

## PARAMETER EXTRACTION METHODOLOGY FOR A SIMPLIFIED RF NMOSFET EQUIVALENT CIRCUIT

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*In this paper, a parameter extraction methodology is proposed for the simplified small-signal NMOSFET equivalent circuit utilizing Cadence PSpice circuit simulator. A direct extraction procedure is realized based on the two-port Y-parameters. Using postprocessing in the graphical analyzer Probe utilizing corresponding macrodefinitions, a Y- to S- parameter conversion is performed of the simulated results. The magnitude values of the measured S-parameters are introduced in the behavioral model using frequency-dependent elements of EFREQ type. Verification of the extraction methodology is made by comparing the simulated and experimental results for the S-parameters.*

**Keywords:** Cadence PSpice, simplified NMOSFET model, circuit simulations, parameter extraction, verification

### 1. INTRODUCTION

A variety of compact models have been of great interest and studied for deep submicron metal-oxide-semiconductor field effect transistor (MOSFET) simulation. The model parameters extraction intrinsically characterizes properties of designed and fabricated devices. One of the challenges for the MOSFET-based RF circuit design is the prediction of the RF transistor performance characteristics. Therefore robust characterization methodology for MOSFET is crucial for RF circuit simulations. Different approaches have been proposed [1-3]. The extraction procedures encounter serious problems in deep submicron dimensions, such as time-consuming, ineffective extraction process, poor accuracy, and lack the predictive capability in applications.

In this paper, a parameter extraction methodology is proposed for the simplified small-signal NMOSFET equivalent circuit. The extraction procedure is realized using the *Cadence PSpice* circuit simulator. Parameter extraction is performed from experimental results for a 0.35 $\mu\text{m}$  CMOS technology. A direct extraction procedure is realized based on the two-port Y-parameters.

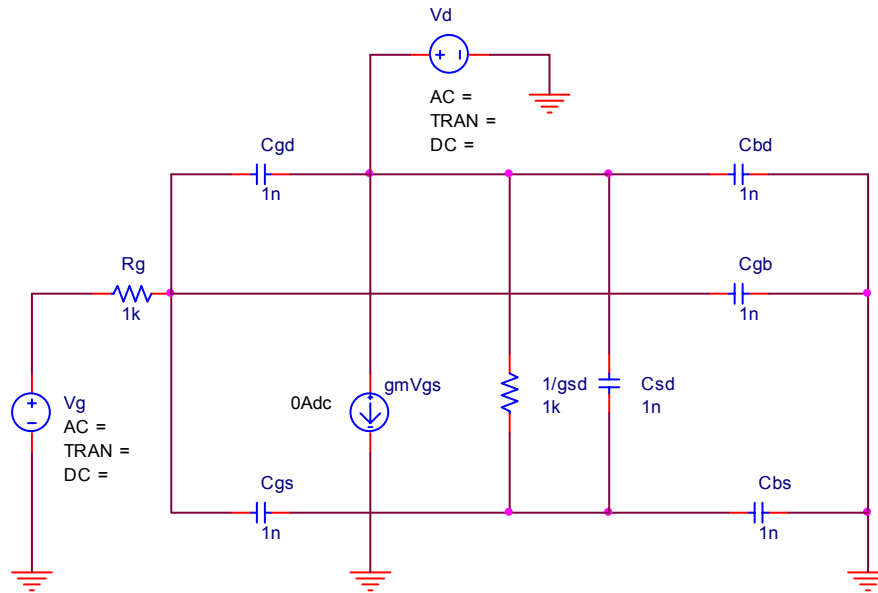
### 2. PARAMETER EXTRACTION FROM Y-PARAMETER MOSFET EQUIVALENT CIRCUIT

#### 2.1. Y-parameter definition for the equivalent circuit

Transistor impedance matching is critical in RF applications. Basic condition for a good prediction of input and output transistor characteristics is the proper definition of the intrinsic charges. These charge relations may be described in terms of

capacitances that depend on bias conditions [1, 2]. At high frequencies these intrinsic and extrinsic capacitances of the device typically dominate the responses and, hence, must be accurate.

In order to verify the intrinsic capacitances, a simplified NMOSFET equivalent circuit is used. The circuit is based on an assumption of steady-state (known as the quasistatic assumption) and is shown in Fig. 1 [1]. The circuit includes the gate resistance but neglects the drain and source resistances. Further, it is assumed that the bulk and source are effectively tied together so that the bulk transconductance and the source-bulk capacitance may be omitted.



**Fig. 1.** Equivalent quasi-static circuit for MOSFET configured for Y-parameter extraction

It is useful to use Y-parameter definitions in order to achieve expressions in terms of the intrinsic capacitances. The two-port Y-parameters are derived from the equivalent circuit shown in Fig. 1:

$$y_{11} = \left. \frac{I_g}{V_g} \right|_{V_d=0} = \frac{j\omega(C_{gs} + C_{gb} + C_{gd})}{1 + j\omega(C_{gs} + C_{gb} + C_{gd})R_g} \quad (1)$$

$$y_{12} = \left. \frac{I_g}{V_d} \right|_{V_g=0} = \frac{-j\omega C_{gd}}{1 + j\omega(C_{gs} + C_{gb} + C_{gd})R_g} \quad (2)$$

$$y_{21} = \left. \frac{I_d}{V_g} \right|_{V_d=0} = \frac{g_m - j\omega C_{gd}}{1 + j\omega(C_{gs} + C_{gb} + C_{gd})R_g} \quad (3)$$

$$y_{22} = \left. \frac{I_d}{V_d} \right|_{V_g=0} = j\omega(C_{sd} + C_{db}) + g_{sd} + \frac{j\omega C_{gd}(1 + g_m R_g + j\omega(C_{gs} + C_{gb})R_g)}{1 + j\omega(C_{gs} + C_{gb} + C_{gd})R_g} \quad (4)$$

## 2.2. Assumptions and parameter extraction

In order to extract the model parameters in Fig. 1 it is necessary to consider two boundary frequencies: low frequency  $f_l$ , and high frequency  $f_h$ . At low frequency  $f_l$  the following inequality is valid:

$$1 \gg j\omega_l (C_{gs} + C_{gb} + C_{gd})R_g \quad (5)$$

At high frequency  $f_h$  the inequality

$$j\omega_h \text{ s.m.t.} \gg \text{rest} \quad (6)$$

is valid.

For the transistor considered here, i.e. F300p35, the low frequency approximation holds up to approximately 1 ÷ 2GHz – we take  $f_l = 1\text{GHz}$ ; at high frequencies we take  $f_h = 12\text{GHz}$ . Taking into account the inequalities (5) and (6), a direct extraction procedure can be developed consisting of the following steps:

1) Extraction of the parameter  $R_g$  from  $y_{11}$  at  $f_h$ :

$$y_{11} \approx \frac{j\omega_h (C_{gs} + C_{gb} + C_{gd})}{j\omega_h (C_{gs} + C_{gb} + C_{gd})R_g} = \frac{1}{R_g} \Rightarrow R_g = \frac{1}{|y_{11}|_h} \quad (7)$$

2) Extraction of the parameter  $C_{gd}$  from  $y_{12}$  at  $f_l$ :

$$y_{12} \approx \frac{-j\omega_l C_{gd}}{1} = -j\omega_l C_{gd} \Rightarrow C_{gd} = \frac{|y_{12}|_l}{\omega_l} \quad (8)$$

3) Extraction of the parameter  $g_m$  from  $y_{21}$  and  $y_{12}$  at  $f_l$ :

$$y_{21} \approx \frac{g_m - j\omega_l C_{gd}}{1} = g_m - j\omega_l C_{gd} \Rightarrow g_m = \sqrt{|y_{21}|_l^2 + |y_{12}|_l^2} \quad (9)$$

4) Extraction of the parameter  $C'_{gs} = C_{gs} + C_{gb}$  from  $y_{21}$ ,  $y_{12}$  and  $y_{11}$  at  $f_l$  and  $f_h$ :

Let  $C'_{gs} = C_{gs} + C_{gb}$  since  $C_{gs}$  and  $C_{gb}$  are connected in parallel. At high frequencies

$$y_{12} \approx \frac{-j\omega_h C_{gd}}{j\omega_h (C_{gs} + C_{gb} + C_{gd})R_g} = \frac{-|y_{11}|_h}{C'_{gs}/C_{gd} + 1} \Rightarrow |y_{12}|_h = \frac{|y_{11}|_h}{C'_{gs}\omega_l/|y_{12}|_l + 1}$$

Hence

$$C'_{gs} = \frac{|y_{12}|_l}{\omega_l} \left( \frac{|y_{11}|_h}{|y_{12}|_h} - 1 \right) \quad (10)$$

5) Extraction of the parameter  $C'_{sd} = C_{sd} + C_{db}$  from  $y_{12}$  and  $y_{22}$  at  $f_h$ :

Let  $C'_{sd} = C_{sd} + C_{db}$  since  $C_{sd}$  and  $C_{db}$  are connected in parallel. At high frequencies

$$y_{22} \approx j\omega_h C'_{sd} + \frac{j\omega_h C_{gd}(1 + g_m R_g + j\omega_h (C_{gs} + C_{gb})R_g)}{j\omega_h (C_{gs} + C_{gb} + C_{gd})R_g} = j\omega_h \left( C'_{sd} + \frac{C_{gd} C'_{gs}}{C'_{gs} + C_{gd}} \right)$$

$$\Rightarrow |y_{22}|_h = \omega_h \left( C'_{sd} + \frac{C_{gd} C'_{gs}}{C'_{gs} + C_{gd}} \right) = \omega_h \left( C'_{sd} + C_{gd} \frac{1}{1 + C_{gd}/C'_{gs}} \right) \approx \omega_h (C'_{sd} + C_{gd})$$

The following inequality is valid:  $C_{gd}/C'_{gs} \ll 1$ .

$$\frac{C_{gd}}{C'_{gs}} = \frac{\frac{|y_{12}|_l}{\omega_l}}{\frac{|y_{12}|_l \left( \frac{|y_{11}|_h}{|y_{12}|_h} - 1 \right)}{\omega_l}} = \frac{|y_{12}|_h}{|y_{11}|_h - |y_{12}|_h};$$

$\frac{|y_{12}|_h}{|y_{11}|_h - |y_{12}|_h} \ll 1$  since from experimental data at high frequencies (i.e. 12 GHz) we

$$\text{have: } |y_{12}|_h = 3.42 \text{ [mS]} \text{ and } |y_{11}|_h = 26.92 \text{ [mS]} \Rightarrow \frac{|y_{12}|_h}{|y_{11}|_h - |y_{12}|_h} = \frac{3.4}{3.4 - 26.9} \approx 0.1 \ll 1$$

$$\text{Consequently } |y_{22}|_h = \omega_h (C'_{sd} + C_{gd}) \Rightarrow C'_{sd} = \frac{|y_{22}|_h}{\omega_h} - C_{gd} = \frac{|y_{22}|_h}{\omega_h} - \frac{|y_{12}|_l}{\omega_l}$$

$$C'_{sd} = \frac{|y_{22}|_h}{\omega_h} - \frac{|y_{12}|_l}{\omega_l} \quad (11)$$

6) Extraction of the parameter  $g_{sd}$  from  $y_{12}$  and  $y_{22}$ ,  $y_{21}$  and  $y_{22}$  at  $f_i$ :

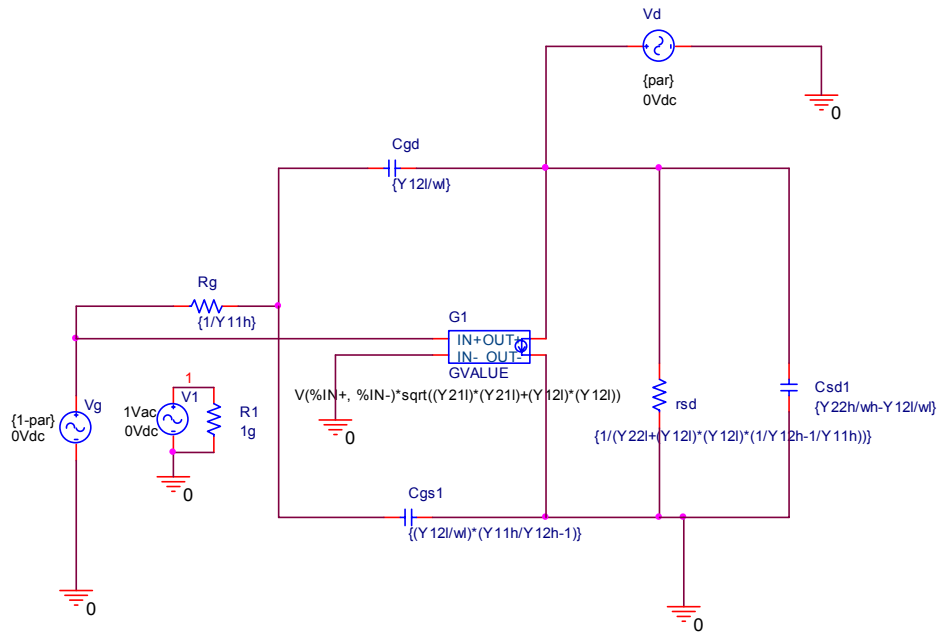
$$y_{22} \approx g_{sd} + \frac{j\omega_l C_{gd} (1 + g_m R_g + j\omega_l (C_{gs} + C_{gb}) R_g)}{1} \approx g_{sd} - \omega_l^2 C_{gd} C'_{gs} R_g \Rightarrow$$

$$|y_{22}|_l = g_{sd} - \omega_l^2 C_{gd} C'_{gs} R_g$$

$$\begin{aligned} g_{sd} &= |y_{22}|_l + \omega_l^2 C_{gd} C'_{gs} R_g = |y_{22}|_l + \omega_l^2 \underbrace{\frac{|y_{12}|_l}{\omega_l}}_{C_{gd}} \underbrace{\frac{|y_{12}|_l}{\omega_l} \left( \frac{|y_{11}|_h}{|y_{12}|_h} - 1 \right)}_{C'_{gs}} \underbrace{\frac{1}{|y_{11}|_h}}_{R_g} = \\ &= |y_{22}|_l + \frac{(|y_{12}|_l)^2}{|y_{11}|_h} \left( \frac{|y_{11}|_h}{|y_{12}|_h} - 1 \right); \quad g_{sd} = |y_{22}|_l + \frac{(|y_{12}|_l)^2}{|y_{12}|_h} - \frac{(|y_{12}|_l)^2}{|y_{11}|_h} \end{aligned} \quad (12)$$

Taking into account  $C'_{gs} = C_{gs} + C_{gb}$  and  $C'_{sd} = C_{sd} + C_{db}$  and the equations (7) ÷ (12) the modification of the equivalent circuit in Fig. 1 is constructed as shown in Fig. 2.

The experimental data given in [3] for the required Y-parameter values are used for the extraction procedure assuming the low frequency  $f_l = 1\text{GHz}$ , and high frequency  $f_h = 12\text{GHz}$  (Table 1 and Table 2). They are defined using PARAMETER statement in the computer model (Fig. 2). The component values are calculated in correspondence to the developed extraction procedure. The two-port Y-parameter calculation is reduced to parametric analysis with parameter  $par=0;1$  [5]. The parameters  $y_{11}$  and  $y_{21}$  are obtained for  $par=0$  and the parameters  $y_{22}$  and  $y_{12}$  are obtained for  $par=1$ . The corresponding parameters obtained from the simulation results of the BSIM3v3 model [3] are presented in Table 3 and Table 4.



**Fig 2.** Parameter extraction of the simplified NMOSFET equivalent circuit using Cadence PSpice simulator

Table 1

Table 2

Vgs = 0 V, Vds = 0 V

Vgs = 0.8 V, Vds = 1.0 V

1) F300p35 — Experimental

Y11l [mS]	1.949152542
Y11h [mS]	20.12711864
Y21l [mS]	0.46179966
Y21h [mS]	7.008488964
Y12l [mS]	0.522033898
Y12h [mS]	6.66779661
Y22l [mS]	1.694915254
Y22h [mS]	16.10169492
Wl [deg/s]	6.283185307 x 10 <sup>9</sup>
Wh [deg/s]	75.398223686 x 10 <sup>9</sup>

Y11l [mS]	2.79286927
Y11h [mS]	26.91850594
Y21l [mS]	0.320882852
Y21h [mS]	3.416808149
Y12l [mS]	1.740237691
Y12h [mS]	17.78438031
Y22l [mS]	2.003395586
Y22h [mS]	14.09168081
wl [deg/s]	6.283185307 x 10 <sup>9</sup>
wh [deg/s]	75.398223686 x 10 <sup>9</sup>

Table 3

Table 4

Vgs = 0 V, Vds = 0 V

Vgs = 0.8 V, Vds = 1.0 V

2) F300p35 — BSIM3v3

Y11l [mS]	1.86440678
Y11h [mS]	19.74576271
Y21l [mS]	0.379661017
Y21h [mS]	3.927118644
Y12l [mS]	0.351945854
Y12h [mS]	3.844331641
Y22l [mS]	2.118644068
Y22h [mS]	23.47457627
Wl [deg/s]	6.283185307 x 10 <sup>9</sup>
Wh [deg/s]	75.398223686 x 10 <sup>9</sup>

Y11l [mS]	3.208828523
Y11h [mS]	31.19694397
Y21l [mS]	2.376910017
Y21h [mS]	21.51952462
Y12l [mS]	0.344651952
Y12h [mS]	3.208828523
Y22l [mS]	1.728813559
Y22h [mS]	19.11864407
wl [deg/s]	6.283185307 x 10 <sup>9</sup>
wh [deg/s]	75.398223686 x 10 <sup>9</sup>

### 3. VERIFICATION OF THE SIMPLIFIED MODEL

The verification of the extraction procedure for the parameters of the simplified model is made by comparing the results of *PSpice* simulation and the data from experiment and from the BSIM3v3 simulation. They are presented in Fig. 3. The good agreement of the measured and simulated results confirms the validity of the proposed extraction methodology.

In order to compare the two-port  $S$ -parameters, a postprocessing in the graphical analyzer *Probe* is made utilizing corresponding macrodefinitions for  $Y$ - to  $S$ -parameter conversion based on the simulated  $Y$ -parameters of the model shown in Fig. 2 [5]. The magnitude values of the measured  $S$ -parameters are introduced in the behavioral model using frequency-dependent elements of EFREQ type. Verification of the extraction methodology is made by comparing the simulated and experimental results for the  $S$ -parameters.

### 4. CONCLUSIONS

A direct parameter extraction methodology has been proposed for the simplified small-signal NMOSFET equivalent circuit. Extracted parameters are used to specify the equivalent circuit component values. The general-purpose circuit simulator *Cadence PSpice* is used for the computer realization of the extraction procedure. Verification of the parameter extraction methodology is made by comparing in the graphical analyzer *Probe* the results obtained in *PSpice* and the experiment.

### 5. REFERENCES

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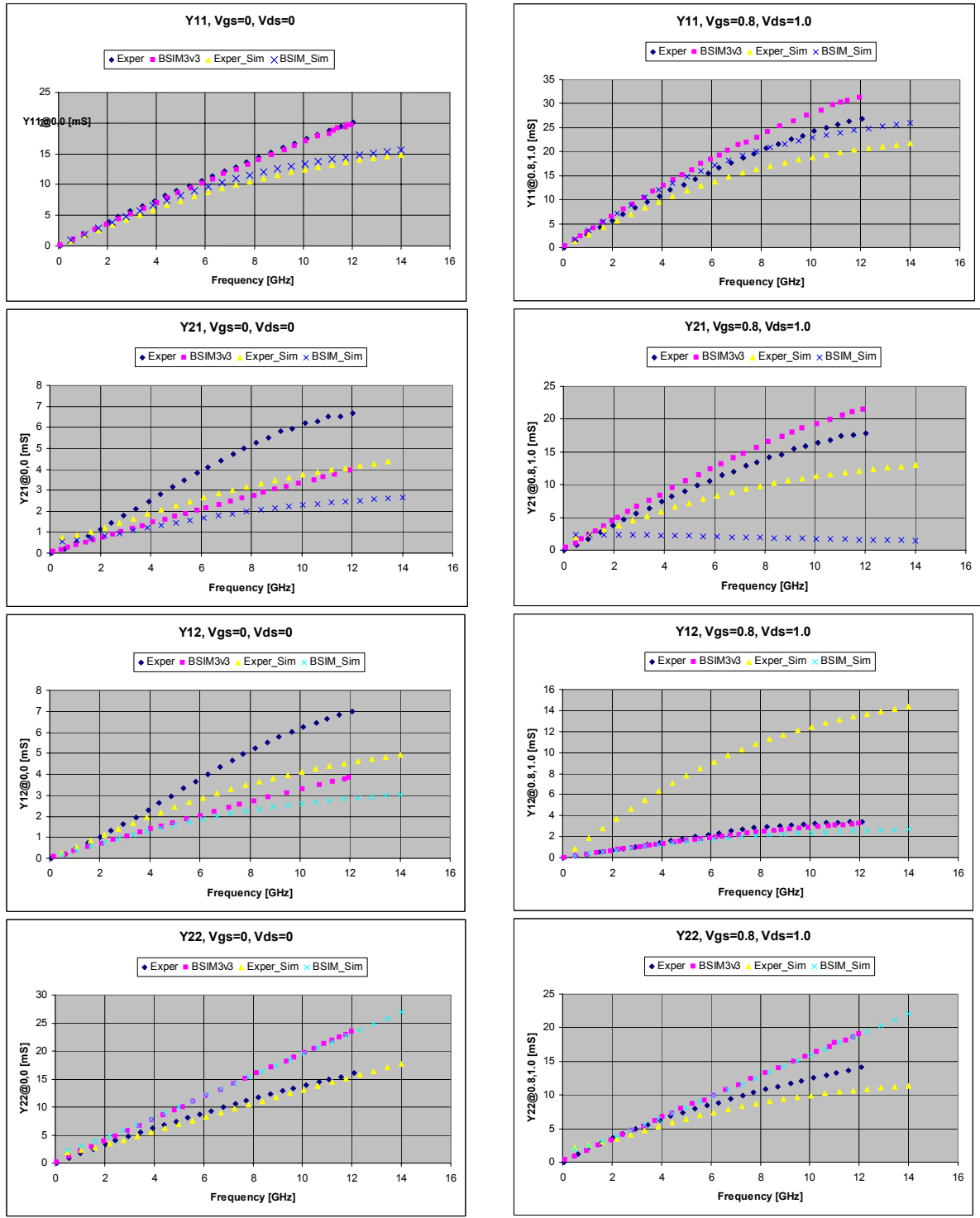


Fig. 3. Verification of the extraction procedure