Physical Modeling of Substrate Resistance in RF MOSFETs

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Contents

- Introduction
- Extraction method of Rsub
- Dependence of Rsub on bias conditions and layout geometries
- Substrate-signal coupling through Rsub
- A scalable model as a function of no. of fingers
- Conclusion

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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**

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Introduction

- **Previous works**
  - **Curve fitting or optimization technique was used to extract R_{sub}.**
    - **Unphysical value can be extracted.**
    - **It is complicated.**
- **Our research**
  - **Simple and efficient method to extract the accurate substrate resistance of RF MOSFETs**

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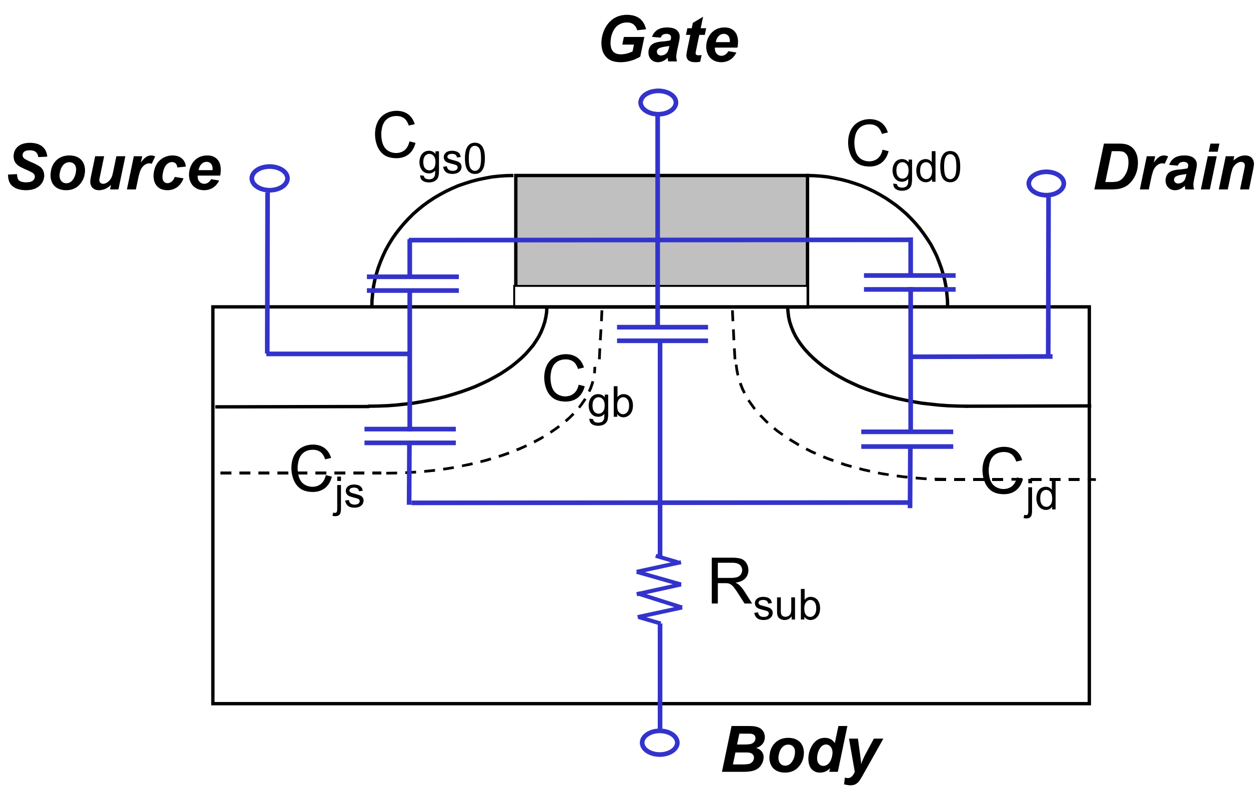
Extraction Method

- **Equivalent circuit of an RF MOSFET, when it is off : Vgs<Vth**



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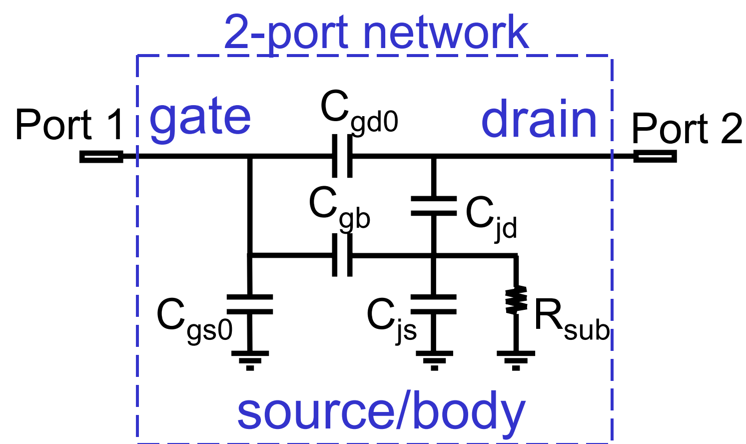
Y-parameters

Some of the y-parameters related to Rsub

$$\mathrm{Im}[Y_{11}] = \omega(C_{gs0} + C_{gd0}) + \frac{\omega C_{gb} + \omega^3 R_{sub}^{\ 2} C_{gb}(C_{js} + C_{jd})(C_{gb} + C_{js} + C_{jd})}{1 + \omega^2 R_{sub}^{\ 2}(C_{gb} + C_{js} + C_{jd})^2}$$

$$\mathrm{Im}[Y_{12}] = -\omega C_{gd0} - \frac{\omega^3 R_{sub}^{\ 2} C_{jd} C_{gb}(C_{gb} + C_{js} + C_{jd})}{1 + \omega^2 R_{sub}^{\ 2}(C_{gb} + C_{js} + C_{jd})^2}$$



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

$$\mathrm{Im}[Y_{22}] = \omega C_{gd0} + \frac{\omega C_{jd} + \omega^3 R_{sub}^{\ 2} C_{jd}(C_{gb} + C_{js})(C_{gb} + C_{js} + C_{jd})}{1 + \omega^2 R_{sub}^{\ 2}(C_{gb} + C_{js} + C_{jd})^2}$$

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 ω^3-terms << ω-terms.

$$\mathrm{Im}[Y_{11}] \approx \omega \left(C_{gs0} + C_{gd0} + C_{gb} \right)$$

$$\mathrm{Im}[Y_{12}] \approx -\omega C_{gd0}$$

$$\mathrm{Re}[Y_{22}] \approx \omega^2 R_{sub} C_{jd}^2$$

$$\mathrm{Im}[Y_{22}] \approx \omega \left(C_{gd0} + C_{jd} \right)$$

⇒

$$C_{gd0} \approx -\frac{\mathrm{Im}[Y_{12}]}{\omega}$$

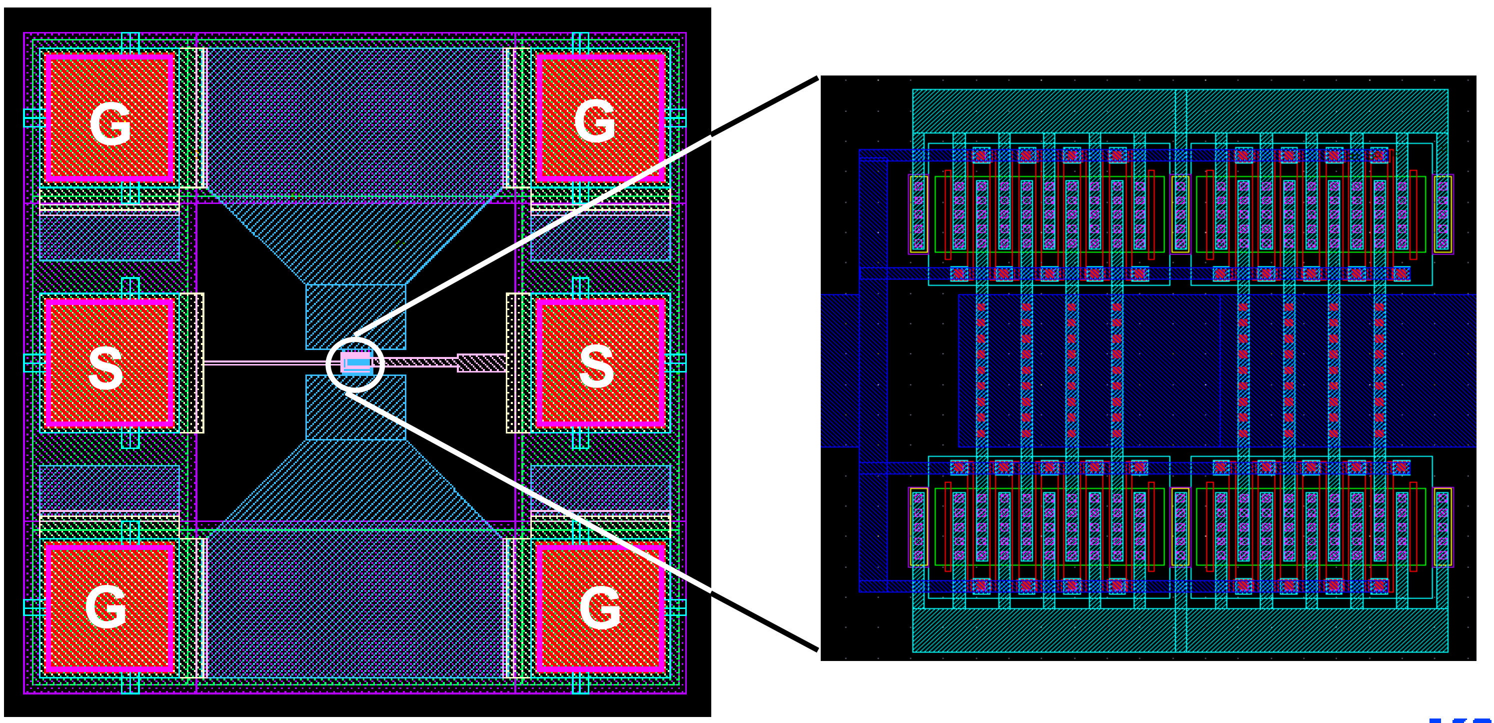
$$C_{gb} \approx \frac{\mathrm{Im}[Y_{11}] + 2\,\mathrm{Im}[Y_{12}]}{\omega}$$

$$C_{jd} \approx \frac{\mathrm{Im}[Y_{22}] + \mathrm{Im}[Y_{12}]}{\omega}$$

$$R_{sub} \approx \frac{\mathrm{Re}[Y_{22}]}{\left(\mathrm{Im}[Y_{22}] + \mathrm{Im}[Y_{12}]\right)^2}$$

S-parameter Measurement

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



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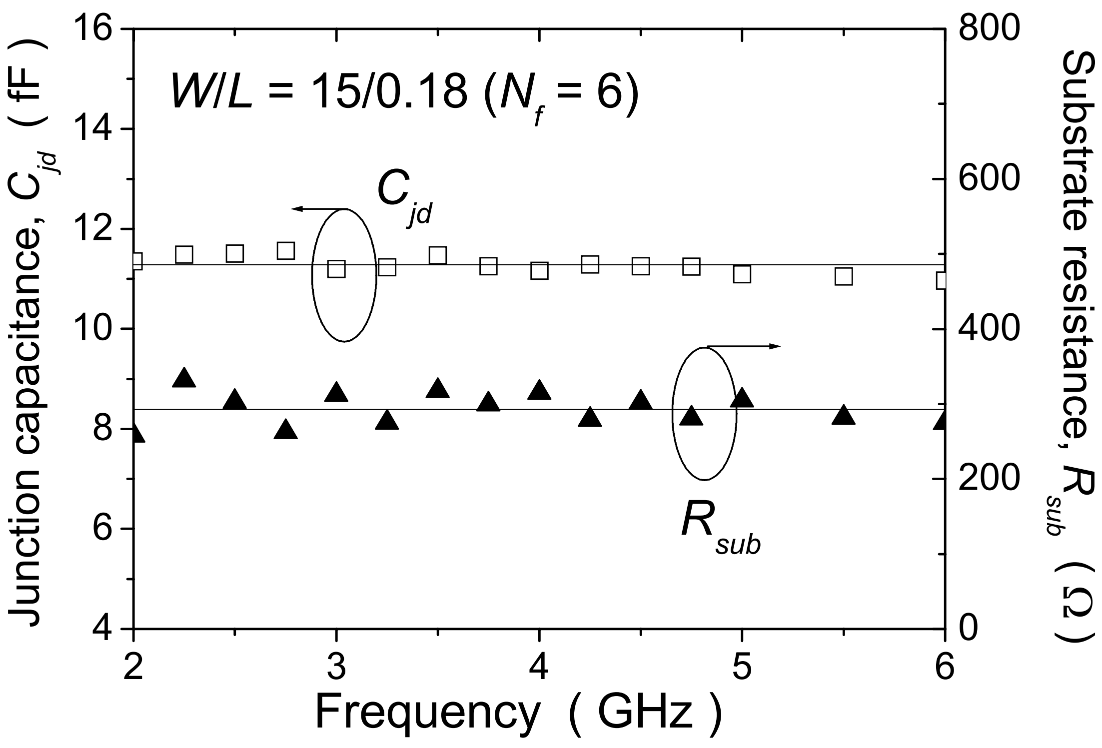
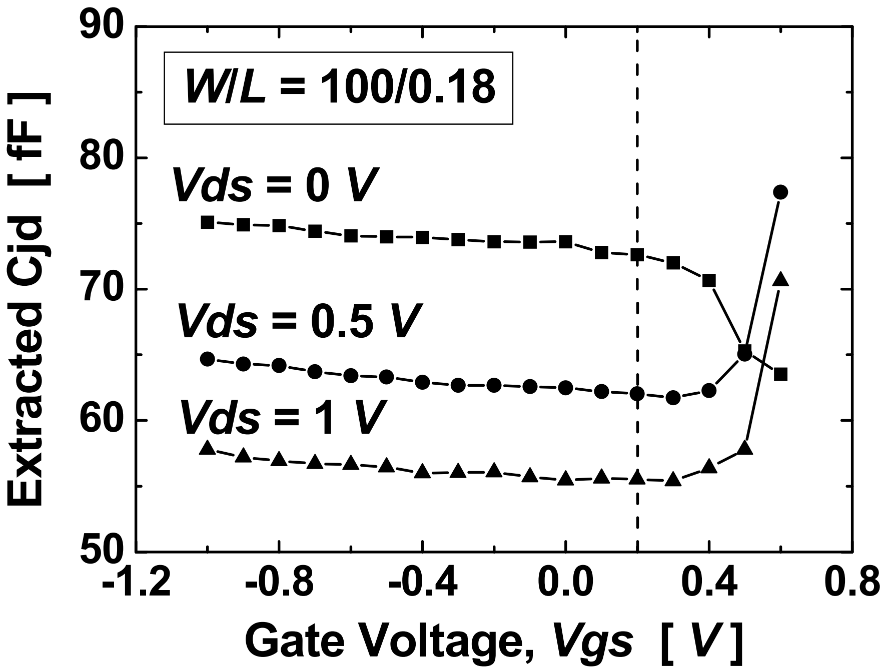
Extraction Results

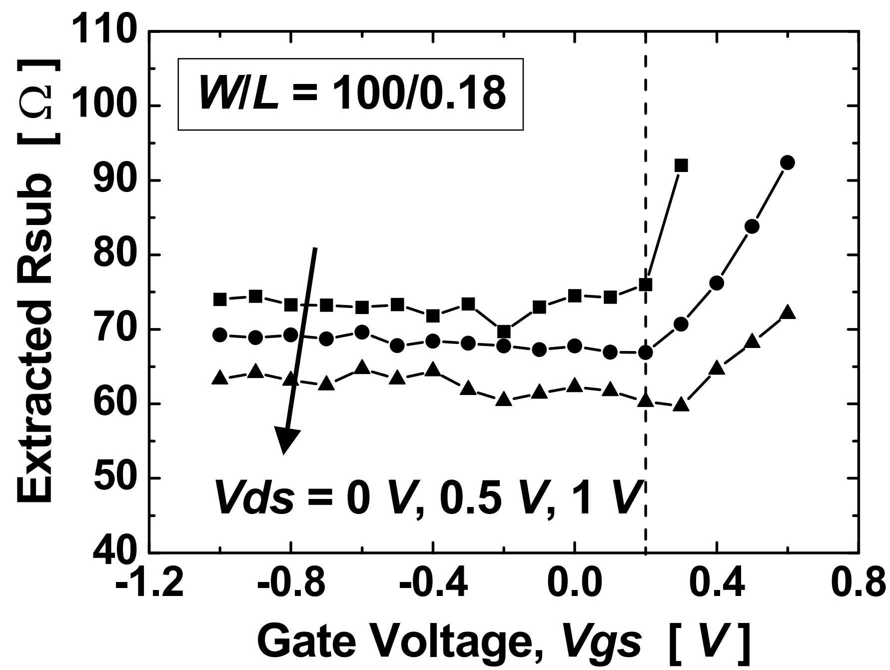
- C_{jd} and R_{sub}



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

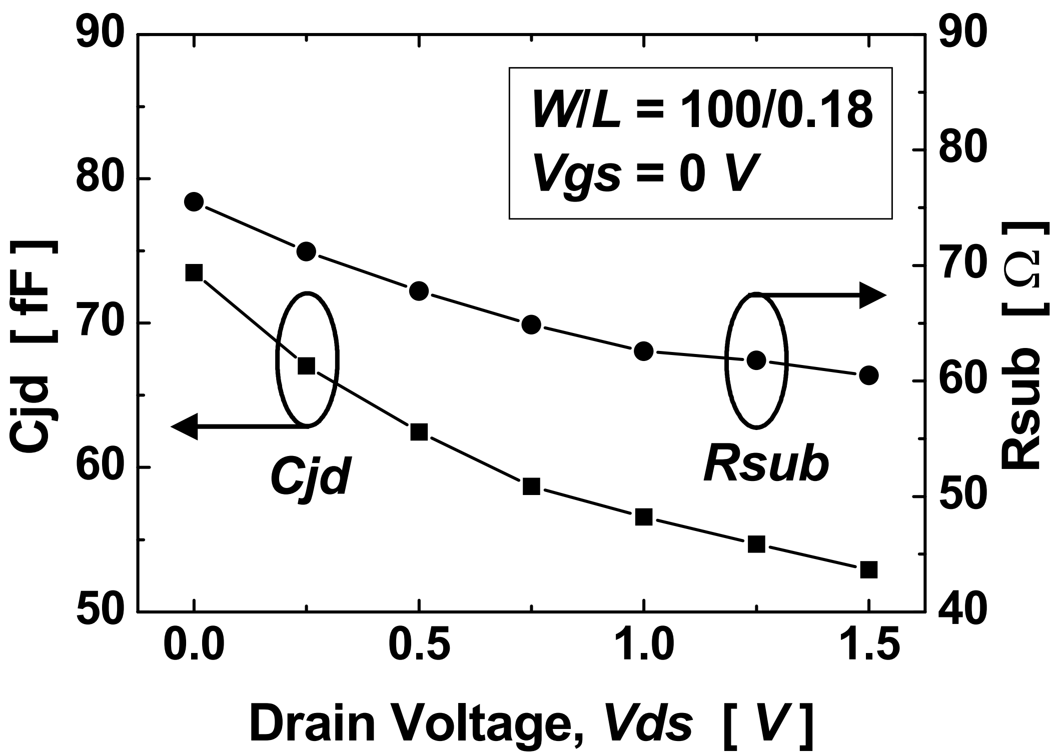
- $V_{gs} \approx V_{th} \Rightarrow$ the intrinsic components of the MOSFET become significant.

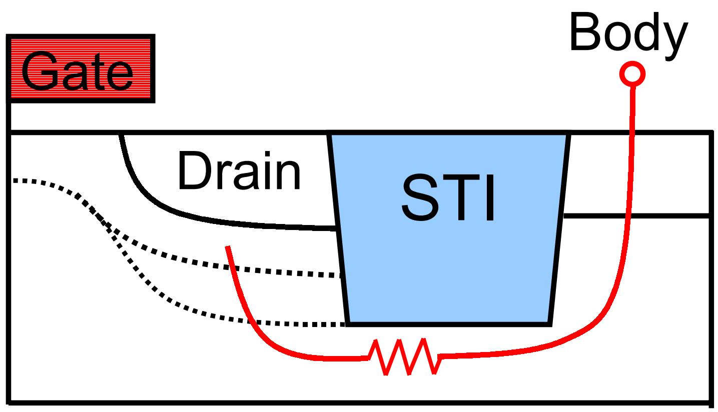




Drain Voltage Dependency

- 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.





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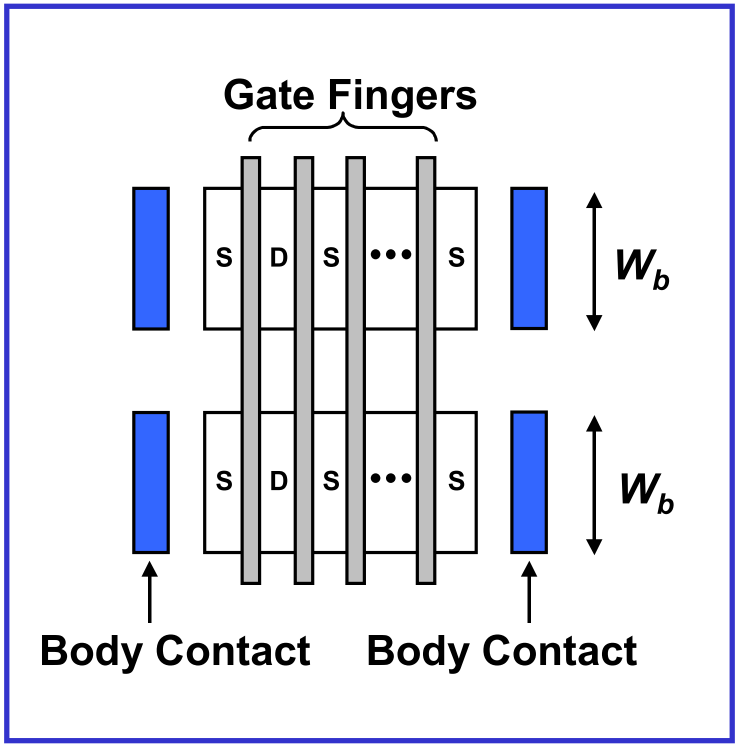
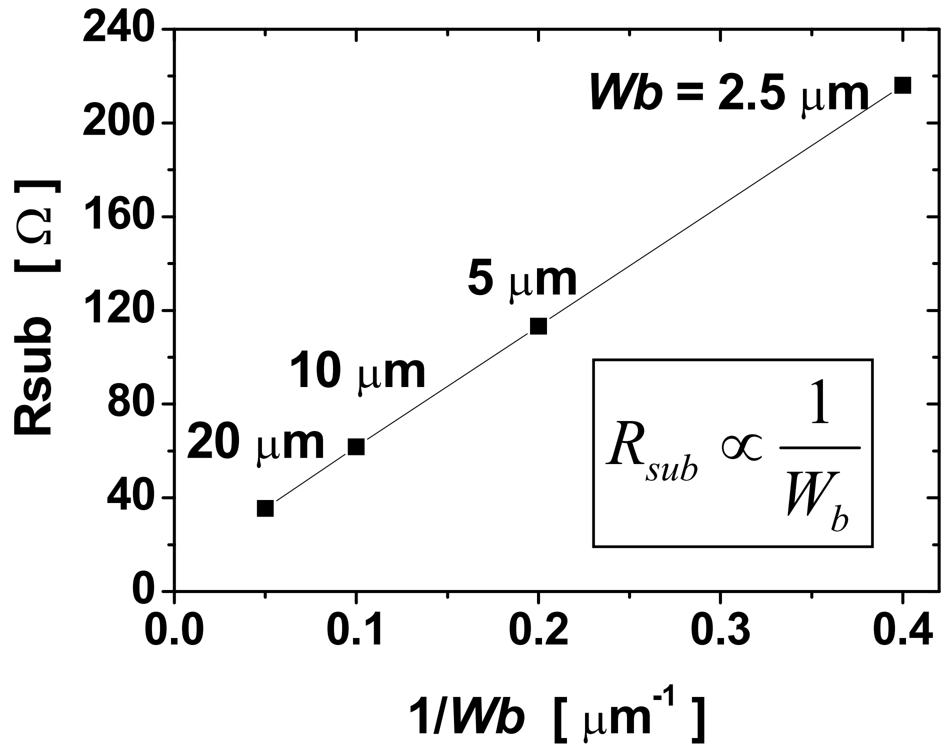
Effect of Geometric Parameters

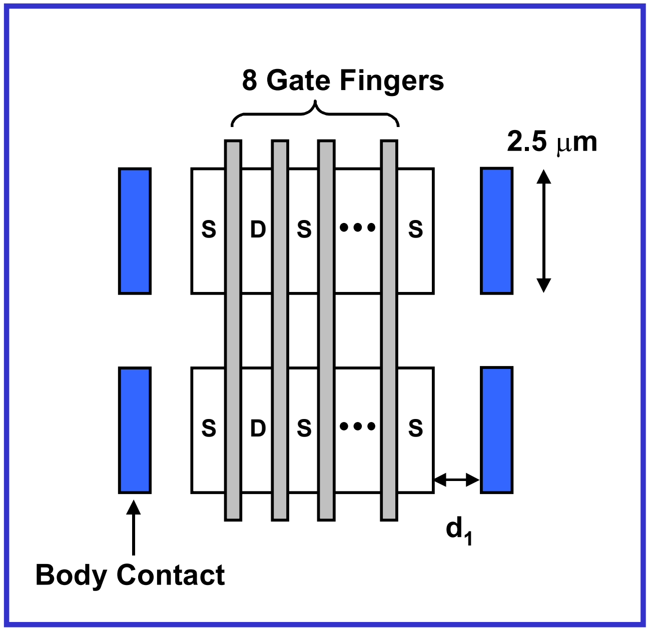
- **The widths of resistive path**
  - W_b = 2.5, 5, 10, and 20 μm for each device.



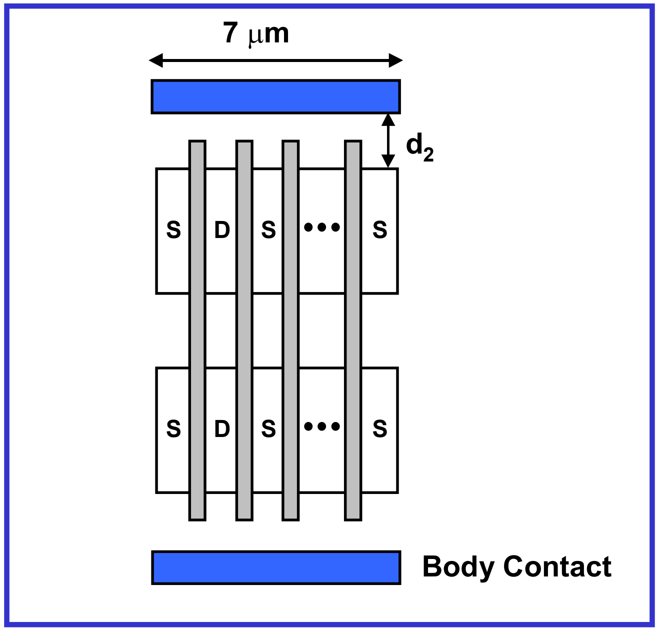


Effect of Geometric Parameters

- **Distance to body contacts**
  - Vertical-type, horizontal-type body contacts
    - d_1 = 1.25*μm* (×1), 2.5*μm* (×2), 3.75*μm* (×3).
    - d_2 = 6.825*μm* (×1), 13.65*μm* (×2), 20.475*μm* (×3)



Vertical-type



Horizontal-type

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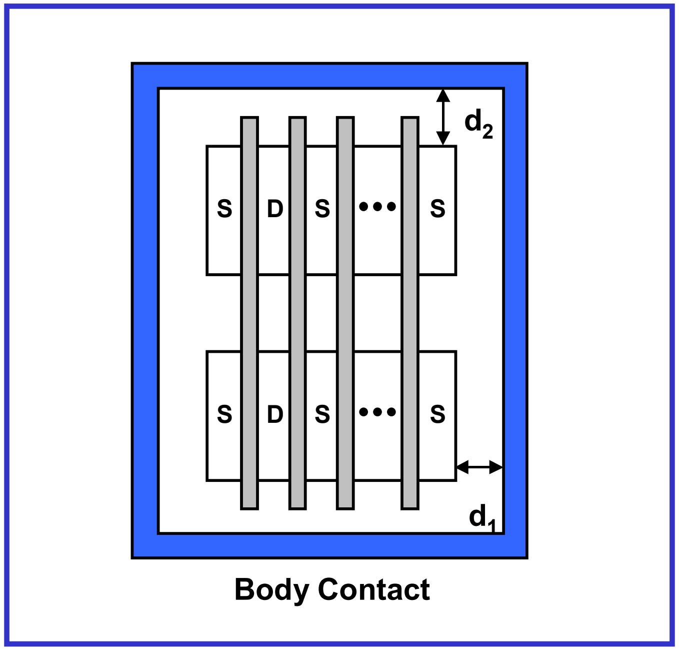
Effect of Geometric Parameters

Distance to body contacts

- Ring-type body contacts
  - d_1 = 1.25μm (×1), 2.5μm (×2), 3.75μm (×3).
  - d_2 = 6.825μm (×1), 13.65μm (×2), 20.475μm (×3)

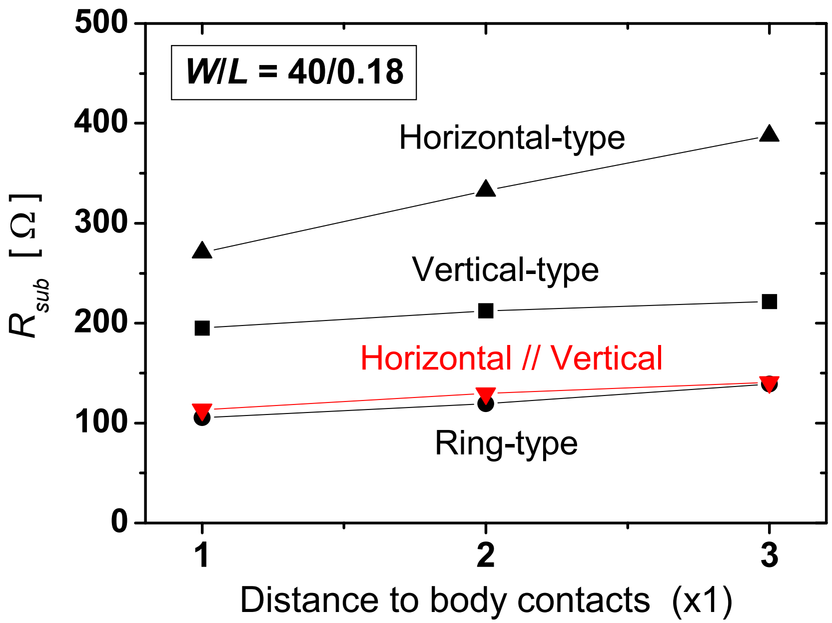


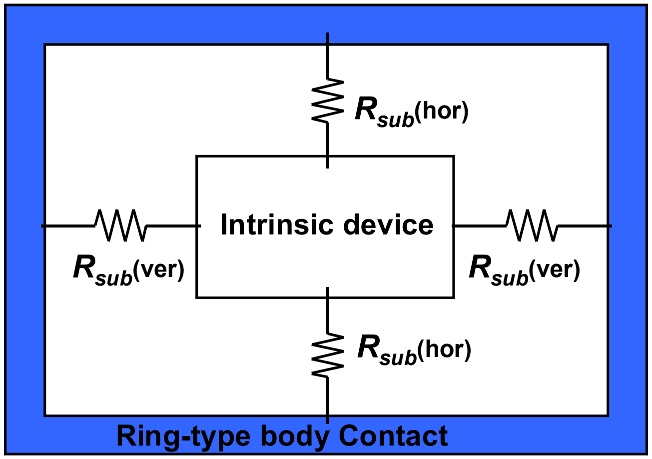
Ring-type

Effect of Geometric Parameters

Distance to body contacts

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

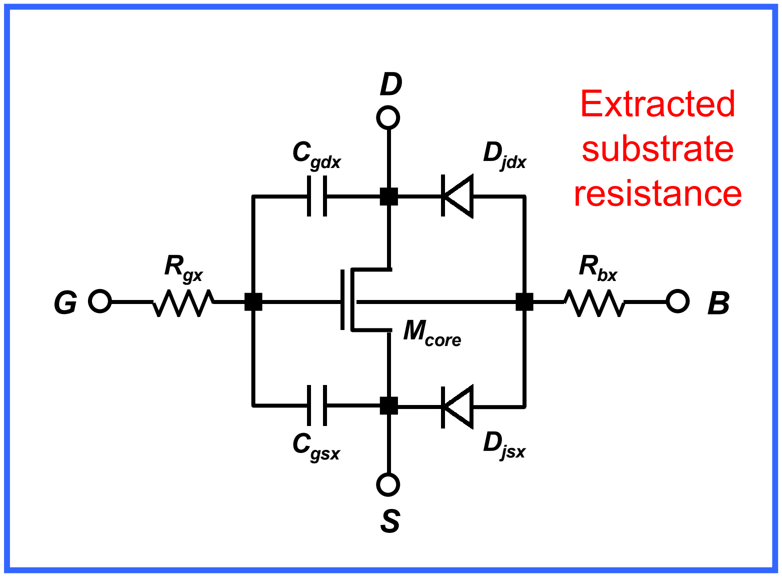




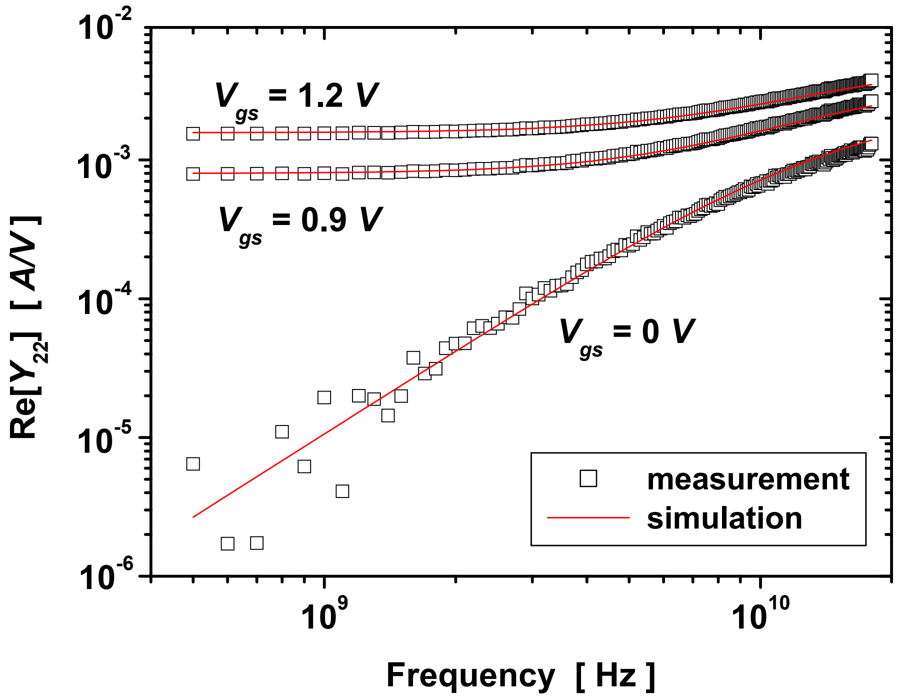
$$R_{sub}(ring) = R_{sub}(ver) // R_{sub}(hor)$$

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



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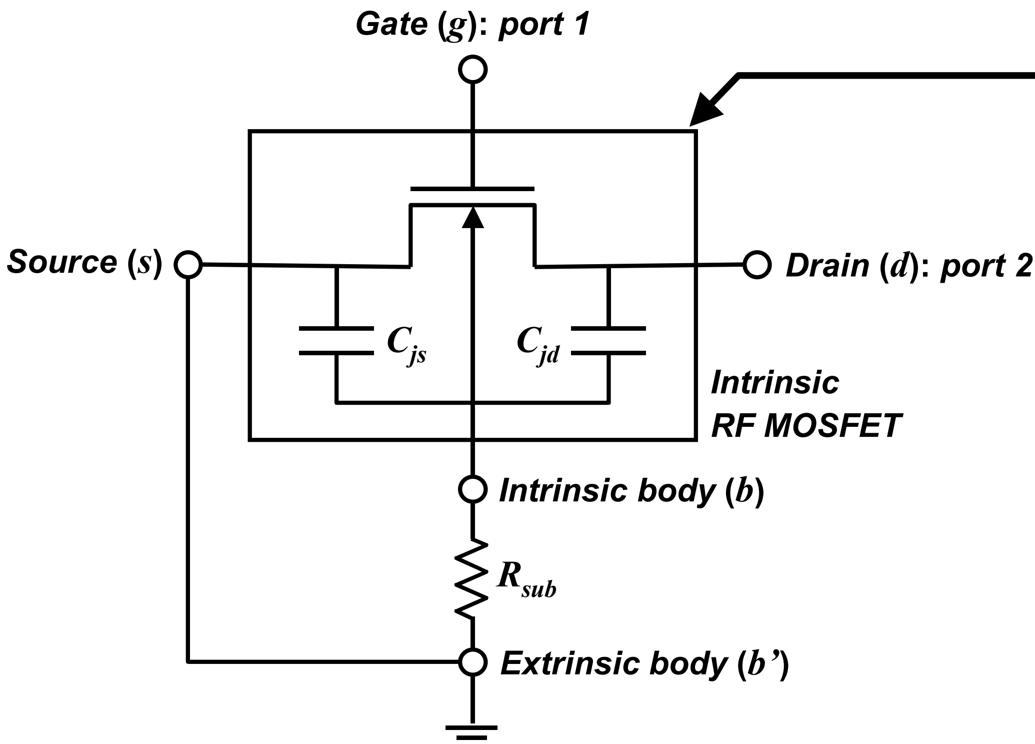
Substrate-signal coupling through Rsub



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

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

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

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

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

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

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

- **One-substrate-resistor model**
- **After deembedding the parasitic series resistances**

[1] Y. Tsividis, *The operation and Modeling of the MOS Transistor*, 2nd ed., New York: McGraw-Hill, 1999.

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Y-Parameter Analysis

- **Substrate coupling voltage due to the drain signal**

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

$$i_b = y_{bd} v_{ds} - y_{bb} R_{sub} i_b$$

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

- **Y_{22} derivation**

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

$$Y_{22} = y_{dd} - \frac{y_{db} y_{bd} R_{sub}}{1 + y_{bb} R_{sub}}$$

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Y_{22} Equations

- $\mathrm{Re}(Y_{22})$

$$g_{sd} + \omega^2 \left\{ \tau (C_{gd} + C_{bd}) - \tau_m{}^2 g_{sd} \right\} + H.O.T_{int}$$

$$+ \frac{1}{1+\omega^2 \tau_{sub}{}^2} \left[\omega^2 \left\{ \underbrace{g_{mb} R_{sub}{}^2 (C_{bd} + C_{jd}) C_B}_{\text{Term A}} + \underbrace{R_{sub} (C_{db} + C_{jd})(C_{bd} + C_{jd})}_{\text{Term B}} \right\} + H.O.T_{ssc} \right]$$

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

$$C_B = C_{gb} + C_{bs} + C_{bd} + C_{gb0} + C_{js} + C_{jd}$$

- $\mathrm{Im}(Y_{22})$

$$\omega (C_{gd} + C_{bd} + C_{gd0} + C_{jd} + C_{sd}) + H.O.T_{int}$$

$$+ \frac{1}{1+\omega^2 \tau_{sub}{}^2} \left[\underbrace{\omega g_{mb} R_{sub} (C_{bd} + C_{jd})}_{\text{Term C}} - \underbrace{\omega^3 R_{sub}{}^2 (C_{bd} + C_{jd})(C_{db} + C_{jd}) C_B}_{\text{Term D}} + H.O.T_{ssc} \right]$$

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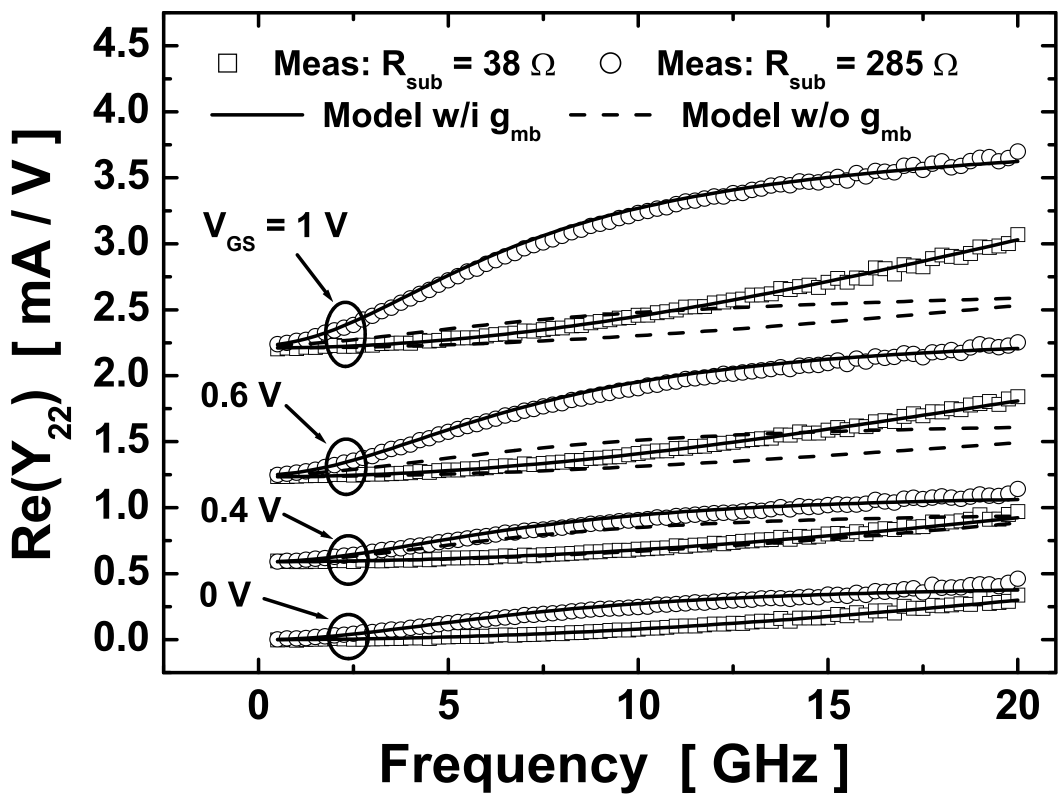
Results: Re(Y_{22})

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



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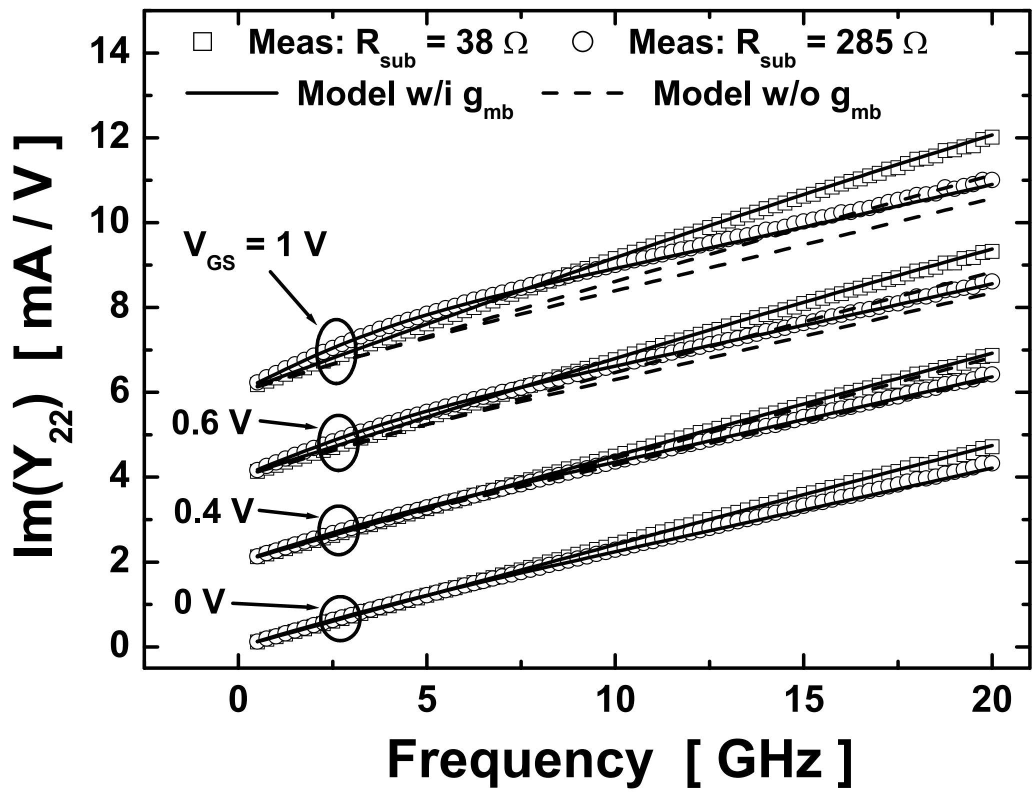
Results: $Im(Y_{22})$

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



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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.