Physical Modeling of Substrate Resistance in RF MOSFETs

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ABSTRACT

A simple and accurate method is presented for extracting the substrate resistance of RF MOSFETs. The extraction results for 0.18 µm MOSFETs are shown for various bias conditions. The dependence of the extracted substrate resistances on the device geometry is also presented. The substrate signal coupling effect on the small-signal output admittance and its gate-bias dependence are analyzed.

Keywords: RF MOSFET, MOSFET modeling, substrate resistance, substrate coupling, parameter extraction

1 INTRODUCTION

Recent RF MOSFET models include the substrate-related components such as the substrate resistance \( R_{\text{sub}} \), since the substrate resistance significantly affects the small-signal output characteristics of RF MOSFETs at high frequencies [1]-[4]. The four-terminal MOSFET with substrate parasitics has significant signal coupling through the substrate \( R-C \) network. It is crucial for MOSFET modeling and RF IC design to extract and predict the substrate resistance of a MOSFET accurately as a function of the bias and the device layout geometry. In this paper, we present a simple and accurate method for extracting the \( R_{\text{sub}} \) of RF MOSFETs. Using the technique, the bias dependence and the layout geometry dependence of \( R_{\text{sub}} \) were extracted and presented. Also, we analyzed the substrate signal coupling effect on the small-signal output admittance and its gate-bias dependence accurately.

2 EXTRACTION METHOD OF \( R_{\text{sub}} \)

The effect of substrate parasitics can be accurately described by a simple subcircuit extension of the conventional MOSFET model by using a single lumped substrate resistance \( R_{\text{sub}} \) [5]. When the gate voltage \( V_{\text{gs}} \), is smaller than the threshold voltage \( V_{\text{th}} \), most intrinsic components of a MOSFET are negligible and the equivalent circuit of an RF MOSFET is simplified as the one presented in Fig. 1. \( C_{\text{gd}} \) and \( C_{\text{gs}} \) represent the gate-to-source and the gate-to-drain zero-bias capacitances, respectively. \( C_{\text{sub}} \) indicates the sum of the intrinsic and the extrinsic gate-to-body capacitances and \( C_{\text{jd}} \) and \( C_{\text{jd}} \), are the source junction capacitances. \( R_{\text{poly}} \) and \( R_{\text{sub}} \) represent the gate and the substrate resistances. From the equivalent circuit in Fig. 1, some of the \( Y \)-parameters are given by equations (1)-(5) up to a few GHz.

\[
\begin{align*}
\text{Re}[Y_{11}] &= \omega^2 R_{\text{poly}} (C_{\text{gd}} + C_{\text{gd}} + C_{\text{gs}})^2 + \omega^2 R_{\text{sub}} C_{\text{sub}}^2 \\
\text{Im}[Y_{11}] &= \omega (C_{\text{gd}} + C_{\text{gd}} + C_{\text{gs}}) \\
\text{Im}[Y_{12}] &= -\omega C_{\text{gd}} \\
\text{Re}[Y_{22}] &= \omega^2 R_{\text{sub}} C_{\text{jd}}^2 + \omega^2 R_{\text{poly}} C_{\text{poly}}^2 \\
\text{Im}[Y_{22}] &= \omega (C_{\text{jd}} + C_{\text{jd}})
\end{align*}
\]

Using (1)-(5), we can extract \( C_{\text{gd}}, C_{\text{gs}}, C_{\text{jd}}, R_{\text{poly}}, \) and \( R_{\text{sub}} \) from the measured \( Y \)-parameters.

Fig. 1. Equivalent circuit of an RF MOSFET when the device is turned off and the intrinsic components of the MOSFET are negligible. The substrate is represented by a single lumped resistor \( R_{\text{sub}} \).

The MOSFETs were fabricated in a commercially available 0.18-µm CMOS technology. The \( S \)-parameters of 0.18-µm nMOSFETs were measured using an Agilent 8510C network analyzer and a CASCADE Summit probe station. Open and short dummy patterns were used to deembed the pad parasitics.

3 BIAS DEPENDENCE OF \( R_{\text{sub}} \)

\( C_{\text{jd}} \) and \( R_{\text{sub}} \) at various gate voltages are illustrated in Fig. 2. When \( V_{\text{gs}} \) increases to near \( V_{\text{th}} \), the intrinsic components of the MOSFET become significant, which makes the equivalent circuit in Fig. 1 and its corresponding parameters invalid. Therefore, it is recommended that the \( C_{\text{jd}} \) and \( R_{\text{sub}} \) should be extracted at \( V_{\text{gs}} \) smaller than about \((V_{\text{th}} - 0.3 \text{ V})\). The extraction of \( R_{\text{sub}} \) at \( V_{\text{gs}} < (V_{\text{th}} - 0.3 \text{ V}) \), or simply at \( V_{\text{gs}} = 0 \text{ V} \) gives a quite proper value because \( R_{\text{sub}} \) has a very weak gate-bias dependence as shown in Fig. 2 [6].

The drain-bias dependence of $C_{jd}$ and $R_{sub}$ are presented in Fig. 3. $C_{jd}$ and $R_{sub}$ were extracted for the devices with various channel widths: 40, 80, 160, and 320 $\mu$m. As the drain bias increased, $C_{jd}$ decreased as expected. Fig. 3 shows that $R_{sub}$ also decreased when the drain voltage increased because the path between the intrinsic body and the (external) body contacts becomes shorter with widening of the depletion region.

### 4 GEOMETRY DEPENDENCE OF $R_{sub}$

The values of $R_{sub}$ were extracted for NMOSFETs with various device layout geometries. Fig. 4 shows the schematic layout of a device with vertical body contacts. The body contacts were placed as vertical strips along the both sides of the device. The widths of the body contacts were the same as the height of the active region, which is denoted by $W_f$ in Fig. 4. The distance from the outmost source junction to the vertical body contact is represented by $d_v$. Fig. 5 shows the values of $R_{sub}$ when $W_f$ varied from 1.5 $\mu$m to 10 $\mu$m with fixed $d_v$ of 0.5 $\mu$m. $R_{sub}$ were inversely proportional to $W_f$.

The MOSFETs with the vertical body contacts were also fabricated with $d_v$ varying from 0.5 $\mu$m to 8 $\mu$m. The intrinsic devices were laid out identically and $W_f$ were fixed at 2.5 $\mu$m. The extracted $R_{sub}$ are plotted as a function of $d_v$ in Fig. 6. $R_{sub}$ increased linearly with $d_v$. The results show that the extracted values of $R_{sub}$ are scalable with the geometric parameters.

Fig. 4. Schematic layout of the device with vertical body contacts. $W_f$ is the width of the gate-finger, which is the same with that of the body contact. $d_v$ is the distance from the outmost source junction to the vertical body contact.

Fig. 5. $R_{sub}$ as a function of $1/W_f$.

Fig. 6. $R_{sub}$ for the devices with the vertical body contacts as a function of $d_v$.

Fig. 7. Schematic layout of the device with horizontal body contacts. $W_b$ is the width of the body contact. $d_h$ is the distance from the outmost junction to the body contact.
The values of $R_{\text{sub}}$ for the devices with the surrounding body contact were close to those calculated from (6) with less than 15% error. This implies that a surrounding body contact can be considered as a parallel combination of vertical body contacts and horizontal body contacts.

5 SIGNAL COUPLING THROUGH $R_{\text{sub}}$

At high frequencies, the four-terminal MOSFET with substrate parasitics has significant signal coupling through the substrate $R-C$ network. In strong inversion region, the substrate signal coupling mainly affects the small-signal output characteristics [2], [7].

5.1 Modeling and Analysis

Fig. 10 shows the schematic of a one-substrate-resistor model. In the development of the analytical equations in this section, the effects of the parasitic resistances in gate, source, and drain terminals are assumed to be de-embedded to focus on the analysis of substrate signal coupling. The intrinsic RF MOSFET shown in Fig. 10 can be completely modeled with nine independent $y$-parameters [8].

Analyzing this model in terms of two-port $Y$-parameters results in the analytical expressions for $Y_{22}$. The real and imaginary parts of $Y_{22}$ have large number of terms, but after careful examination of each term and taking only the significant terms, the following equations are obtained.

\[
\text{Re}(Y_{22}) = \text{Re}(y_{22}) + \frac{1}{1 + \omega^2 R_{\text{sub}}^2 C_B^2} \times \left[ \alpha R_{\text{sub}} C_C (C_{bd} + C_{jd}) + \omega^2 R_{\text{sub}} (C_{bd} + C_{jd})(C_{gb} + C_{jd}) \right]\text{ term A} + \text{ term B}
\]

\[
\text{Im}(Y_{22}) = \text{Im}(y_{22}) + \frac{1}{1 + \omega^2 R_{\text{sub}}^2 C_B^2} \times \left[ \alpha R_{\text{sub}} (C_{bd} + C_{jd}) - \omega^2 R_{\text{sub}} C_C (C_{bd} + C_{jd})(C_{gb} + C_{jd}) \right]\text{ term C} + \text{ term D}
\]

where $C_B = C_{gb} + C_{bi} + C_{bd} + C_{gb0} + C_{sj} + C_{jd}$.

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Table 1. $R_{\text{sub}}$ extracted from the device with a surrounding body contact, and $R_{\text{sub}}$ calculated from (6).
In Eqs. (7) and (8), there are two types of coupling terms: the terms containing $g_{mb}$ and those not containing $g_{mb}$. The former makes an influence on $Y_{22}$ mainly in the strong inversion region because $g_{mb}$ has a strong gate bias dependence and is nearly zero below threshold voltage [9], while the latter affects $Y_{22}$ for all operation regions.

### 5.2 Measured Results and Discussions

The $S$-parameters of two RF MOSFETs were measured. Channel length and width of the devices were 0.18 $\mu$m and 40 $\mu$m, respectively. The measured devices were laid out identically except that their body contacts were placed at different distances from their outermost source junctions. Their DC characteristics were measured and verified to be exactly the same. The parasitic resistances in gate, source, and drain terminals were determined and removed by using the technique reported in [10]. Extracted values of $R_{sub}$ are 38 $\Omega$ for the device with close body contacts and 285 $\Omega$ for the device with body contacts far from its outermost source junctions.

![Fig. 11. Re($Y_{22}$) of two measured MOSFETs at $V_{DS} = 1$ V. For clarity, the curves measured at $V_{DS} = 0.4$, 0.6, and 1 V were shifted by 0.5, 0.6 and 0.5 mS, respectively.](image)

Fig. 11 compares Re($Y_{22}$)'s of the two devices. We can observe that the difference between Re($Y_{22}$)'s of two devices becomes larger as gate voltage increases. It is because the effect of the term $A$ in Eq. (7) becomes significant with increasing gate voltage due to larger $g_{mb}$. The discrepancy at $V_{DS} = 0$ V is wholly due to the effect of the term $B$ in Eq. (7). At low frequencies, Re($Y_{22}$) of the device having large $R_{sub}$ increases more rapidly than that of the device having small $R_{sub}$ does. However, as frequency increases, the term $1/2g_{mb}^2C_g^2$ in the denominator of Eq. (7) starts to be dominant, and therefore Re($Y_{22}$) for large $R_{sub}$ increase more slowly than that for small $R_{sub}$. It can be seen that the results calculated using Eq. (7) agree very well with the measurement results. All the parameters (including the intrinsic parameters such as $g_{mb}$ and $C_{gd}$) were extracted to verify the validity of the developed theory. Similar results were obtained for Im($Y_{22}$).

### 6 CONCLUSION

A simple and accurate method was presented for extracting $R_{sub}$ of RF MOSFETs of which the substrate is represented by a single resistor. The proposed gate voltage to extract $R_{sub}$ is about 0 V, where the intrinsic components of the MOSFETs are negligible. The bias dependence and the geometry dependence of $R_{sub}$ were also extracted and presented. The extracted values of $R_{sub}$ are scalable with the geometric parameters. Signal coupling effect through $R_{sub}$ was also analyzed.

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### REFERENCES


