RF MOSFET을 위한 SPICE 기판 모델의 스케일링 정확도 분석

(Scaling Accuracy Analysis of Substrate SPICE Model for RF MOSFETs)

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요 약

RF 직렬 추출 방법을 통해 얻은 정확한 MOSFET 기판 파라미터를 이용하여 기판저항만을 가진 BSIM4 모델은 스케일링 부정확성 때문에 넓은 영역의 게이트 길이에 적용하기에는 물리적으로 맞지 않는다는 것이 증명됐다. BSIM4의 비물리적인 문제점을 제거하기 위해서 추가적인 유전체 기판 캐패시터를 가진 수정된 BSIM4 모델이 사용되었고, 이 모델의 물리적 타당성은 우수한 게이트 길이 scalability를 관찰함으로써 증명되었다.

Abstract

Using accurate MOSFET substrate parameters obtained by a RF direct extraction method, it is demonstrated that a BSIM4 model with only substrate resistances is not physically valid to apply in the wide range of gate length because of scaling inaccuracy. In order to remove the unphysical problem of the BSIM4, a modified BSIM4 model with additional dielectric substrate capacitance is used and its physical validity is verified by observing excellent gate length scalability.

Keywords: MOSFET, RF, Modeling, SPICE model, substrate model, scalable model, parameter extraction

I. INTRODUCTION

For the accurate SPICE RF circuit simulation, the Berkeley short-channel IGFET model 4 (BSIM4) has been widely recognized as a standard MOSFET model[1]. Since substrate modeling becomes quite important in designing output matching circuits for RF ICs[2∼3], BSIM4 provides a flexible substrate model with resistance network. Generally, a scalable SPICE RF model in the wide range of the gate length $L_g$ should be developed to apply for a wide use of RF IC design, but a scaling validity of the BSIM4 substrate resistance model with regard to $L_g$ in the high frequency region has not been reported yet.

Therefore, in this paper, a scaling accuracy of the BSIM4 substrate model in terms of $L_g$ is physically analyzed in detail. The modified BSIM4 substrate model is proposed to improve the $L_g$ scaling accuracy in the high frequency region.
II. EXTRACTION AND ANALYSIS

S-parameters are measured on multi-finger N-MOSFETs (unit finger width $W_u = 5 \mu m$ and the number of gate finger $N_f = 16$) with different $L_g$ of $0.13 \mu m$, $0.18 \mu m$ and $0.25 \mu m$. An accurate de-embedding procedure was carried out to remove pad and interconnection parasitics from each measured $S$-parameters$^{[4]}$.

Since a five substrate resistance network in BSIM4 is too complex to be directly determined, a simple substrate model with single resistance$^{[5]}$ is generally used. Fig. 1(a) shows an AC equivalent circuit of the simple BSIM4 model with the substrate resistance $R_{BPB}$ at $V_{gs}=0V$. The substrate equivalent circuit of Fig. 1(b) is defined by $Y_{d}^{22}+Y_{d}^{12}$ of Fig. 1(a) for $R_{BPB} \gg R_s$ and $R_g$, where $Y_{d}$-parameters are obtained by subtracting the drain resistance $R_d$ from measured S-parameters. Fig. 1(b) is represented by the simple circuit block of the parallel resistance $R_p$ and capacitance $C_p$. Using the direct method$^{[6]}$, $R_d$ is extracted from $y$-intercepts of high-frequency $\text{Real}(Z_{22}-Z_{12})$ versus $\omega^{-2}$ at $V_{gs}=0V$.

To extract $R_p$ and $C_p$ accurately, an RF direct method$^{[7]}$ is performed using the following equations derived from Fig. 1(b):

$$R_p = \frac{1}{\text{Real}(1/Z_s)}$$  \hspace{1cm} (1)

$$C_p = \frac{1}{\omega} \text{Imag}(1/Z_s)$$ \hspace{1cm} (2)

where

$$Z_s = \frac{1}{Y_{d}^{22}+Y_{d}^{12}} - \frac{1}{\omega_0 C_{jd}}$$  \hspace{1cm} (3)

As shown in Fig. 2, the drain junction capacitance $C_{jd}$ in (3) is extracted by the following equation derived from Fig. 1(b) at low-frequencies (LF):

$$C_{jd} \approx \frac{1}{\omega} \text{Imag}(Y_{d}^{22}+Y_{d}^{12})_{LF}$$  \hspace{1cm} (4)

![Graph](image-url)
This direct extraction method for $R_p$ and $C_p$ is much simpler than the previous ones using two different data in the high and low frequency region[8]. The extracted values of $R_p$ and $C_p$ seem to be frequency-independent up to 30 GHz as shown in Fig. 3, verifying the extraction accuracy.

In a simple BSIM4 model of Fig. 1(a), $R_p \approx RBPB$ and $C_p = C_{gb} + C_{js}$, where $C_{gb}$ is the gate-bulk capacitance and $C_{js}$ is the source junction capacitance. The value of $C_{gb}$ is extracted at $V_{ds} = 0$ using low-frequency data of the following equation[9].

$$C_{gb} \approx \left(\frac{1}{\omega}\right) \text{Imag}(Y_{11} + 2Y_{12})_{LF}$$

As shown in Fig. 4(a), the extracted values of $C_{gb}$ increase linearly as a function of $L_g$. Using (2) and (5), $C_{js}$ data are extracted by $C_{js} = C_p - C_{gb}$ and plotted as a function of $L_g$ in Fig. 4(b). Theoretically, as $L_g$ is longer, $C_{gb}$ increases but $C_{js}$ is unchanged. However, the extracted $C_{js}$ data show an abrupt decrease with increasing $L_g$ which is not physically acceptable. This unphysical extraction of $C_{js}$ indicates that the simple substrate model in Fig. 1(a) is invalid. Even if five substrate resistances offered in BSIM4 are fully used, this unphysical scaling problem of $C_{js}$ extraction still occurs, because of the connection of these resistances to $C_{js}$.

In order to avoid this unphysical scaling problem of $C_{js}$ vs. $L_g$ in Fig. 4(b), we propose a modified BSIM4 model that includes parallel substrate capacitances($C_{subd}$, $C_{subb}$)[2-3, 8] to represent a lossy dielectric Si substrate region in Fig. 5(a). Also, the substrate equivalent circuit of Fig. 5(b) is defined by $Y_{22}^{s} + Y_{12}^{s}$ of Fig. 5(a) at $V_{gs} = 0V$.

$R_{subd}$ and $C_{subd}$ are extracted by (1) and (2), respectively. In Fig. 6, extracted $R_{subd}$ values are...
Fig. 5. (a) Modified BSIM4 Macro model using a lossy dielectric substrate circuit. AD=AS=PD=PS=0 is set to remove internal source and drain junction diodes. (b) The substrate equivalent circuit of \( Y_{d_{22}^+} + Y_{d_{12}^-} \).

Proportional to \( L_g \), while \( C_{subd} \) values are inversely proportional to \( L_g \). This \( L_g \) scalability is physically valid because the MOSFET lossy substrate region between the drain and bulk contacts is shown to be longer with increasing \( L_g \). This verifies the \( L_g \) scaling accuracy of the lossy dielectric substrate model in Fig. 5(a).

Fig. 7 shows AC equivalent circuits of the simple and modified BSIM4 models in the saturation region. In order to extract other intrinsic model parameters directly without any optimization, the equivalent circuits without \( C_{bs} \) neglected in the low frequency region are used to derive the following equations\(^{[8,10]}\).

\[
C_{gs} = \frac{1}{\omega} \text{Imag}(Y_{11} + Y_{12}') \\
C_{gd} = -\frac{1}{\omega} \text{Imag}(Y_{12}') \\
r_{ds} = \frac{1}{\text{Real}(Y_{22}')} \\
g_{mo} = Y_{21}' - Y_{12}'
\]

where \( Y_{i} \)-parameters of the intrinsic MOSFET are obtained by subtracting \( C_{bs} \) substrate parameters,
Fig. 7. AC equivalent circuit of BSIM4 model in the saturation region. (a) Simple model (b) Modified model

$R_s$ and $R_g$ from measured $Y^d$-parameters. Using the direct method\cite{6}, $R_g$ and $R_s$ are extracted from y–intercepts of high–frequency $\text{Real}(Z_{11}–Z_{12})$ and $\text{Real}(Z_{12})$ versus $\omega^{-2}$ at $V_{gs}=0V$, respectively.

In Fig. 8, the scaling accuracy of a modified BSIM4 model in Fig. 7(b) is reconfirmed by finding better agreement between measured and modeled $S_{22}$ -parameter than a simple one of Fig. 7(a) at $L_g=0.25\mu m$.

### III. CONCLUSIONS

RF MOSFET substrate parameters are accurately extracted using a RF direct method. The original BSIM4 model with only substrate resistances is proved to be physically unacceptable for the $L_g$ scaling. The $L_g$ scaling accuracy of a modified BSIM4 model including the dielectric substrate capacitance is justified by observing the physical validity that $R_{\text{sub}}$ and $C_{\text{sub}}$ in a lossy dielectric substrate is proportional to $L_g$ and $1/L_g$, respectively. The simulated S–parameters of the modified BSIM4 model have better agreements with
measured ones than a simple BSIM4 model, verifying the scaling accuracy of its model.

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