

A Practical Method to Extract Parasitic Parameters for the Silicon MOSFET Small-Signal Model

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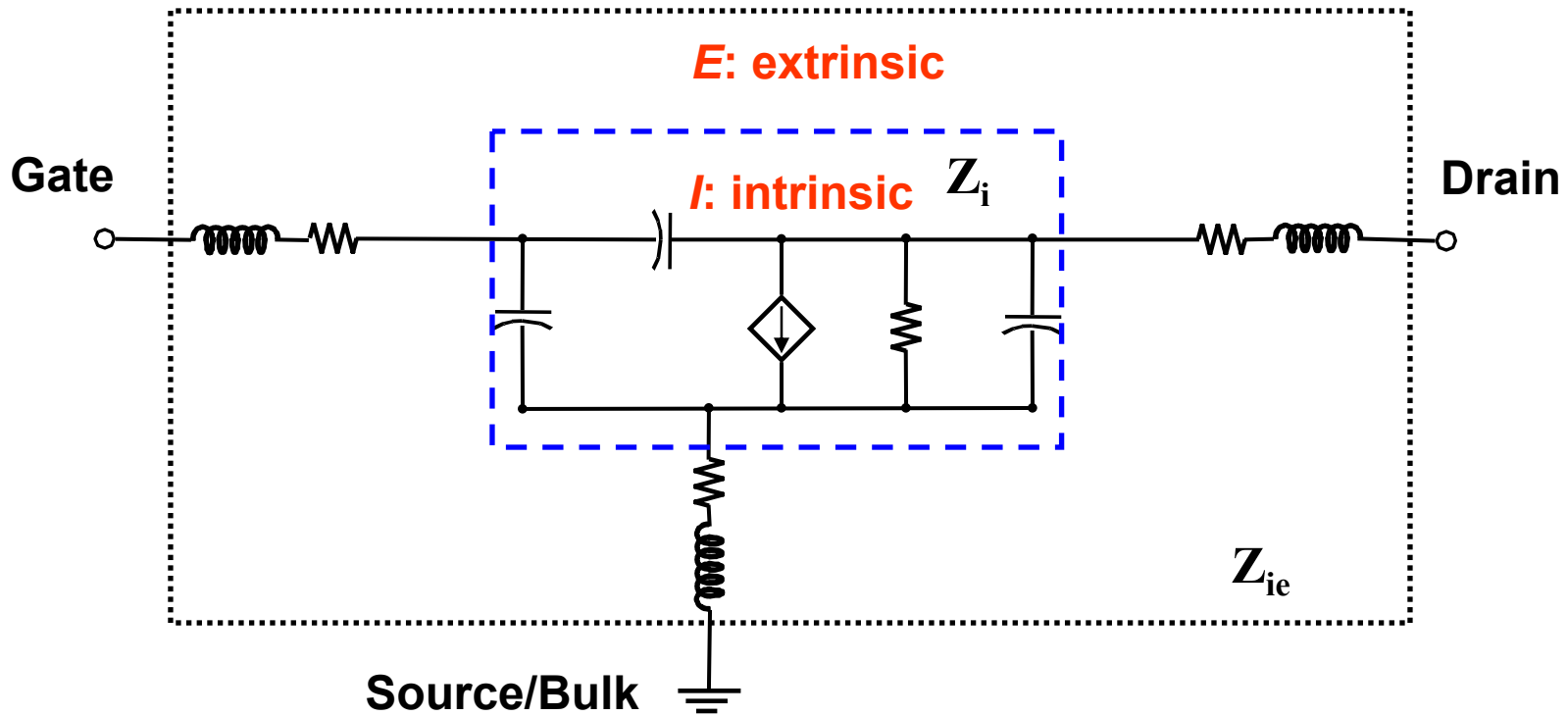


Outline

- Conventional MOS small-signal model
- Lee's method to extract the extrinsic parameters
- Improved MOS Small-signal model
- Modified extrinsic extraction method
- Modeling results
- conclusions



Conventional Small-Signal Equivalent Circuit



Extracting Extrinsic Parameters

Using curve-fitting method by S. Lee et al., 1997

$$\text{Re}(Z_{ie,12}) = R_s + \frac{A_s}{\omega^2 + B}$$

$$\frac{1}{\omega} \text{Im}(Z_{ie,12}) = L_s - \frac{E_s}{\omega^2 + B}$$

$$\text{Re}(Z_{ie,22} - Z_{ie,12}) = R_d + \frac{A_d}{\omega^2 + B}$$

$$\frac{1}{\omega} \text{Im}(Z_{ie,22} - Z_{ie,12}) = L_d - \frac{E_d}{\omega^2 + B}$$

$$\text{Re}(Z_{ie,11} - Z_{ie,12}) = R_g + \frac{A_g}{\omega^2 + B}$$

$$\frac{1}{\omega} \text{Im}(Z_{ie,11} - Z_{ie,12}) = L_g - \frac{E_g}{\omega^2 + B} - \frac{F_g}{\omega^2 \cdot (\omega^2 + B)}$$

B , A_s , A_d , A_g , E_s , E_d , E_g , and F_g are all frequency-independent parameters

Reference: S. Lee et al., "A novel approach to extracting small-signal model parameters of silicon MOSFET's," IEEE Microwave Guided Wave Lett., Vol. 7, pp. 75-77, 1997.

Extracting Intrinsic Parameters

Using direct-extraction method by D. Lovelace et al., 1994

$$Z_{i,11} = Z_{ie,11} - (R_g + R_s) - j\omega(L_g + L_s)$$

$$Z_{i,22} = Z_{ie,22} - (R_d + R_s) - j\omega(L_d + L_s)$$

$$Z_{i,12} = Z_{ie,12} - R_s - j\omega L_s$$

$$Z_{i,21} = Z_{ie,21} - R_s - j\omega L_s$$

$$\longrightarrow Y_i = \frac{1}{Z_i} \longrightarrow$$

$$C_{gd} = \frac{-\text{Im}(Y_{i,12})}{\omega}$$

$$C_{gs} = \frac{\text{Im}(Y_{i,11}) + \text{Im}(Y_{i,12})}{\omega}$$

$$C_{ds} = \frac{\text{Im}(Y_{i,22}) + \text{Im}(Y_{i,12})}{\omega}$$

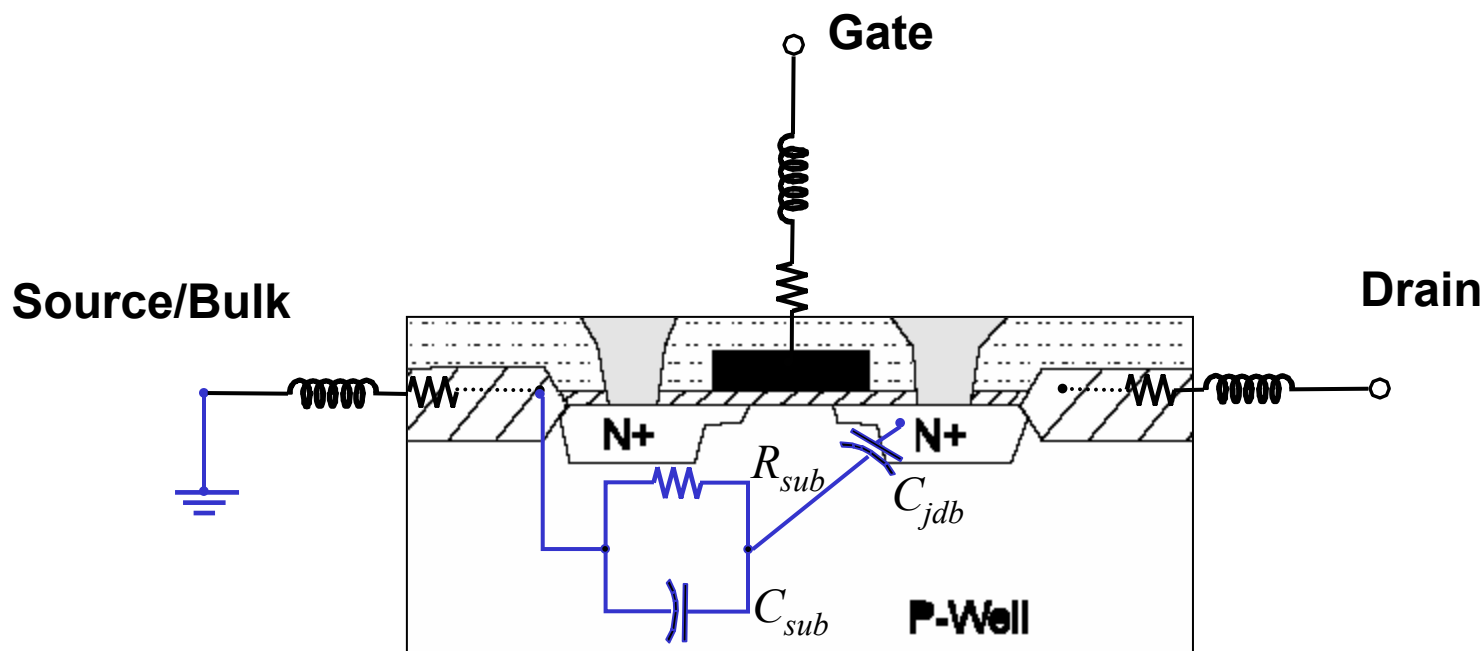
$$R_{ds} = \frac{1}{\text{Re}(Y_{i,22})}$$

$$g_m = |Y_{i,21} - Y_{i,12}|$$

$$\tau = -\tan^{-1}\left(\frac{\text{Im}(Y_{i,21} - Y_{i,12})}{\text{Re}(Y_{i,21} - Y_{i,12})}\right) / \omega$$

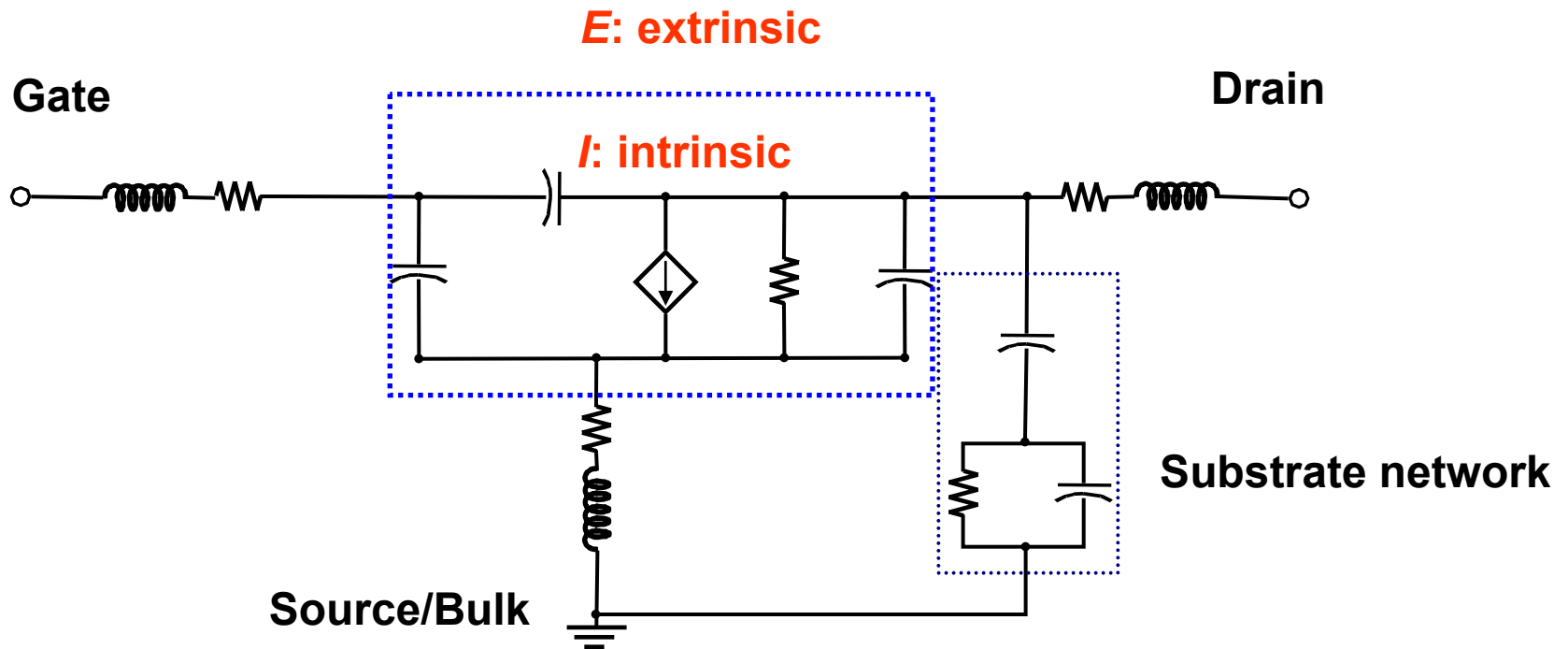
Reference: D. Lovelace et al., "Extracting small-signal model parameters of silicon MOSFET transistors," in IEEE MTT-S Tech. Dig., pp. 865-868, 1994.

Silicon MOSFET Cross-Section View

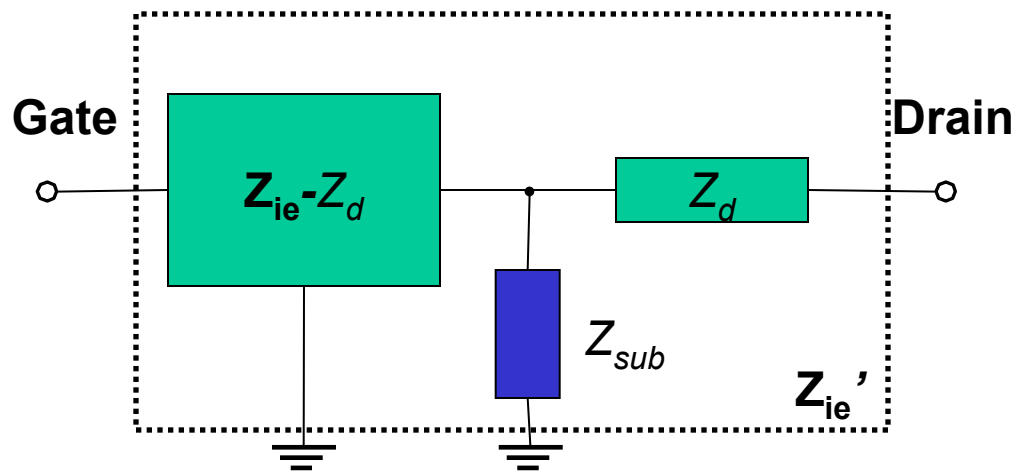


Substrate effects must be added!

Improved Small-Signal Model



Substrate Effects on Extracting L's and R's

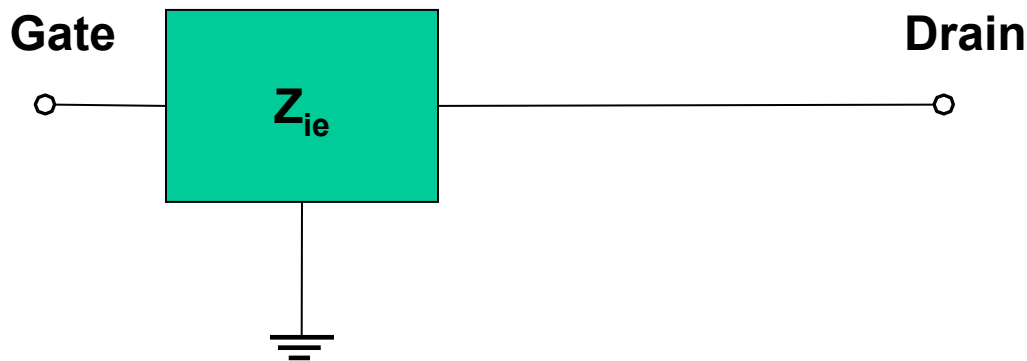


$$Z'_{ie,12} = \frac{Z_{ie,12}}{1 + Z_{ie,22}/Z_{sub}}$$

$$Z'_{ie,22} = \frac{Z_{ie,22}}{1 + Z_{ie,22}/Z_{sub}} + Z_d$$

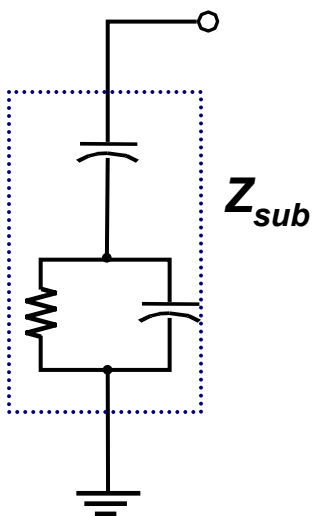
$$Z'_{ie,21} = \frac{Z_{ie,21}}{1 + Z_{ie,22}/Z_{sub}}$$

$$Z'_{ie,11} = Z_{ie,11} - (Z_{ie,12}/Z_{sub}) \frac{Z_{ie,21}}{1 + Z_{ie,22}/Z_{sub}}$$



Z_{ie}' approaches to Z_{ie} only when $Z_{ie,22}/Z_{sub}$ approaches zero!

When does $Z_{ie,22}/Z_{sub}$ approach zero?



$$Z_{sub} = \frac{R_{sub}}{1 + \omega^2 C_{sub}^2 R_{sub}^2} - j \left(\frac{\omega C_{sub} R_{sub}}{1 + \omega^2 C_{sub}^2 R_{sub}^2} + \frac{1}{\omega C_{jdb}} \right)$$

Mag(Z_{sub}) would approach about R_{sub} as freq \uparrow

$$Z_{ie,22} = R_s + j\omega L_s + j\omega(C_{gs} + C_{gd})/D$$

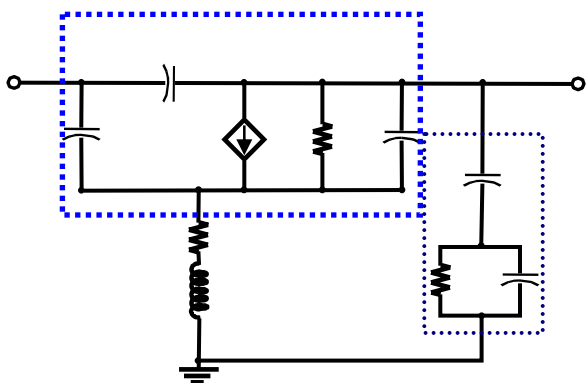
$$D = -\omega^2(C_{gs} + C_{ds} + C_{gs}C_{gd} + C_{gd}C_{ds}) + j\omega[g_m C_{gd} + g_{ds}(C_{gs} + C_{gd})]$$

Mag($Z_{ie,22}$) \downarrow as freq \uparrow

That means, the curve-fitting method will be valid only at high frequencies!

Extracting Z_{sub}

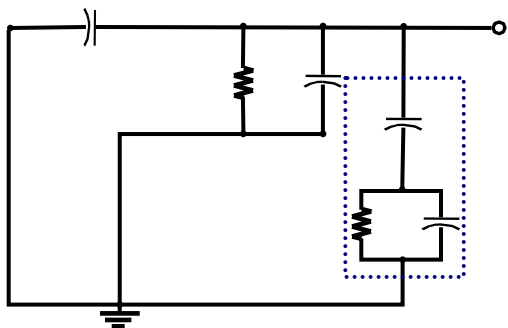
Using curve-fitting method by S. Lee et al., 1997



After de-embedding R_g , R_d , L_g and L_d :

$$\text{Re}(Y_{22} + Y_{12}) = \frac{1}{R_{ds}} + \frac{K_1 \omega^2}{1 + K_2 \omega^2}$$

$$\frac{1}{\omega} \text{Im}(Y_{22} + Y_{12}) = C_{jdb} \left(\frac{1 + M_1 \omega^2}{1 + M_2 \omega^2} \right) + C_{ds}$$



$Y_{22} + Y_{12}$

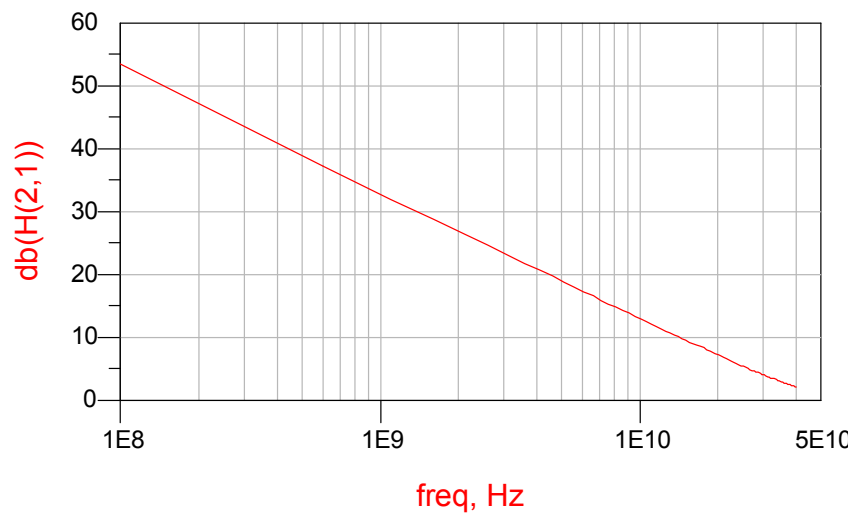
$$R_{sub} = \frac{K_2}{K_1} \left(1 - \frac{M_1}{M_2} \right)^2 \quad C_{sub} = \frac{M_1 C_{jdb}}{M_2 - M_1}$$

Reference: S. Lee et al., "A small-signal RF model and its parameter extraction for substrate effects in RF MOSFET's," *IEEE Trans. Electron Devices*, vol. 48, pp. 1374–1379, 2001.

Experiments

Technology: UMC 0.18 um RF CMOS

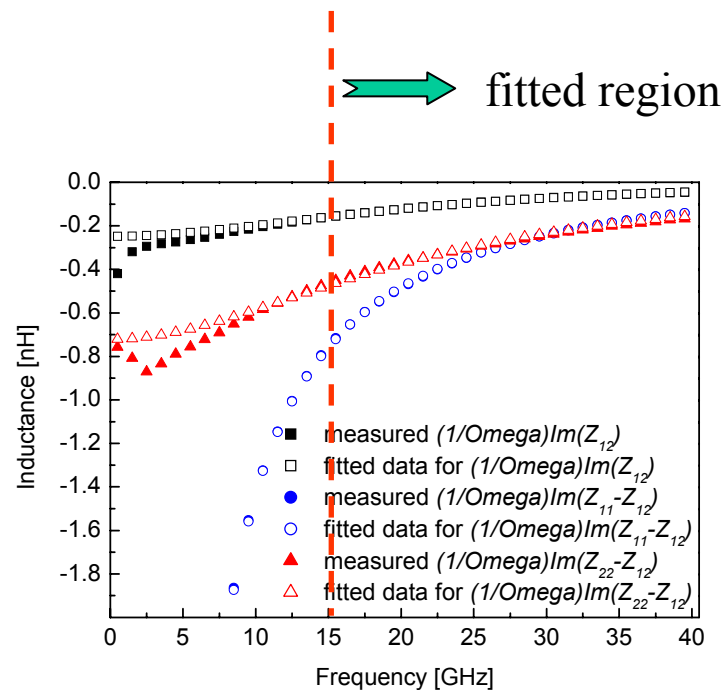
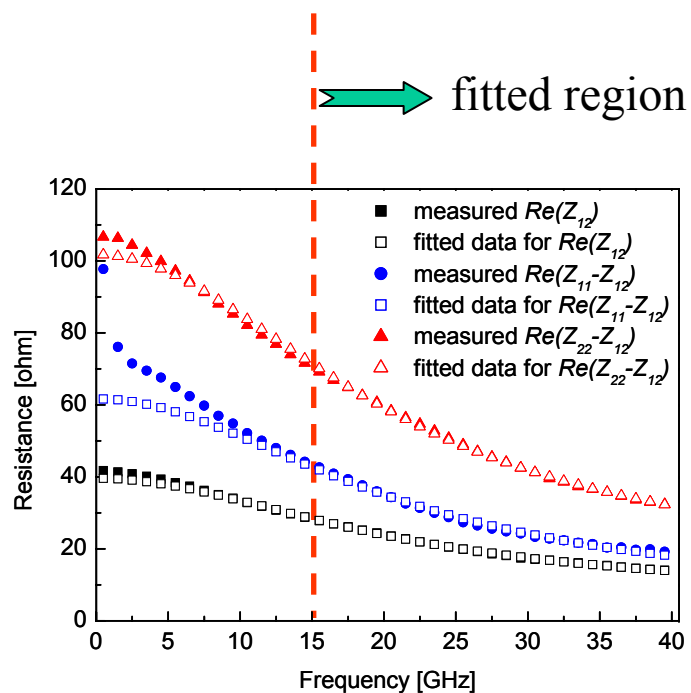
Geometry: $L=0.18\mu\text{m}$ $L_f=5\mu\text{m}$ $N_f=4$



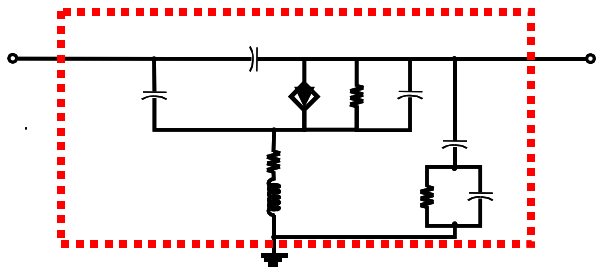
$$V_{gs} = V_{ds} = 1.8V$$

$$f_t = 45\text{GHz}$$

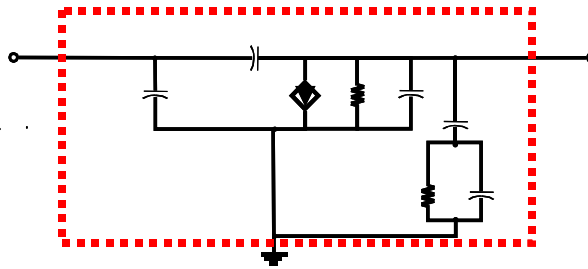
Curve-fitting L's and R's



Curve-fitting Substrate Network

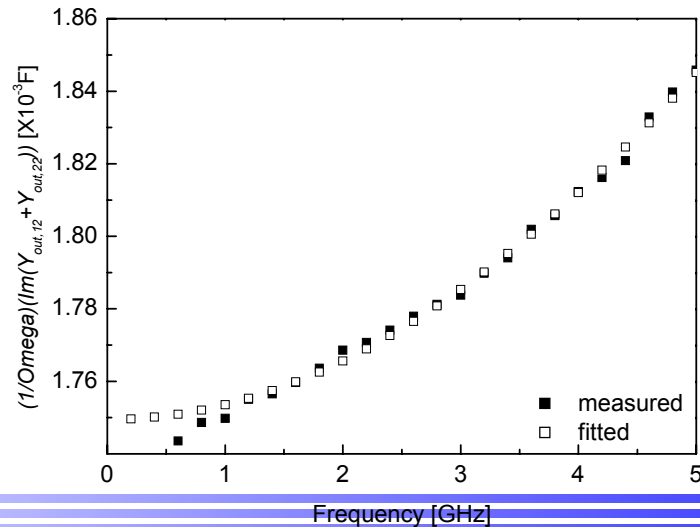
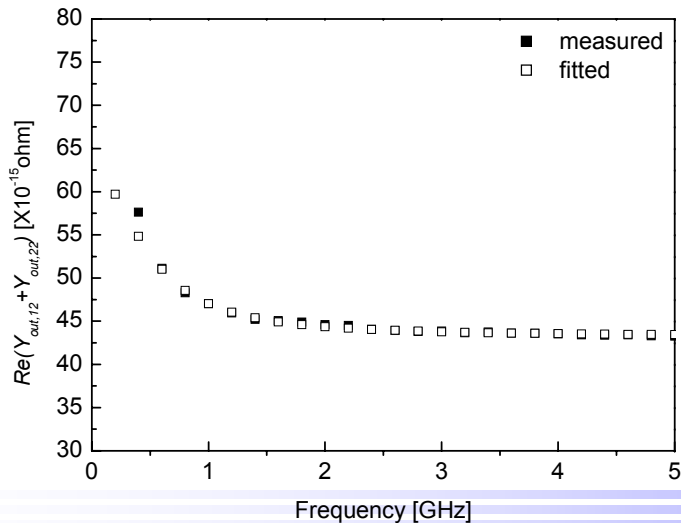


de-embedding gate- and drain-side series resistances and inductances

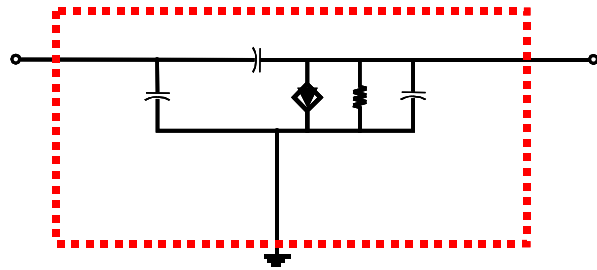


neglecting the voltage drop across source-side resistance and inductance

$$Y_{22} + Y_{12}$$

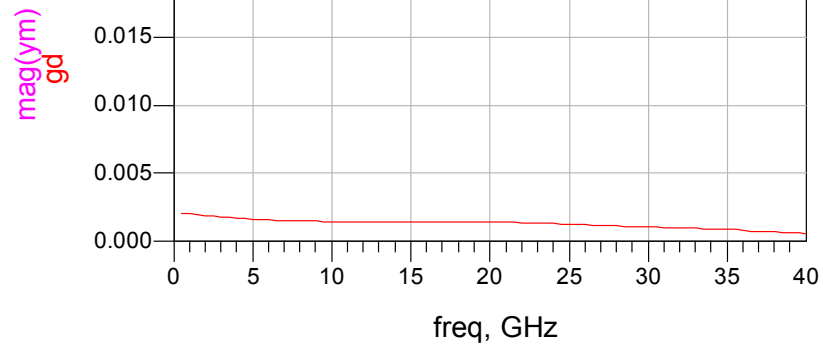
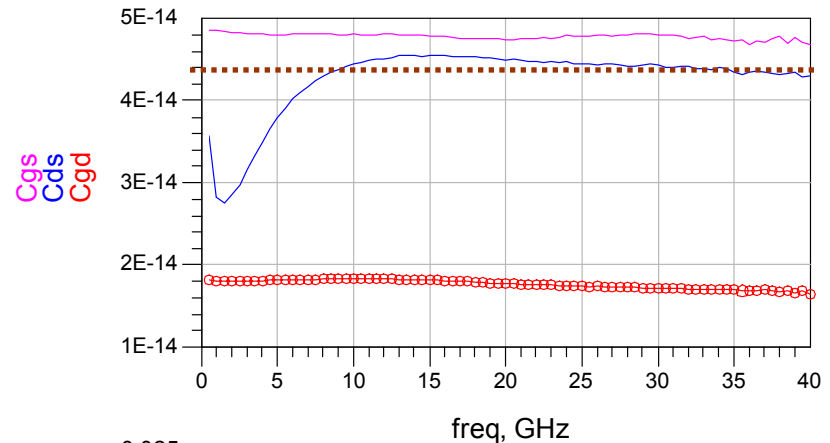


Extracted Intrinsic Parameters

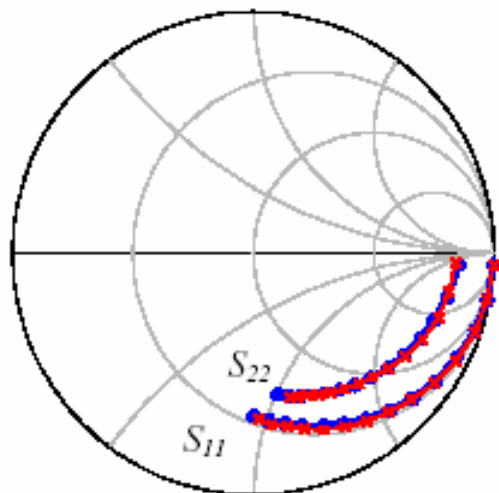


intrinsic part of MOSFET devices

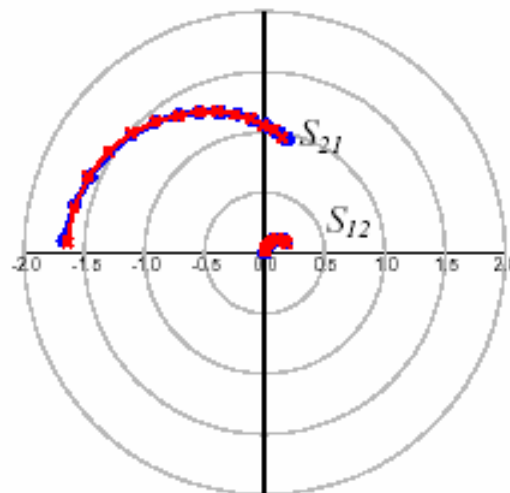
Reference: D. Lovelace et al., "Extracting small-signal model parameters of silicon MOSFET transistors," in *IEEE MTT-S Tech. Dig.*, pp. 865-868, 1994.



Simulation Results



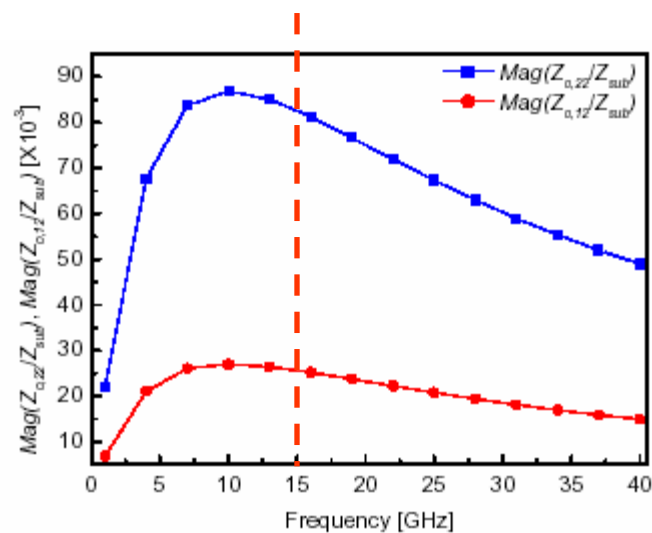
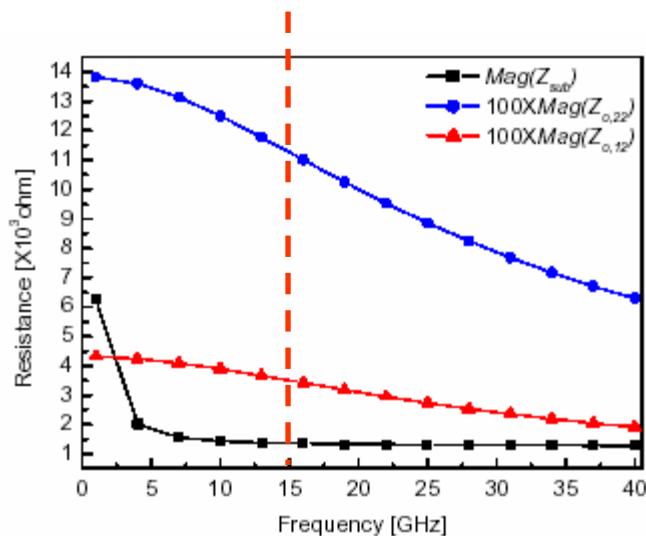
freq (1.000GHz to 40.00GHz)



freq (1.000GHz to 40.00GHz)

Good agreement between measured and simulated data up to 40GHz

Checking $Z_{ie,22}/Z_{sub}$



The 15GHz frequency point is a reasonable choice.

Conclusions

- At high frequencies, the substrate parasitic must be taken into account due to the junction capacitance coupling effect.
- With limiting the lowest fitted frequency point to a certain high-enough one, we find that the drain-side substrate effect will become less significant, so Lee's curve-fitting method can still work well.
- The good modeling results up to 40GHz have verified the feasibility and accuracy of this modified extraction method.



Thanks for Your Attending!

