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# Accurate Small-Signal Modeling and Parameter Extraction for RF MOSFETs

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## 1. Introduction

For modeling and parameter extraction of RF silicon MOSFETs, a simple small-signal model omitting the substrate effect has been widely used [1], but its inappropriateness was recently pointed out [2]. At high frequencies, the influence of the substrate admittance on device output characteristics increases substantially. This effect is basically originated from the lossy dielectric property of the bulk Si well/substrate region. Recently, a conventional small-signal model in Fig. 1(a) has been reported [2,3], but is not sufficient to model the lossy Si bulk region at the GHz range. Therefore, in this paper, we propose a new small-signal MOSFET model based on a physically acceptable substrate network in Fig. 2(a), and the direct extraction method will be presented.

## 2. Modeling and Parameter Extraction

$S$-parameters are measured and de-embedded for N-MOSFETs with 0.8 μm mask gate length and 10 x 10 μm gate width on 2 kΩ·cm high resistivity Si wafers. In order to extract substrate parameters, the substrate model block should be separated from the rest of device. As the first extraction step, extracted $R_d$ value determined by fitting $\mathrm{Re}(Z_{22} - Z_{12}) = R_d + A_d/(\omega^2+B)$ up to 30 GHz [1] was subtracted to obtain corrected $Y^c$-parameters from measured $S$-parameters. In the saturation region where $Rs \ll r_{ds}$, the substrate networks with $r_{ds}$ that are represented as the admittance of $Y_{22}^c + Y_{12}^c$ are simplified by Figs. 1(b) and 2(b). Thus, new substrate parameters in Fig. 2(b) are directly extracted using the following equations:

$$C_{sub}^{\ c} = \frac{1}{\omega}\mathrm{Im}(Y_{22}^{\ c} + Y_{12}^{\ c}) = C_{jd}\left[\frac{1+m_1\omega^2}{1+m_2\omega^2}\right] \qquad (1)$$

$$\frac{1}{R_{sub}^{\ c}} = \mathrm{Re}(Y_{22}^{\ c} + Y_{12}^{\ c}) = \frac{1}{r_{ds}} + \frac{k_1\omega^2}{1+k_2\omega^2} \qquad (2)$$

where $m_1$, $m_2$, $k_1$, and $k_2$ are functions of substrate parameters, and independent of frequency. Here, the pole frequency of the substrate admittance is defined as: $\omega_c = 1/[R_{bk}(C_{bk} + C_{jd})]$. If $R_{sub}^{\ c}$ and $C_{sub}^{\ c}$ in the low ($\omega \ll \omega_c$) and high frequency ($\omega \gg \omega_c$) limit can be measured, it is easy to extract the substrate parameters. However, it is practically difficult to measure $S$-parameters at these bound frequencies. Thus, in this work, $C_{jd}$, $m_1/m_2$, and $k_1/k_2$ are obtained by fitting frequency response of (1) and (2). Using these values, $C_{bk}$ and $R_{bk}$ are determined by :

$$C_{bk} = \frac{C_{jd}}{(m_2/m_1) - 1}, \qquad R_{bk} = \frac{k_2}{k_1}\left[1 - \frac{m_1}{m_2}\right]^2 \qquad (3)$$

Fig. 3 shows good correspondences between measured data and fitted curves at different $Vbs$, verifying the extraction accuracy. Since $\omega_c \approx 2$ GHz, measured data below 7 GHz are practically sufficient to fit substrate parameters accurately. In Fig. 3, $R_{sub}^{\ c}$ and $C_{sub}^{\ c}$ data decrease abruptly. This frequency-dependence, so called, dispersion effect is obviously caused by the lossy substrate effect, which is incorporated into Fig. 2(a).

Fig. 4 shows extracted $Vbs$-dependence of $C_{jd}$, $C_{bk}$, and $R_{bk}$. The reduction of extracted $C_{jd}$ is observed at more negative $Vbs$ (higher $Vsb$), because the depletion region expands with increasing $Vsb$. However, extracted $C_{bk}$ increases with $Vsb$, probably indicating the reduction of bulk region due to the increase of the depletion width.

To validate the physical validity of the new substrate network, the rest of parameters are extracted as follows: After corrected $Z^d$-parameters are obtained by subtracting extracted $C_{jd}$, $C_{bk}$, and $R_{bk}$ from corrected $Z^c$–parameters, $Rg$ is obtained by fitting $\mathrm{Re}(Z_{11}^{\ d} - Z_{12}^{\ d}) = Rg + Ag/(\omega^2+B)$ vs. frequency [1]. The $Rs$ is extracted by fitting $\mathrm{Re}(Z_{22} - Z_{12})$ vs. frequency for a test MOSFET where source and drain are interchanged. After $Rs$ and $Rg$ are subtracted from the $Z^d$-parameters, intrinsic parameters were extracted by previous $Y$-parameter equations [2]. In Fig. 5, good agreement is achieved between measured and modeled $S$-parameters, verifying the model accuracy.

To confirm the accuracy of the new model, the extracted $r_{ds}$ that is the most sensitive parameter to the substrate model is compared with those of conventional models. To obtain $r_{ds}$ in Fig. 1(b), $C_{ds}$, $C_{db}$, and $R_{db}$ are extracted by fitting the following equation vs. frequency:

$$\frac{1}{\omega}\mathrm{Im}(Y_{22}^{\ c} + Y_{12}^{\ c}) = C_{ds} + \frac{C_{db}}{1+\omega^2 R_{db}^2 C_{db}^2} \qquad (4)$$

After these parameters, *R*s, and *R*g are sequentially subtracted from the $Z^c$-parameters, $r_{ds}$ in Fig. 1 were extracted [2]. Also, the $r_{ds}$ in the model without bulk effect [1] is extracted. Fig. 6 shows extracted $r_{ds}$ values vs. frequency between conventional models (Ref. [1], Fig. 1) and new model (Fig. 2). In this plot, the $r_{ds}$ data obtained from the new model are nearly independent of frequency, in contrast to those from conventional ones. This frequency-independence justifies the use of a new model.

## 3. Conclusions

A new model with substrate network incorporating the lossy substrate effect is proposed to predict the dispersion behavior of $R_{sub}^c$ and $C_{sub}^c$ and to eliminate the severe frequency-dependence of $r_{ds}$ observed from conventional networks. The accurate extraction method using the simple curve-fit is also developed to determine substrate parameters directly. The physical validity of the substrate network is demonstrated by observing that $r_{ds}$ obtained from the new model is independent of frequency.

## References


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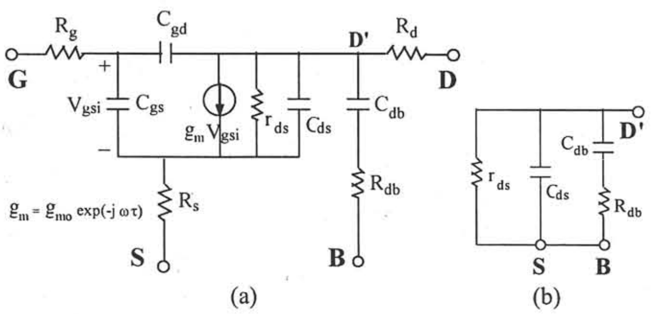


Fig. 1. (a) A conventional small-signal MOSFET model. (b) A substrate network with $r_{ds}$ simplified in the saturation region.

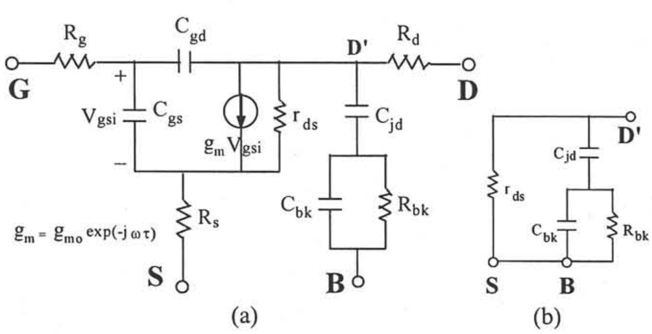


Fig. 2. (a) A new small-signal MOSFET model. (b) A substrate network with $r_{ds}$ simplified in the saturation region ($Rs \ll r_{ds}$).

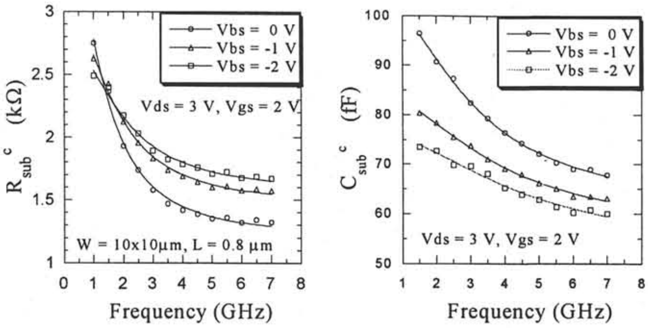


Fig. 3. The measured data (symbols) and fitted curves of $R_{sub}^c$ and $C_{sub}^c$ at different *V*bs using frequency-dependent (1) and (2).

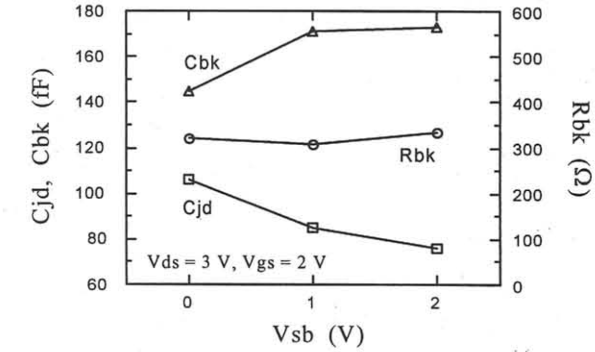


Fig. 4 *V*sb (= -*V*bs) dependence of extracted $C_{jd}$, $C_{bk}$, and $R_{bk}$.

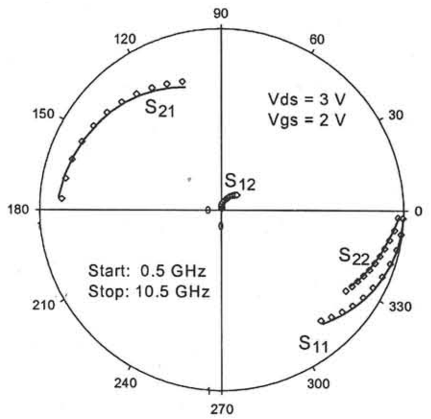


Fig. 5. Measured (circles) and modeled (lines) S-parameters.

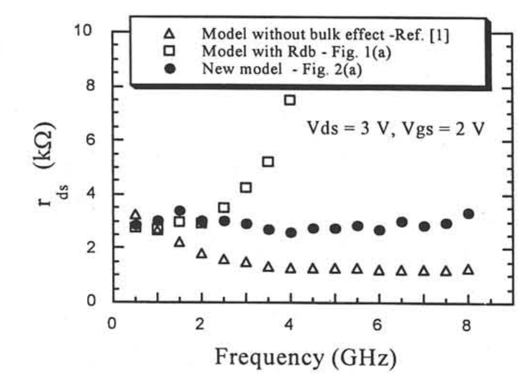


Fig. 6. Extracted $r_{ds}$ vs. frequency for previous and new models.