured on multi-finger N-MOSFETs with the gate length (L_g=0.13μm), the gate finger number (Nf=16) and the unit finger width (W_u=5μm). An accurate de-embedding procedure was carried out to remove pad and interconnection parasitics from measured S-parameters [7, 8]. After the series resistances (R_d, R_g, R_s) and substrate parameters (C_{jd}, R_{bk}, C_{bk}) are determined at V_{gs} = 0V by using the RF direct extraction method [9, 10], Y^i-parameters are determined by subtracting them from the measured S-parameters.

The intrinsic output equivalent circuit of most BSIM4 macro models used in general has only one output resistance r_{ds} that is the DC drain-source resistance due to the channel length modulation in the saturation region. Thus, it is unable to model the frequency-dependent characteristics of intrinsic effective drain-source capacitance $(1/\omega)\mathrm{Im}(Y^i_{22}+Y^i_{12})$ and drain-source conductance $\mathrm{Re}(Y^i_{22}+Y^i_{12})$ shown in Fig. 2.

In order to simulate the decrease of $(1/\omega)\mathrm{Im}(Y^i_{22}+Y^i_{12})$ as well as the increase of $\mathrm{Re}(Y^i_{22}+Y^i_{12})$ with the frequency simultaneously, a physically acceptable intrinsic output equivalent circuit with C_{ds} and r_{ch} in Fig.

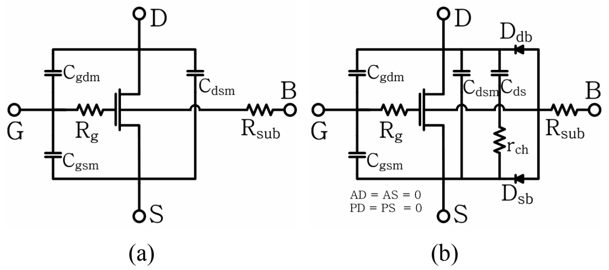

Fig. 3. Two modified BSIM4 macro large-signal models (a) Conventional BSIM4 macro model, (b) A new BSIM4 macro model adding C_{ds} and r_{ch}

1 should be used.

However, a conventional BSIM4 macro model in Fig. 3(a) is inaccurate to simulate output characteristics because C_{ds} and r_{ch} are not considered. The parasitic capacitances between metal interconnects (C_{gsm}, C_{gdm}, C_{dsm}) and external resistances (R_g, R_{sub}) are added as external macro elements in Fig. 3.

Thus, in this work, a new RF MOSFET macro model where C_{ds} and r_{ch} are added to the conventional model of Fig. 3(a) is proposed in Fig. 3(b). The intrinsic drain/source-bulk junction diodes (D_{db}, D_{sb}) are removed by setting AD=AS=PD=PS=0 in conventional BSIM4 model for including C_{ds} and r_{ch} in the new model. As shown in Fig. 3(b), the new model is constructed by adding C_{ds}, r_{ch}, D_{db} and D_{sb} to outside of BSIM4.

In order to construct large-signal model equations of C_{ds} and r_{ch}, bias-dependent C_{ds} and r_{ch} data are extracted using small-signal MOSFET equivalent circuit model in Fig. 1.

The C_{ds} values are obtained from low-frequency(LF) data of Y^i-parameter derived from Fig. 1:

$$C_{ds} = \frac{1}{\omega}\mathrm{Im}(Y^i{}_{22} + Y^i{}_{12})_{LF} \tag{1}$$

Fig. 4 shows the extracted C_{ds} as a function of V_{gs} at various V_{ds} using (1). This bias-dependence of C_{ds} can be explained by a physical cross-section of MOSFET in the saturation region in Fig. 5. Since C_{ds} is the depletion capacitance between the drain and the end of the channel, C_{ds} rises with increasing V_{gs} or decreasing V_{ds} due to the shrinkage of the depletion width [6].

To determine the channel resistance r_{ch} directly, the following equation combining the real and the imaginary part of the Y^i-parameters is derived by [6]:

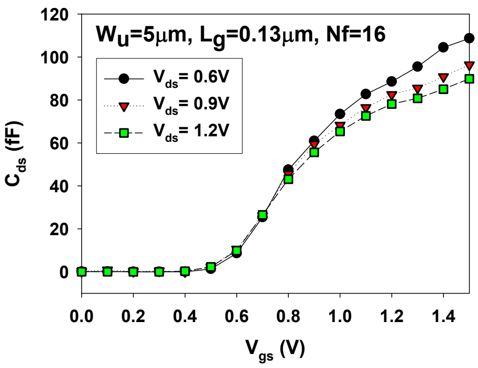

Fig. 4. Extracted values of C_{ds} against V_{gs} at various V_{ds}

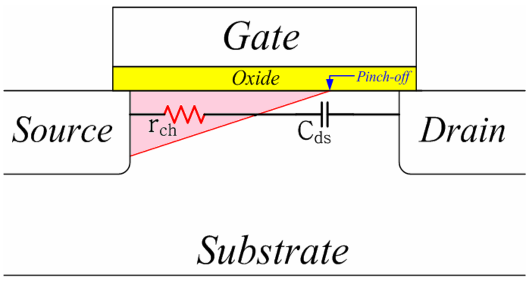

Fig. 5. MOSFET cross-section showing C_{ds} and r_{ch} components in saturation region

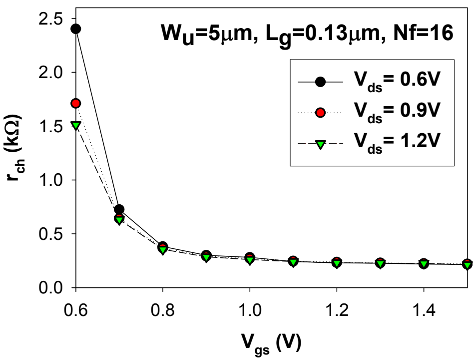

Fig. 6. Extracted values of r_{ch} against V_{gs} at various V_{ds}

$$r_{ch} = \frac{\mathrm{Re}(Y^{i}_{22} + Y^{i}_{12} - 1/r_{ds})}{\omega C_{ds}\,\mathrm{Im}(Y^{i}_{22} + Y^{i}_{12})} \tag{2}$$

where r_{ds} is extracted from $1/\mathrm{Re}(Y^{i}_{22})$ in the low-frequency region.

Fig. 6 shows the extracted r_{ch} as a function of V_{gs} at various V_{ds} using (2). It is observed that r_{ch} decreases with increasing V_{gs} or V_{ds}. Since r_{ch} is the series resistance existing in the inversion channel in the saturation region in Fig. 5, the decrease of r_{ch} at higher V_{ds} is caused by the channel length reduction due to the increase of depletion width between drain and channel end. In addition, the reduction of r_{ch} with increasing V_{gs} is explained by the rise of conductivity due to the increase of inversion charge.

III. MODELING

In order to model bias-dependence of C_{ds}, a new V_{gs}-dependent empirical equation with a hyperbolic tangent function is proposed:

$$C_{ds} = a\left[1 + \tanh\left(\frac{V_{gs} - V_{th} - b}{c}\right)\right](V_{gs} + d) \tag{3}$$

The abrupt increase of C_{ds} after the channel formation in the V_{gs} range of above threshold voltage V_{th} in Fig. 4 is modeled by a tanh function of V_{gs} in (3). The smaller increase of C_{ds} at V_{gs} > 0.9V is due to the shrinkage of the depletion width between the drain and channel end, and is modeled by a linear function of V_{gs} in (3).

The V_{ds}-dependent data of a, b, c, and d are extracted by fitting (3) to match with the V_{gs}-dependent C_{ds} data at each V_{ds} in Fig. 4. To model these V_{ds}-dependent data of a, b, c, and d empirically, the following V_{ds}-dependent fitting equations are used:

$$a = a_0 + a_1 \exp(-a_2 V_{ds}) \tag{4}$$

$$b = b_0 + b_1 V_{ds} \tag{5}$$

$$c = c_0 + c_1 V_{ds} \tag{6}$$

$$d = d_0 + d_1(1 - d_2^{\,V_{ds}}) \tag{7}$$

The above parameters (a_0=2.07257x10^{-14}, a_1=1.64342x10^{-13}, a_2=4.04279, b_0=0.703933, b_1= 9.45667x10^{-3}, c_0=0.128652, c_1=3.72167x10^{-2}, d_0=-4.2193, d_1=4.82713, d_2=2.66086x10^{-2}) are determined by fitting (4)-(7) to the extracted V_{ds}-dependent a, b, c, d data as close as possible, respectively.

In order to model bias-dependence of r_{ch}, a new V_{gs}-dependent model equation representing the channel resistance in the saturation region of $V_{gs} \geq V_{th}$ is proposed:

$$r_{ch} = \frac{1}{e(V_{gs} - V_{th})^2 + \delta} + f \tag{8}$$

where δ is a minimum value set to avoid the infinity at $V_{gs} = V_{th}$.

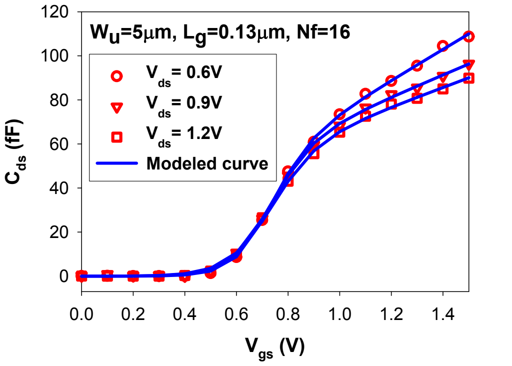

Fig. 7. Extracted and modeled C_{ds} against V_{gs} at various V_{ds}

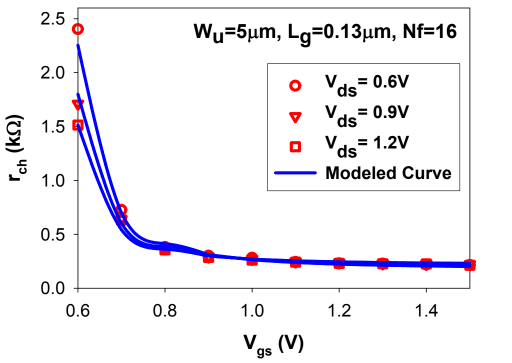

Fig. 8. Extracted and modeled r_{ch} against V_{gs} at various V_{ds}

As shown in Fig. 6, e is related to the decreasing rate of V_{gs} < 0.8V and f is a saturated value at high V_{gs}. The V_{ds}-dependent data of e and f are extracted by fitting (8) to the V_{gs}-dependent r_{ch} data at each V_{ds} in Fig. 6.

To model these V_{ds}-dependent data of e and f empirically, the following V_{ds} dependent equations are used:

$$e = e_0 + e_1 V_{ds} \tag{9}$$

$$f = f_1 V_{ds} / (f_2 + V_{ds}) \tag{10}$$

The above parameters (e_0=0.0194103, e_1=0.0480552, f_1=272.274, f_2=0.301099) are determined by fitting (9)-(10) to the extracted V_{ds}-dependent e and f data as close as possible, respectively.

Substituting all parameters extracted above into (4)-(7) for C_{ds} and (9)-(10) for r_{ch}, bias-dependent C_{ds} and r_{ch} model equations are finally constructed. In Fig. 7 and Fig. 8, bias-dependent data of V_{ds} and V_{gs} are compared with the modeled curves, showing excellent agreement.

In order to verify the accuracy of the new BSIM4 macro model with bias-dependent C_{ds} and r_{ch} empirical equations in Fig. 3(b), S_{22}-parameters for the new and conventional

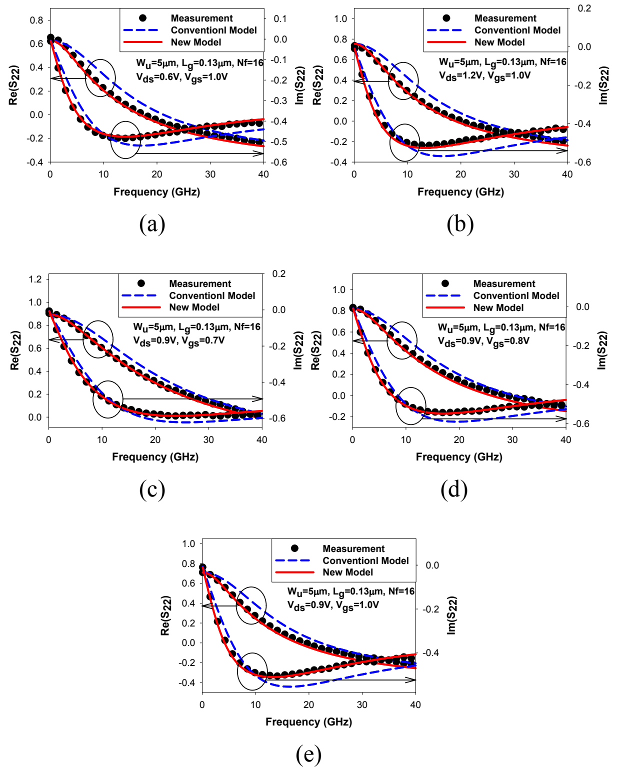

Fig. 9. Simulated S_{22}-parameter of conventional and new models compared with measured data at (a) V_{ds} = 0.6V, V_{gs} = 1.0V, (b) V_{ds} = 1.2V, V_{gs} = 1.0V, (c) V_{ds} = 0.9V, V_{gs} = 0.7V, (d) V_{ds} = 0.9V, V_{gs} = 0.8V, (e) V_{ds} = 0.9V, V_{gs} = 1.0V

models are compared with the measurement data at various bias points. For simulating two models in Fig. 3, same values of C_{gsm}, C_{gdm}, C_{dsm}, R_g and R_{sub} determined from measured S-parameters at V_{gs} = 0V are used.

As shown in Fig. 9, the new model shows much better agreement with the measured data up to 40 GHz than the conventional one, verifying the accuracy of the new one.

IV. Conclusions

In order to model the accurate RF large-signal output characteristics of RF MOSFETs, a new RF BSIM4 macro model is developed by connecting the series elements of C_{ds} and r_{ch} in parallel into the intrinsic output of a conventional BSIM4 model. Using bias-dependent C_{ds} and r_{ch} data extracted from S-parameter sets, the new empirical bias-dependent equations are constructed in various bias range. The new large-signal model has been demonstrated by observing the much better agreement up to 40 GHz between the measured and modeled data of S_{22}-parameter than the conventional one.

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