Physical Modeling of Substrate Resistance in RF MOSFETs

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Introduction

- Substrate parasitics in MOSFETs
  - Lossy silicon substrate
    - The influence of the substrate resistance becomes significant as the operation frequency increases.
  - Four-terminal nature of MOSFETs
    - Signals in RF MOSFETs are coupled through the substrate R-C network.

- Careful modeling and accurate extraction of the substrate parasitics are very important for RF CMOS modeling
- Careful analysis of substrate signal coupling is needed
Introduction

Previous works

- Curve fitting or optimization technique was used to extract $R_{\text{sub}}$.
  - Unphysical value can be extracted.
  - It is complicated.

Our research

- Simple and efficient method to extract the accurate substrate resistance of RF MOSFETs
Equivalent circuit of an RF MOSFET, when it is off: $V_{gs} < V_{th}$
$\textbf{Y-parameters}$

Some of the y-parameters related to $R_{\text{sub}}$

\[
\text{Im}[Y_{11}] = \omega (C_{g_{s0}} + C_{g_{d0}}) + \frac{\omega C_{gb} + \omega^3 R_{\text{sub}}^2 C_{gb} (C_{js} + C_{jd})(C_{gb} + C_{js} + C_{jd})}{1 + \omega^2 R_{\text{sub}}^2 (C_{gb} + C_{js} + C_{jd})^2}
\]

\[
\text{Im}[Y_{12}] = -\omega C_{g_{d0}} - \frac{\omega^3 R_{\text{sub}}^2 C_{jd} C_{gb} (C_{gb} + C_{js} + C_{jd})}{1 + \omega^2 R_{\text{sub}}^2 (C_{gb} + C_{js} + C_{jd})^2}
\]

\[
\text{Re}[Y_{22}] = \frac{\omega^2 R_{\text{sub}} C_{jd}^2}{1 + \omega^2 R_{\text{sub}}^2 (C_{gb} + C_{js} + C_{jd})^2}
\]

\[
\text{Im}[Y_{22}] = \omega C_{g_{d0}} + \frac{\omega C_{jd} + \omega^3 R_{\text{sub}}^2 C_{jd} (C_{gb} + C_{js})(C_{gb} + C_{js} + C_{jd})}{1 + \omega^2 R_{\text{sub}}^2 (C_{gb} + C_{js} + C_{jd})^2}
\]
Equations for Extracting $R_{sub}$

At low frequencies up to a few GHz

Assuming that $\omega^2 R_{sub}^2 (C_{gb} + C_{js} + C_{jd})^2 << 1$
and that $\omega^3$-terms $<< \omega$-terms.

\[
\begin{align*}
\text{Im}[Y_{11}] & \approx \omega \left(C_{gs0} + C_{gd0} + C_{gb}\right) \\
\text{Im}[Y_{12}] & \approx -\omega C_{gd0} \\
\text{Re}[Y_{22}] & \approx \omega^2 R_{sub} C_{jd}^2 \\
\text{Im}[Y_{22}] & \approx \omega \left(C_{gd0} + C_{jd}\right) \\
C_{gd0} & \approx -\frac{\text{Im}[Y_{12}]}{\omega} \\
C_{gb} & \approx \frac{\text{Im}[Y_{11}] + 2\text{Im}[Y_{12}]}{\omega} \\
C_{jd} & \approx \frac{\text{Im}[Y_{22}] + \text{Im}[Y_{12}]}{\omega} \\
R_{sub} & \approx \frac{\text{Re}[Y_{22}]}{(\text{Im}[Y_{22}] + \text{Im}[Y_{12}])^2}
\end{align*}
\]
S-parameter Measurement

- MOSFET test patterns: 0.18 μm CMOS technology
- S-parameter measurement
  - Vector network analyzer
  - Probe station
Extraction Results

\[ C_{jd} \text{ and } R_{sub} \]

\[ W/L = 15/0.18 \ (N_f = 6) \]

\[ C_{jd} \]

\[ R_{sub} \]

Junction capacitance, \( C_{jd} \) (fF)

Substrate resistance, \( R_{sub} \) (\( \Omega \))

Frequency (GHz)
$V_{gs} \approx V_{th} \Rightarrow$ the intrinsic components of the MOSFET become significant.

Extraction Results ($C_{jd}$, $R_{sub}$) - Gate Voltage Dependency

- $W/L = 100/0.18$
  - $V_{ds} = 0$ V
  - $V_{ds} = 0.5$ V
  - $V_{ds} = 1$ V

Gate Voltage, $V_{gs}$ [V] vs. Extracted $C_{jd}$ [fF]

Gate Voltage, $V_{gs}$ [V] vs. Extracted $R_{sub}$ [$\Omega$]
**Drain Voltage Dependency**

As the $V_{ds}$ increases, $R_{sub}$ decreases, because the path between the intrinsic body and substrate contact becomes shorter with the depletion region widening.

**Graphical Representation**

- **$W/L = 100/0.18$**
- **$V_{gs} = 0$ V**

- **Cjd $[\text{fF}]$**
- **Rsub $[\Omega]$**

- **Cjd $R_{sub}$ $W/L = 100/0.18$ $V_{gs} = 0$ V**

- **Gate**
- **Body**

- **Drain**
- **STI**
Effect of Geometric Parameters

The widths of resistive path

- $W_b = 2.5, 5, 10, \text{ and } 20 \, \mu m$ for each device.

![Diagram showing the effect of geometric parameters](image)

The resistance $R_{sub}$ is inversely proportional to $W_b$:

$$R_{sub} \propto \frac{1}{W_b}$$
**Effect of Geometric Parameters**

**Distance to body contacts**

- Vertical-type, horizontal-type body contacts
  - $d_1 = 1.25\mu m (\times 1), 2.5\mu m (\times 2), 3.75\mu m (\times 3)$.
  - $d_2 = 6.825\mu m (\times 1), 13.65\mu m (\times 2), 20.475\mu m (\times 3)$

![Diagram showing vertical and horizontal body contacts with distances $d_1$ and $d_2$.](image)
Effect of Geometric Parameters

Distance to body contacts

- Ring-type body contacts
  - \( d_1 = 1.25\mu m \times 1, 2.5\mu m \times 2, 3.75\mu m \times 3 \).
  - \( d_2 = 6.825\mu m \times 1, 13.65\mu m \times 2, 20.475\mu m \times 3 \)
Effect of Geometric Parameters

- Distance to body contacts

\[ R_{sub} \text{ of the ring-type body contacts can be considered as a parallel combination of } R_{sub} \text{ of the vertical-type body contacts and } R_{sub} \text{ of the horizontal-type body contacts} \]

\[ R_{sub}(ring) = R_{sub}(ver) \parallel R_{sub}(hor) \]
Validity of $R_{sub}$ Values

Macro-modeling

The macro model for $Y_{22}$ agrees very well with the measurement, indicating that the extracted $R_{sub}$ value is valid for strong inversion.

Macro model including substrate resistance

Extracted substrate resistance

$\text{Re}[Y_{22}] [\text{A/V}]$

- $V_{gs} = 1.2 \text{ V}$
- $V_{gs} = 0.9 \text{ V}$
- $V_{gs} = 0 \text{ V}$

$V_{gs}$

Measurement

Simulation

Frequency [Hz]
Substrate-signal coupling through $R_{sub}$

One-substrate-resistor model

After deembedding the parasitic series resistances

$y_{gs} \approx \frac{-j\omega C_{gs}}{1 + j\omega \tau} - j\omega C_{gs0}$

$y_{gd} \approx \frac{-j\omega C_{gd}}{1 + j\omega \tau} - j\omega C_{gd0}$

$y_{gb} \approx -j\omega (C_{gb} + C_{gb0})$

$y_{bs} \approx \frac{-j\omega C_{bs}}{1 + j\omega \tau} - j\omega C_{js}$

$y_{bd} \approx \frac{-j\omega C_{bd}}{1 + j\omega \tau} - j\omega C_{jd}$

$y_m \approx \frac{g_m}{1 + j\omega \tau_m}$  \quad $y_{mb} \approx \frac{g_{mb}}{1 + j\omega \tau_m}$

$y_{sd} \approx \frac{-g_{sd}}{1 + j\omega \tau_m}$  \quad $y_{mx} \approx 0$

Substrate coupling voltage due to the drain signal

\[ i_b = y_{bd}v_{ds} + y_{bb}v_{bs}, \quad v_{bs} = -R_{sub}i_b \]

\[ i_b = y_{ba}v_{ds} - y_{bb}R_{sub}i_b \]

\[ v_{bs} = -\frac{y_{bd}R_{sub}}{1 + y_{bb}R_{sub}}v_{ds} \]

\[ Y_{22} \text{ derivation} \]

\[ i_d = y_{dd}v_{ds} + y_{db}v_{bs} = y_{dd}v_{ds} - \frac{y_{db}y_{bd}R_{sub}}{1 + y_{bb}R_{sub}}v_{ds} \]

\[ Y_{22} = y_{dd} - \frac{y_{db}y_{bd}R_{sub}}{1 + y_{bb}R_{sub}} \]
Re($Y_{22}$)

\[ g_{sd} + \omega^2 \left\{ \tau (C_{gd} + C_{bd}) - \tau_m^2 g_{sd} \right\} + H.O.T_{int} \]
\[ + \frac{1}{1 + \omega^2 \tau_{sub}^2} \left[ \omega^2 \left\{ g mb R_{sub}^2 (C_{bd} + C_{jd}) C_B + R_{sub} (C_{db} + C_{jd}) (C_{bd} + C_{jd}) \right\} + H.O.T_{ssc} \right] \]

Term A

\[ \tau_{sub} = \sqrt{2 \tau R_{sub} (C_{bs} + C_{bd}) + R_{sub}^2 C_B^2} \approx R_{sub} C_B \]

\[ C_B = C_{gb} + C_{bs} + C_{bd} + C_{gbd0} + C_{js} + C_{jd} \]

Im($Y_{22}$)

\[ \omega (C_{gd} + C_{bd} + C_{gbd0} + C_{jd} + C_{sd}) + H.O.T_{int} \]
\[ + \frac{1}{1 + \omega^2 \tau_{sub}^2} \left[ \omega g mb R_{sub} (C_{bd} + C_{jd}) - \omega^3 R_{sub}^2 (C_{bd} + C_{jd}) (C_{db} + C_{jd}) C_B + H.O.T_{ssc} \right] \]

Term C

Term D
Results: $\text{Re}(Y_{22})$

\[
\frac{1}{1 + \omega^2 R_{\text{sub}}^2 C_B^2} \left[ \omega^2 g_{mb} R_{\text{sub}}^2 (C_{bd} + C_{jd}) C_B + \omega^2 R_{\text{sub}} (C_{db} + C_{jd})(C_{bd} + C_{jd}) \right]
\]

Term A

Term B

![Graph showing the results of $\text{Re}(Y_{22})$ for different frequencies and drain-source voltages (VGS)](image)
Results: $\text{Im}(Y_{22})$

\[
\frac{1}{1 + \omega^2 R_{\text{sub}}^2 C_B^2} \left[ \omega g_{mb} R_{\text{sub}} (C_{bd} + C_{jd}) - \omega^3 R_{\text{sub}}^2 (C_{bd} + C_{jd})(C_{db} + C_{jd})C_B \right]
\]

Term C

Term D

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Graph showing $\text{Im}(Y_{22})$ as a function of frequency for different $V_{GS}$ values and measured $R_{\text{sub}}$ values.
Conclusions

- A simple and efficient method to extract the accurate substrate resistance of an RF MOSFET was presented.
- The extracted results have been presented for various bias conditions and various layout geometries.
- The amount of substrate-signal coupling was predicted and verified.