CHAPTER-5
PARAMETER EXTRACTION
AND SIMULATION
RESULTS
# CHAPTER 5

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5.1 Circuit Analysis

The equivalent small signal RF model is shown in Fig. 5.1. Circuit analysis of the small signal RF model yielded the following results.

In the frequency ranges \( \omega \ll [R_g (C_{gs} + C_{gd})]^{-1} \), a simplified expression for small signal \( Y \)-parameters \( Y'_{11}, Y'_{21}, Y'_{12}, \) and \( Y'_{22} \) of the circuit enclosed by dashed line in Fig. 5.1 can be derived as: [1],[2].

**Y-Parameters:**

\[
Y'_{11} = \omega^2 R_g (C_{gs} + C_{gd})^2 + j \omega (C_{gs} + C_{gd}) \\
Y'_{21} = g_m - j \omega C_{gd} \\
Y'_{12} = -j \omega C_{gd} \\
Y'_{22} = g_{ds} + j \omega C_{gd} + \frac{j \omega g_m R_{sub} C_{db}}{1 + j \omega R_{sub} (C_{sub} + C_{db})} + \frac{j \omega C_{db} (1 + j \omega R_{sub} C_{sub})}{1 + j \omega R_{sub} (C_{sub} + C_{db})} 
\]

**Z-Parameters:**

\[\text{Re}[Z_{12}] = R_s + BC_{gd} / \left( \omega^2 A^2 + B^2 \right)\]
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\[ \text{Im}[Z_{12}] \equiv -\omega AC_{gd} / (\omega^2 A^2 + B^2) \]  
(5.6)  
\[ \text{Re}[Z_{22}] \equiv R_g + R_d + (C_{gs} + C_{gd}) B / (\omega^2 A^2 + B^2) \]  
(5.7)  
\[ \text{Im}[Z_{22}] \equiv \omega BR_g (C_{gs} + C_{gd})^2 - \omega A (C_{gs} + C_{gd})^2 / (\omega^2 A^2 + B^2) \]  
(5.8)  

Where,  
\[ A = C_{gd} C_{gs} + C_{db} (C_{gs} + C_{gd}) \]  

And  
\[ B = g_{ds} (C_{gd} + C_{gs}) + g_m C_{gd} \]

In order to determine the other parameters, they can be shown in terms of real and imaginary part of \( Y' \) or \( Z' \) as shown below.

**Trans-conductance,**  
\[ g_m \quad \text{Re}(al(Y'_{21})) \]  
(5.9)  

**Drain-to-source trans-conductance,**  
\[ g_{ds} \quad \text{Re}(al(Y'_{22})); \quad \text{when } \omega \rightarrow 0 \]  
(5.10)  

**Gate resistance,**  
\[ R_g \quad \text{Re}(al(Y'_{11}) / \text{Im}(Y'_{11}))^2 \]  
(5.11)  

**Gate-to-drain capacitance,**  
\[ C_{gd} = \frac{-\text{Im}(Y'_{12})}{\omega} \]  
(5.12)  

**Gate-to-source capacitance,**  
\[ C_{gs} = \frac{\text{Im}(Y'_{11})}{\omega} - C_{gd} \]  
(5.13)

The corresponding plots of the above parameters are shown below in Fig. 5.6 to Fig. 5.10 at the two different bias points.

### 5.2 Extraction of Substrate Parameters \( R_{\text{sub}}, C_{\text{db}} \) and \( g_{mb} \)

The extraction equations are given as follows:

\[ R_{\text{sub}} = \frac{\text{Re}(Y_{22}) - g_{ds}}{(\text{Im}(Y_{22}) + \text{Im}(Y_{12}))^2 - g_{mb}(\text{Re}(Y_{22}) - g_{ds})} \]  
(5.14)  
\[ C_{\text{db}} = \frac{\text{Re}(Y_{22}) - g_{ds}}{R_{\text{sub}} \omega (\text{Im}(Y_{22}) + \text{Im}(Y_{12}))} \]  
(5.15)  
\[ g_{mb} \approx 0.2 \times g_m \]  
(5.16)
5.2.1 Extraction of $R_s$ & $R_d$

By plotting $\text{Re}[Z_{12}]$ versus $\text{Im}[Z_{12}]$ as in Fig. 5.2, the value of $R_s$ is obtained from the y-intercept of the best fit line, as at high frequency, $-\text{Im}[Z_{12}]/\omega$ tends to zero.

![Graph showing extraction of $R_s$.](image)

The $Z$-parameter analysis as shown earlier in section 5.1 reveals that if $\text{Re} [Z_{22}]$ is plotted versus $\text{Re}[Z_{12}]$, the slope $m$ of the regression line can be derived as

$$m \frac{d \text{Re}[Z_{22}]}{d \text{Re}[Z_{12}]} = \frac{C_{gs} + C_{gd}}{C_{gs}}$$

Similarly, the y-axis intercept, $c$ of the regression line can be derived in terms of $R_s$, $R_d$ and $m$ using $\text{Re}[Z_{22}]$ and $\text{Re}[Z_{12}]$ as

$$c = (1-m) R_s + R_d$$

Once $c$ & $m$ have been determined from the Fig. 5.3, $R_d$ can be determined from the above equation since $R_s$ is already known. [4]

![Graph showing extraction of $R_d$.](image)
5.3 Extraction Equation Implementation

Fig 5.4 shows the steps involved in generation of S or Y-parameters of device under test (DUT) [3].

Step-I

![Step-I Diagram](image1)

(a)

Step-II

![Step-II Diagram](image2)

(b)

Step-III

![Step-III Diagram](image3)

(c)

Fig 5.4 Pads de-embedding and generation of S or Y-parameters of DUT (a) measured (b) pad de-embedding (c) DUT
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Fig 5.5 shows the implementation of extraction equation and extraction result in ADS [3].

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Fig. 5.5 Parameter Extraction Equation Implementation Using ADS [3]
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5.4 Extraction of remaining parameters

For determining the other parameters, two different bias points that have been used are given as in Table 5.1.

<table>
<thead>
<tr>
<th>TABLE 5.1 BIAS POINTS</th>
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<tr>
<td></td>
</tr>
<tr>
<td>V_g</td>
</tr>
<tr>
<td>V_d</td>
</tr>
<tr>
<td>I_d</td>
</tr>
<tr>
<td>I_g</td>
</tr>
</tbody>
</table>

In order to determine the other parameters, they can be shown in terms of real and imaginary part of Y’ or Z’ as shown below.

- **Trans-conductance**, $g_m = \text{Real} \ (Y’_{21})$
- **Drain-to-source trans-conductance**, $g_{ds} = \text{Real} \ (Y’_{22})$ ; when $\omega \rightarrow 0$
- **Gate resistance**, $R_g = \text{Real} \ (Y’_{11}) / \text{Im} \ (Y’_{11})^2$
- **Gate-to-drain capacitance**, $C_{gd} = -[\text{Im}(Y’_{12}) / \omega]$
- **Gate-to-source capacitance**, $C_{gs} = [\text{Im}(Y’_{11}) / \omega] - C_{gd}$

The corresponding plots of the above parameters are shown below in Fig. 5.6 to Fig. 5.10 at the two different bias points.
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Fig. 5.6 Plot for $g_m$ Vs Frequency

Fig. 5.7 Plot for $g_{ds}$ Vs Frequency

Fig. 5.8 Plot for $R_g$ Vs Frequency
In the plots shown above, the lines indicate the values for the two different bias points. The bias points have been indicated by different legend values as indicated in each plot. For example, \( C_{gs1} \) indicates the plot for \( C_{gs} \) at the bias point 1 and similarly \( C_{gs2} \) for bias point 2. This trend has been followed throughout this project report.
5.5 Extraction of Substrate Parameters $R_{sub}$, $C_{db}$ and $g_{mb}$

Fig. 5.11 Plot for $R_{sub}$, $C_{db}$ and $g_{mb}$ Vs Frequency
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TABLE 5.2 Extraction Results

For Vgs = 0.3 V  Vds = 0 V, Rs = 3 Ω  Rd = 5.95 Ω

<table>
<thead>
<tr>
<th></th>
<th>Bias point 1 ( V_g = 0.3 ) V, ( V_d = 1.0 ) V</th>
<th>Bias point 2 ( V_g = 0.3 ) V, ( V_d = 1.5 ) V</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g_m )</td>
<td>3.8 mS</td>
<td>4.5 mS</td>
</tr>
<tr>
<td>( g_{ds} )</td>
<td>1.06 mS</td>
<td>1.241 mS</td>
</tr>
<tr>
<td>( R_g )</td>
<td>1.606 Ω</td>
<td>1.38 Ω</td>
</tr>
<tr>
<td>( C_{gs} )</td>
<td>319.07 fF</td>
<td>308.5 fF</td>
</tr>
<tr>
<td>( C_{gd} )</td>
<td>117.01 fF</td>
<td>112.96 fF</td>
</tr>
<tr>
<td>( R_{sub} )</td>
<td>22 mΩ</td>
<td>14.49 mΩ</td>
</tr>
<tr>
<td>( C_{db} )</td>
<td>90.0 fF</td>
<td>88.12 fF</td>
</tr>
<tr>
<td>( g_{mb} )</td>
<td>0.76 mS</td>
<td>0.9 mS</td>
</tr>
</tbody>
</table>

All the circuit components have been determined by taking plots using the Y and Z parameters. The extraction results for the two bias points are shown in Table 5.2. In the second bias point, the gate voltage is higher as compared to its value in bias point 1. As a result, \( g_m \) is high for the second bias point and so \( C_{gs} \) is also high for second bias point.
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5.6 Model Simulation

Taking extracted value $R_s$, $R_d$ and $R_s$ from Fig 5.5 and rest of the parameter from table 5.2 at $V_{GS} = 0.3V$ and $V_{DS} = 1.0V$ simulation are performed. The values used in the schematic shown in Fig. 3.6 are optimized for best S- and Y-parameters simulation result [3].

![Model Simulation Diagram](image)

Fig: 5.12 Model Simulation

![Extraction Equations](image)

Fig: 5.13 Extraction Equations
5.7 Model Testing

The component in the RF model has been determined, hence the RF model is known. For model testing, S-parameters of the model are generated and compared with the Fabricated NMOS Device S-parameters. The comparison of Fabricated NMOS Device and modelled S-parameters will show that if the Fabricated NMOS Device and modelled plots are close then model is accurate within the permissible limit. The s-parameter is generated from the model using ADS. [A.2]

5.7.1 Comparison of Generated and Modelled S-parameters

The comparison of the Modelled and Generated from Fabricated NMOS S-parameters is shown herewith.

Fig. shows the comparison S-parameters at bias point 1 i.e. $V_g = 0.3 \text{ V}$ and $V_d = 1.0 \text{ V}$.

Fig. 5.14(a) Plot for $S_{11}$ and $S_{12}$ Vs Frequency at bias point 1
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Fig. 5.14(b) Plot for $S_{21}$ and $S_{22}$ Vs Frequency at bias point 1

Comparison of S-parameters at Bias Point 2 i.e. $V_g = 0.3$ V and $V_d = 1.5$ V

Fig. 5.15(a) Plot for $S_{11}$ and $S_{12}$ Vs Frequency at bias point 2
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![Graphs showing S11 and S22 vs Frequency at bias point 2](image)

5.8 Summary:

The MOSFET has been successfully fabricated using ATLAS (SILVACO) TCAD tool. The device is solved for dc-iv characteristics and S-parameters are obtained. To overcome some of the short channel effects at nano-scale lightly doped drain and source have been used.

The coupling through the substrate is an important effect for mixed mode high-frequency IC design and should be appropriately accounted. At low frequency (<1GHz), it is good enough to model the substrate by a purely resistive network. However, at high frequency (>1GHz) where most of the wireless communication systems operate, both resistive and dielectric losses are important and must be appropriately modeled by a combination of $R_{\text{sub}}$ and $C_{\text{db}}$. When this is done and appropriate account is taken of the back gate trans-conductance effect, a much more accurate RF model is developed, which can be used for evaluation output reflection coefficient in individual transistors as well as carrying out circuit design.
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References:


